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THE GEOLOGICAL SOCIETY OF FINLAND  
**Special Volume**  
Abstracts of  
**The 32<sup>nd</sup> Nordic Geological Winter Meeting**  
13<sup>th</sup>–15<sup>th</sup> January 2016, Helsinki, Finland



UNIVERSITY OF HELSINKI



FEDERATION OF FINNISH LEARNED SOCIETIES  
*Delegation of the Finnish Academies of Science and Letters*

**GTK**



# **32<sup>nd</sup> Nordic Geological Winter Meeting**

Helsinki, 13–15 January, 2016

Editors:  
Stratos Staboulis  
Toni Karvonen  
Antti Kujanpää

Conference website:  
[http://www.geologinenseura.fi/winter\\_meeting/](http://www.geologinenseura.fi/winter_meeting/)



# Welcome to Helsinki

We warmly welcome you to the Science Campus of the University of Helsinki on the occasion of the 32<sup>nd</sup> Nordic Geological Winter Meeting! The Geological Society of Finland and the University of Helsinki are proud to organize this meeting. Since the first Nordic Geological Winter meeting held in Gothenburg, Sweden in 1954, this gathering has transformed into a strong tradition that combines geoscientists from all the Nordic countries. The meeting covers a wide range of topics and offers an appreciated venue for presenting research, networking, and meeting old and making new friends.

The 32<sup>nd</sup> NGWM offers an intensive programme that comprises 13 symposia divided into 41 sessions, as well as four stand-alone sessions. During the three days of the meeting, parallel sessions are held in seven lecture rooms. In mid-afternoons, the programme is devoted to poster sessions, which offer the possibility to discuss various geoscientific topics at the poster stands.

We have invited three plenary talks that represent exciting new scientific results and compilations of existing data. On Wednesday, Ritske Huismans will discuss lithosphere deformation and the formation of sedimentary basins. On Thursday, Anna Hughes will present a new compilation and synthesis of the deglaciation of the last Eurasian Ice Sheet. The third plenary talk will be given on Friday by the winner of the Nordic Geoscientist award. The prize was awarded for the first time in Reykjavik at the 30<sup>th</sup> NGWM in 2012 to Haakon Fossen, structural geologist from Bergen, Norway. The winner at the second time, delivered at the 31<sup>st</sup> NGWM held in Lund in 2014, was Stefan Bengtson from the Swedish Museum of Natural History, Stockholm. This year's winner will be announced at the banquet on Thursday evening.

The organization of the 32<sup>nd</sup> NGWM has required one full year of preparation, and a large group of people has been involved in the process. Especially, we would like to thank the Scientific Programme Committee for creating a great programme, the assigned conveners for promoting exciting sessions, the plenary speakers for their commitment, and the many sponsors who have made this event financially possible. We would also like to thank Toni Karvonen, Antti Kujanpää, and Stratos Staboulis from Parsity Partnership for organizing registration, the conference web site, the abstract volume, and many other practicalities.

We hope that the 32<sup>nd</sup> Nordic Geological Winter Meeting will be successful, lead to new insights into the rapidly evolving fields of geosciences, and enhance pertinent Nordic collaboration.

Sincerely,

*The Organizing Committee of the 32<sup>nd</sup> NGWM*

# 32<sup>nd</sup> Nordic Geological Winter Meeting

Helsinki, 13–15 January, 2016

## Organizing committee

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Registration, conference website and the book of abstracts by  
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# 32<sup>nd</sup> Nordic Geological Winter Meeting program and abstracts

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## **1 Venue information and general schedule**

## Venue information

The conference takes place at the Kumpula Campus of the University of Helsinki, about 4 kilometres from the city centre. The campus houses the Faculty of Science.

## Social program

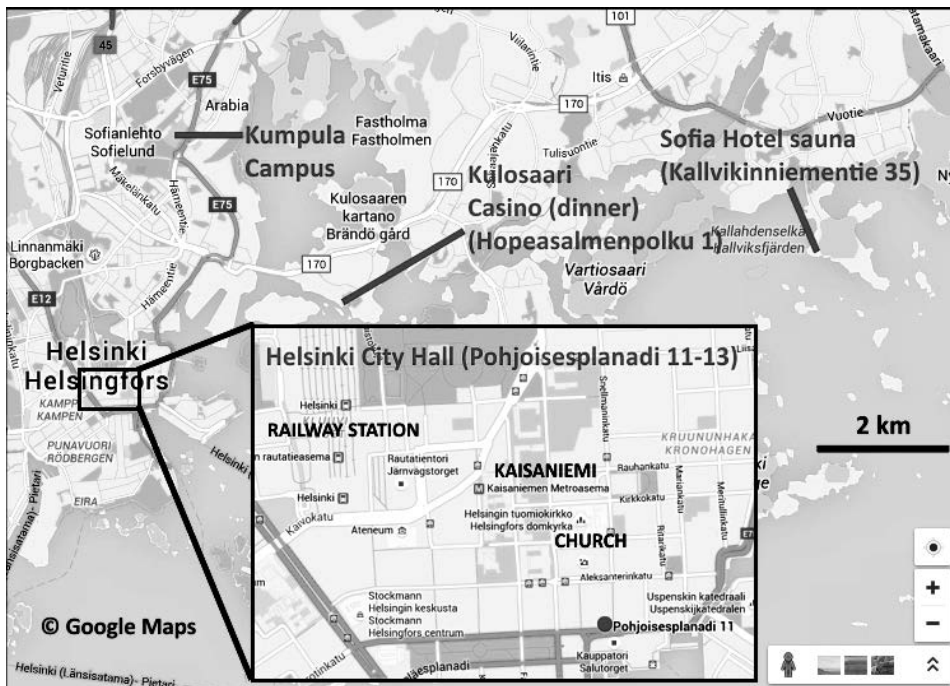
The following three social events are organized during the conference:

- On Wednesday, 13 January, there is a reception at the Helsinki City Hall (Pohjoisesplanadi 11–13) from 18:00 to 19:30.
- On Wednesday, 13 January, after the City Hall reception, a sauna for max. 80 conference participants is reserved at Culture Centre Sofia (Kallvikinniementie 35) from 20:00 to 22:30. Attending the sauna costs 25 EUR per person.
- The conference dinner is served at Kulosaaren Casino (Hopeasalmenpolku 1) on Thursday, 14 January, from 19:00 to 00:30.

See the subsection below for transport information related to the above social events.

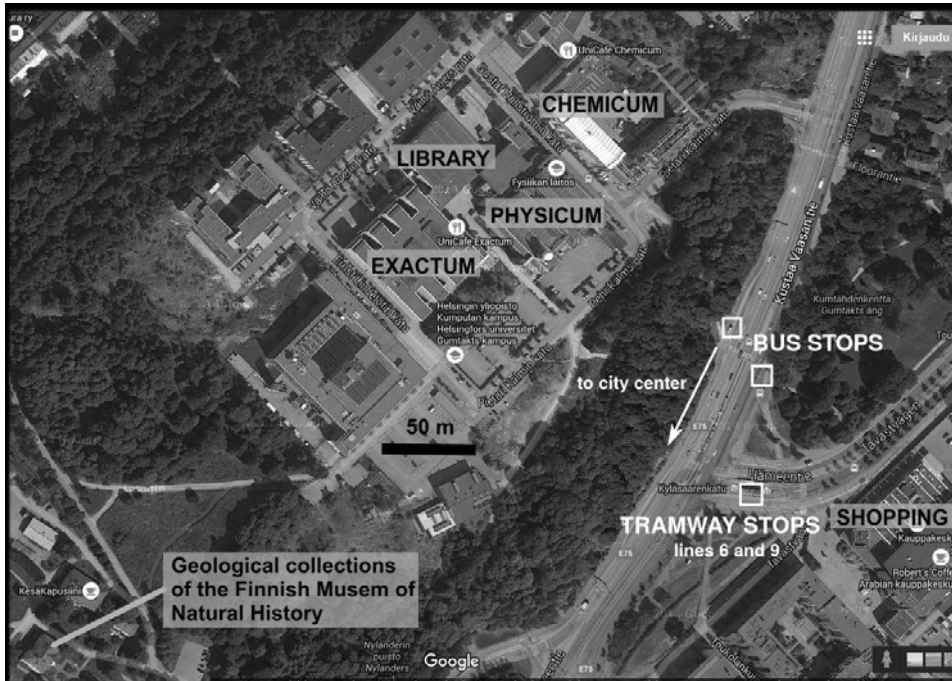
## Hotspots of the conference

Central locations of the meeting are shown below. On Wednesday, there is a back-and-forth bus transportation to the Sofia sauna (start: 19:30 from the Senate Square by the CHURCH on the map; return: 22:30) and on Thursday to conference dinner at Kulosaari casino (start: around 18:00 from Mikonkatu by the Central Railway Station/Järnvägstorget and from Kumpula campus; return: around midnight). Helsinki City Hall may be easily reached by walking from the city centre.



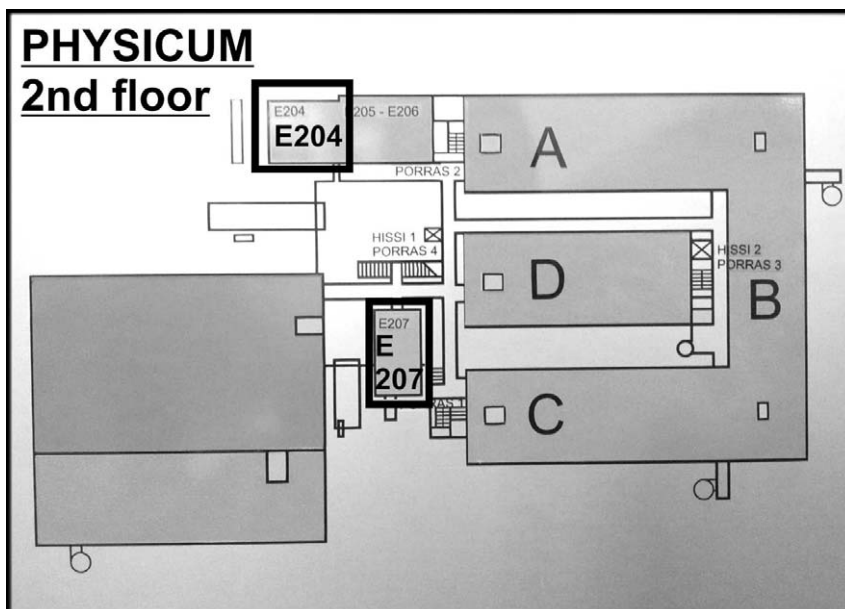
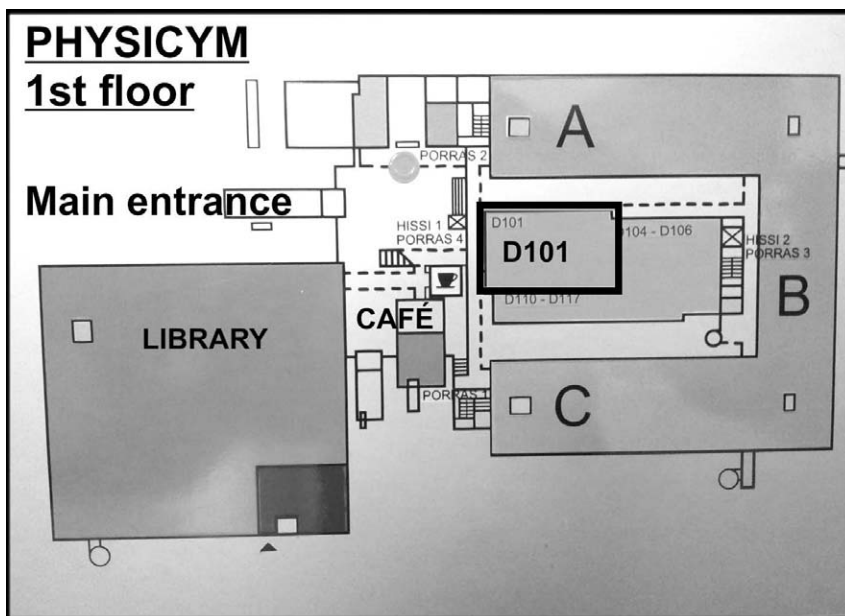
### Map of Kumpula Campus and its surroundings

The main buildings of Kumpula Campus are shown below. Most of the activities will take place at Chemicum, Physicum, and Exactum. Department of Geosciences and Geography is found on the ground floor of Physicum (sections A, B, and C on the floor map on p. 14). The white squares mark the bus and tram stops. The geological collections of the Finnish Museum of Natural History are currently not open to the general public — the participants of the meeting will be informed about possible visiting hours.

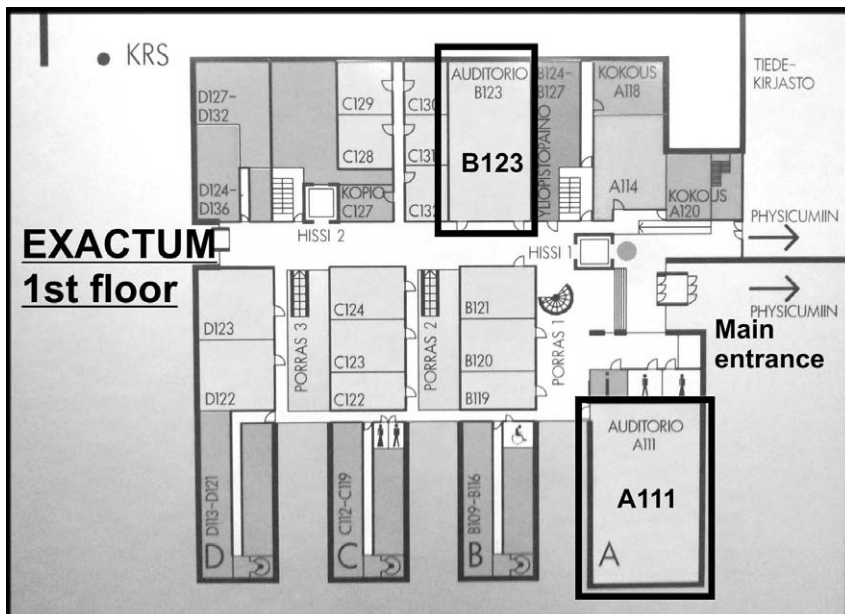
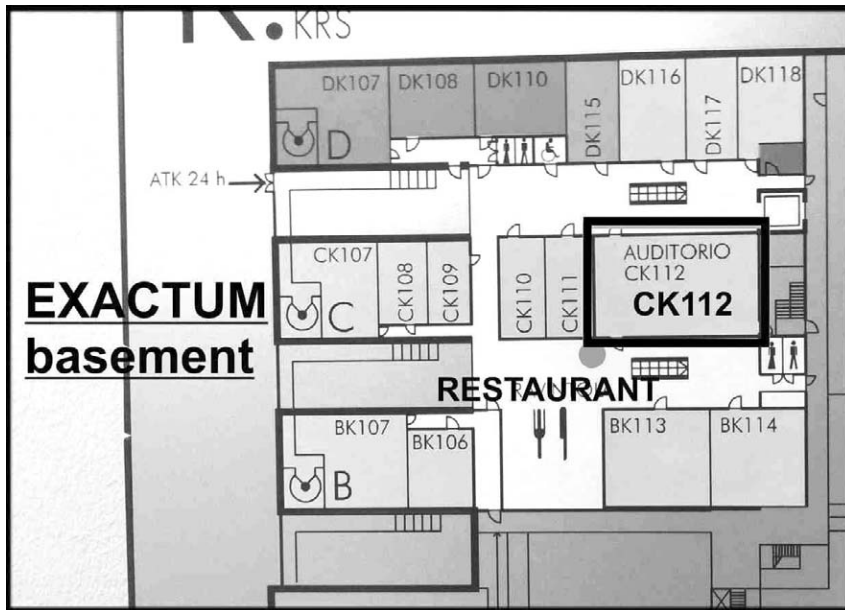


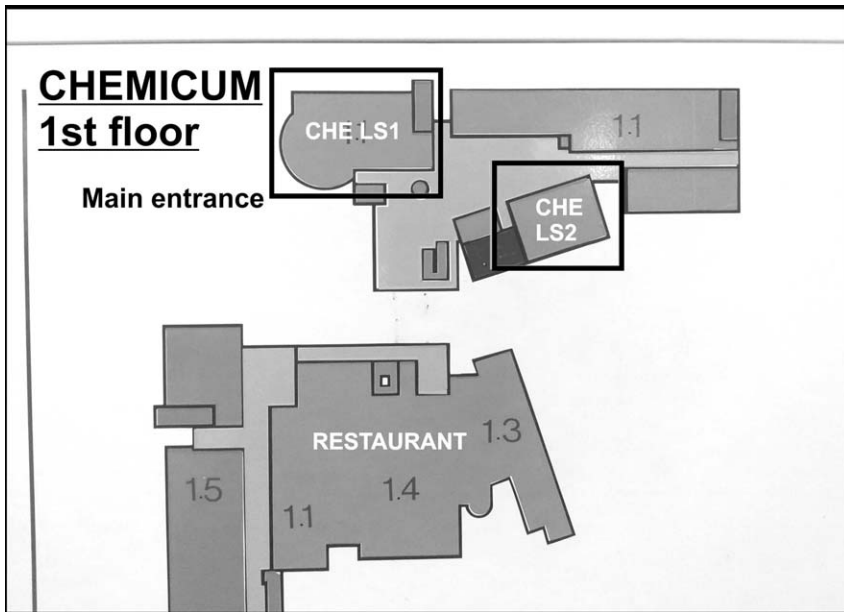
### Floor maps of Kumpula Campus

The conference rooms and restaurants are marked on the below maps. The registration and info desks of the conference, as well as sponsor related and other exhibitions are all located in the lobby of the main entrance of Physicum. Poster sessions are held on the 1<sup>st</sup> (ground) floor of Exactum and Physicum and in the hallway connecting the two buildings. Toilets can be found on all floors.









## Lunch and coffee options

Your registration fee includes three lunch tickets. Lunch is served at the restaurants and cafes at Physicum, Exactum and Chemicum. You can choose freely from the menu. Lunch always includes a side salad, bread, butter and water/juice/milk but not coffee nor dessert.

A soup lunch is served at the Physicum café (incl. bread, butter, water) and a special dietary lunch at the Chemicum restaurant.

Coffee and tea are served at the hallways of Physicum, Exactum and Chemicum near the lecture halls.

## Our vision:

Expert-based GTK produces solutions, new business activities and sustainable growth.

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**Digitalisation:** We add the opportunities and systemic advantages of digitalisation to all processes, innovative operating models aimed at increasing data capital, and customer solutions.

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**Mineral economy:** We promote the use of mineral-based raw materials and their further processing, and create solutions for developing material needs.

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## List of minisymposia and sessions

<b>S1: Applied and environmental geology</b>
S1.1 Geohazards in the Nordic and Arctic regions
S1.2 Hydrogeology
S1.3 Mining and the environment: Towards socially and environmentally acceptable mining
S1.4 Geoenergy
S1.5 Nuclear waste disposal
S1.6 Weathering and Alteration processes of Rocks and Minerals
S1.7 Environmental geology
<b>S2 Economic geology — timely concepts and new developments</b>
S2.1 Critical metals — petrology, geochemistry and ore geology
S2.2 Fluid and melt processes in the earth
S2.3 Geochemical and geophysical exploration methods
S2.4 Precambrian metallogeny
<b>S3 Education and outreach</b>
S3.1 Geoscience outreach
S3.2 Higher education in geosciences: Experiences, practices and development
<b>S4 Geophysics</b>
S4.1 Drilling projects
<b>S5 Lithosphere of Northern Europe</b>
S5.1 Archean of the Fennoscandian shield: From bits and pieces towards a bigger picture
S5.2 Archean-Proterozoic transition
S5.3 Proterozoic orogens
S5.4 Challenges in isotope dating of Precambrian terrains
<b>S6 Marine geology</b>
S6.1 Marine geology
<b>S7 Mineralogy</b>
S7.1 Mineralogy
<b>S8 Palaeoclimatology and palaeoecology</b>
S8.1 Palaeoclimatology: New insights from proxy data and palaeoclimate modeling
<b>S9 Palaeontology — "Life on Earth"</b>
S9.1 Life-Earth Processes in Deep Time
S9.2 What is the Anthropocene?

**S10 Petrology**

- S10.1 Petrology general
- S10.2 Chronicles of petrological processes: In-situ geochemical studies of minerals and melts
- S10.3 Recent developments in metamorphic geology
- S10.4 Mafic-ultramafic intrusions and related ore deposits: Petrology and origin
- S10.5 Precambrian granitic systems of Fennoscandia: From genesis to emplacement

**S11 Quaternary geology**

- S11.1 Glacial geology — processes, deposits and landforms
- S11.2 Glacial history of Scandinavia
- S11.3 Recent developments in Quaternary dating methods

**S12 Sedimentology**

- S12.1 Sedimentology

**S13 Structural geology, tectonics and volcanism**

- S13.1 Burial, uplift and exhumation of Scandinavia and surrounding regions: Timing, magnitude and mechanisms
- S13.2 Dynamics and evolution of the lithosphere from Archean to present
- S13.3 The evolution and architecture of rifts and rifted passive margins: observations and modelling
- S13.4 Imaging and modelling geological structures from microscopic to orogen scales
- S13.5 Impact cratering as a geological process
- S13.6 Interactions between climate, erosion and tectonics
- S13.7 Supercontinents through time
- S13.8 Volcanology

**S15 Stand-alone sessions**

- S15.1 Applied 3D and 4D modelling in geosciences
- S15.2 LIDAR in geology
- S15.3 Arctic research
- S15.4 Nordic collaboration

### Timetable — Wednesday, January 13

8:15	Registration Main lobby of Physicum (Registration also possible on Tue 12 January at 15–18)						
9:30	Opening ceremony D101						
9:45							
10:00	S1.1 E204	S11.1 D101	S8.1 CK112	S13.3 A111 (Starts at 9:45)	S10.4 B123	S2.3 LS1	S13.7 LS2
10:15							
10:30							
12:00	Lunch			Nordic geological societies' Lunch meeting B143			
13:00	Ritske Huismans plenary D101						
14:00	S1.1 E204	S11.3 D101	S8.1 CK112	S13.3 A111	S10.1 B123	S2.2 LS1	S9.2 LS2
14:30	Coffee						
15:00	Poster session 1						
16:00	S1.5 E204	S11.1 D101	S15.2 CK112	S5.2 A111	S10.1 B123	S2.2 LS1	S9.2 LS2
17:15							
17:30							
18:00	Helsinki City Reception Helsinki City Hall						
19:30	Sauna Cultural centre Sofia						

**Timetable — Thursday, January 14**

8:15							
8:30							
9:00	S1.6 E204	S3.2 D101	S15.2 CK 112	S5.2 A111	S10.3 B123	S2.4 LS1	S7.1 LS2
10:00	Coffee						
10:30	S1.2 E204	S11.2 D101	S9.1 CK 112	S13.5 A111	S10.2 B123	S2.4 LS1	S13.4 LS2
12:00	Lunch				Open discussion: Future NordVulk B143		
13:00	Anna Hughes plenary D101						
14:00	S1.7 E204	S11.2 D101	S5.4 CK 112	S1.4 A111	S10.2 B123	S13.2 LS1	S13.4 LS2
14:30	Coffee						
15:00	Poster Session 2						
16:00	S1.7 E204	S11.2 D101	S5.4 CK 112	S1.4 A111	S10.2 B123	S13.2 LS1	S13.4 LS2
17:00							
17:15							
17:30							

### Timetable — Friday, January 15

8:30							
8:45							
9:00	S2.1 E204			S5.1 A111	S10.5 B123	S13.6 LS2	
9:15	S6.1 D102		S3.1 CK112				S15.4 LS1
9:30							
10:00	Coffee						
10:30	S2.1 E204	S6.1 D102	S3.1 CK112	S5.3 A111	S4.1 B123	S15.1 LS1	S13.1 LS2
12:00	Lunch				NordQUA E207		
13:00	Nordic Geoscientist Award plenary D101						
14:00	S1.3 E204	S13.8 D102	S15.3 CK112	S5.3 A111	S12.1 B123	S15.1 LS1	S13.1 LS2
14:30	Coffee						
15:00	S1.3 E204	S13.8 D102	S15.3 CK112	S5.3 A111	S12.1 B123		
15:30							S13.1 LS2
15:45							
16:00							
16:15							







## 2 Plenary talks

The plenary talks are given in hall D101 of Physicum. Real-time video broadcasts of the talks are shown at the nearby hall A111 of Exactum.

### **State of the art forward modeling mountain belt and rifted passive margin formation**

RITSKE S. HUISMANS

*Department of Earth Science, University of Bergen, Norway*

Wednesday, January 13 13:00–13:45 in lecture hall D101

### **Database of the Eurasian Deglaciation, DATED: what did we learn, and what next?**

ANNA HUGHES

*Department of Earth Science, University of Bergen and Bjerknes Centre for Climate Research, Bergen Norway,*

Thursday, January 14 13:00–13:45, in lecture hall D101

### **Nordic Geoscientist Award plenary**

THE NORDIC GEOSCIENTIST AWARD WINNER (to be announced)

Friday, January 15 13:00–13:45, in lecture hall D101

## State of the art forward modeling mountain belt and rifted passive margin formation

R. S. HUISMANS<sup>1</sup>

<sup>1</sup>Department of Earth Science, University of Bergen, Norway

The last 3 decades have seen the development and use of process based forward models applied to solid earth processes including tectonics, landscape evolution, deposition, magmatism. Forward numerical model experiments play an increasingly important role for understanding complex non-linear process interactions and feedback relations that at first sight may be counter intuitive and challenging to understand. As such they can serve to train and enhance our physical intuition. While in the early stages computational power limited spatial and temporal resolution, current computational infrastructure and smart algorithms allow resolving these processes over a large range of scales in 2 and 3 dimensions. Current challenges and focus areas of the geodynamics community include resolving tectonic deformation from seismic to long term time scale over a large range of scales, interaction of tectonics with surface processes, magmatism, fluid flow, and phase changes, and high resolution 3D forward modelling.

Here I will present the current state of the art in modelling mountain belt and rifted margin formation. I will focus on relationships between tectonic deformation and sedimentary basin formation. Resolving the interaction and feedback between tectonic crust-lithosphere scale deformation and surface processes through erosion of elevated areas and formation of sedimentary basins over multiple scales has been a long-standing challenge. While forward process based models have been successful at showing that a feedback is expected between tectonic deformation and redistribution of mass at the earth's surface by erosion, transport, and deposition, demonstrating this coupling for natural systems has been an even greater challenge and is strongly debated. Observational constraints on crust-lithosphere deformation and surface processes are typically collected at highly varying spatial and temporal scales, while forward process based models are typically run at either very large lithosphere-mantle scale, or at the scale of the sedimentary basin making it difficult to investigate and explore the detailed interaction and feedback between these systems. I will report on recent advances in forward modelling linking crust-lithosphere deformation with surface processes over a large range of scales resolving tectonic plate scale deformation and sedimentary basin formation at stratigraphic scales. The forward numerical models indicate a linkage and interaction between the structural style of thick-skinned large-scale mountain belt and rift-passive margin formation, erosion-transport-deposition processes operating at the surface, and the thin-skinned deformation occurring in the associated sedimentary basins.

## Database of the Eurasian Deglaciation, DATED: what did we learn, and what next?

A. L. C. HUGHES<sup>1</sup>, R. GYLLENCREUTZ<sup>2</sup>, J. MANGERUD<sup>1</sup>, AND J. I. SVENDSEN<sup>1</sup>

<sup>1</sup>Department of Earth Science, University of Bergen and Bjerknes Centre for Climate Research, Bergen Norway,  
(\*correspondence: anna.hughes@uib.no)

<sup>2</sup>Department of Geological Sciences, Stockholm University, Sweden

Data compilation and synthesis are an integral part of geological research. Development and testing of new theoretical interpretations largely depend upon evaluation of accumulated observations. Yet over time the task of compiling information becomes increasingly daunting as the volume (and complexity) of data increases. Databases provide an increasingly valuable means by which to collate and share data amongst diverse communities, facilitated by advances in GIS tools and increasing use of online data repositories. This is especially true in the case of palaeo-ice sheet reconstruction which combines a range of approaches and expertise. Glacial geologists require state-of-the-art syntheses of past ice extent to set individual records in context. Glacial modellers require ice-sheet scale empirical constraints that are specified in time and include uncertainty estimates. In 2005, motivated by these dual demands, we started a project (Database of the Eurasian Deglaciation, DATED) to compile and archive all published dates relating to the build-up and retreat of the last Eurasian ice sheets including the British-Irish, Scandinavian and Svalbard-Barents-Kara Seas ice sheets (BIIS, SIS and SBKIS respectively). Over 5000 dates were assessed for reliability and used together with mapped ice-sheet margin positions to reconstruct time-slice maps of the ice sheets' extent every 1000 years between 25-10 ka, and selected older periods. Ten years after the idea for a database was conceived, the first version of results (DATED-1) has now been released (Hughes et al. 2015).

We observe that: i) both the BIIS and SBKIS achieve maximum extent, and commence retreat earlier than the larger SIS; ii) the eastern terrestrial margin of the SIS reached its maximum extent up to 7000 years later than the westernmost marine margin; iii) maximum ice volume (~24 m sea-level equivalent) was reached c. 21 ka; iv) large uncertainties exist; predominantly across marine sectors (e.g. the timing of coalescence and separation of the SIS and BKIS) but also in well-studied areas due to conflicting yet equally robust data.

In this talk, we examine the ice sheet evolution against documented climatic and oceanographic changes of the last glacial period to explore possible driving mechanisms behind the observed changes, and discuss the implications of the documented uncertainty. In just three years since the DATED-1 census (1 January 2013), the volume of new information (from both dates and pattern information) has grown significantly, and we discuss the implications of these additional data and plans for the next version of the database, DATED-2. We also discuss the advantages and challenges of data synthesis from historical data and make recommendations for geological database building, archiving and maintenance. Key considerations to maximise the potential of databases to strengthen future geological research include: data reporting in and appropriate citation of original data sources, the needs of database users and selection of database metadata, access to resulting datasets, clear description of uncertainties and separation of data from interpretations, data standardisation, and access to long-term funding for database maintenance.

### References:

Hughes, A. L. C., Gyllencreutz, R., Lohne, Ø. S., Mangerud, J., Svendsen, J. I.: 2015. The last Eurasian ice sheets — a chronological database and time-slice reconstruction, DATED-1. *Boreas*. 10.1111/bor.12142





### **3 Scientific programme**

## Parallel session — Wednesday morning

### S1.1 Geohazards in the Nordic and Arctic regions

10:00–12:00 in lecture hall E204

CONVENERS: ÞORSTEINN SÆMUNDSSON, REGINALD HERMANNSSON

10:00 What did trigger the rockslide in the Askja caldera on the 21st of July 2014?

ÞORSTEINN SÆMUNDSSON

*University of Iceland*

10:15 Lime stabilisation of soil in the Vinge urban development area, Denmark

LOUISE JOSEFINE BELMONTE

*Technical University of Denmark*

10:30 Permafrost in steep slopes in Norway

BERND ETZELMULLER

*University of Oslo*

10:45 Contaminated area instability — the example of Ångerman River, northern Sweden

ANDREAS STRÖBERG

*Department of Physical Geography, Stockholm University.*

11:00 The influence of steep rock walls on the ground thermal regime

KRISTIN SÆTERDAL MYHRA

*University of Oslo*

11:15 Wind wave climate of west Spitsbergen - seasonal variability and extreme events

KACPER WOJTYSIAK

*Institute of Geophysics, Polish Academy of Sciences, Department of Polar and Marine Research, Poland*

11:30 The origins of large, coastal, paleo-landslides in central Sweden

COLBY SMITH

*Geological Survey of Sweden*

11:45 Ages of rock-avalanche deposits allow tracing the decay of the Scandinavian ice sheet

REGINALD HERMANNSSON

*NGF*

### S11.1 Glacial geology — processes, deposits and landforms

10:00–12:00 in lecture hall D102

CONVENERS: JAN PIOTROWSKI, MARK JOHNSON, ANNE HORMES

10:00 **KEYNOTE** Active subglacial drumlins at Múlajökull, Iceland

ÍVAR ÖRN BENEDIKTSSON

*Institute of Earth Sciences, University of Iceland*

10:30 Conceptual model: Erosional origin of drumlins and mega-scale glacial lineations

NIKO PUTKINEN

*Geological Survey of Finland*

10:45 Subglacial sediment homogenization by clast ploughing

JAN A. PIOTROWSKI

*Department of Geoscience, Aarhus University*

11:00 The role of sub-glacial hydraulic conditions for the formation of fractures in basal tills, examples from recent Icelandic tills and Pleistocene tills in Denmark

KNUD ERIK S. KLINT

*GEUS*

11:15 Different styles of glaciotectionism during an active retreat of a marine terminating glacier - Examples from W-Iceland

THORBJORG SIGFUSDOTTIR

*Lund University*

11:30 Surge-type glaciers in Svalbard identified through remote sensing

WESLEY FARNSWORTH

*University Centre in Svalbard*

11:45 Rates of glacio-isostatic uplift as an age modelling tool

HREGGVIDUR NORDDAHL

*University of Iceland*



**S8.1 Palaeoclimatology: New insights from proxy data and palaeoclimate modeling**

10:15–12:00 in lecture hall CK112

Conveners: ASLAUG GEIRSDOTTIR, HANS PETER SEJRUP, HEIKKI SEPPÄ, SIIM VESKI

10:15 **KEYNOTE Palaeoclimate Modelling of the Late Quaternary: Challenges for the next decade**

PAUL VALDES

*University of Bristol*

10:45 Effects of melting ice sheets and orbital forcing on the early Holocene warming in extratropical Northern Hemisphere

YURUI ZHANG

*University of Helsinki*

11:00 Palaeoclimatic indicators of the Holsteinian Interglacial in Eastern Europe in the light of research in the Polish-Belarusian cross border area

ALEKSANDRA MAJECKA

*Institute of Geology, Warsaw University*

11:15 Past precipitation changes in Finland inferred from annually laminated lake sediments

SAIIA SAARNI

*University of Turku*

11:30 Mid- to late Holocene aeolian activity recorded in a coastal dunefield and lacustrine sediments on Andøya, northern Norway

PÅL RINGKJØB NIELSEN

*University of Bergen*

11:45 Novel Bayesian models for past climate reconstruction from pollen records

LIISA ILVONEN

*University of Oulu***S13.3 The evolution and architecture of rifts and rifted passive margins: observations and modelling**

9:45–12:00 in lecture hall A111

Conveners: RITSKE HUISMANS, ARTO LUTTINEN, JARMO KOHONEN

9:45 **KEYNOTE How to form hyperextended continental margins**

SUSANNE BUITER

*Geological Survey of Norway*

10:15 **KEYNOTE Splitting continents: Lessons from Afar**

TIM WRIGHT

*The University of Leeds*

10:45 Results and regional context of outcrop samples and shallow cores on the outer continental margin of the Norwegian Sea

HARALD BREKKE

*Norwegian Petroleum Directorate*

11:00 Coupling of mantle and flood basalt provinciality in continental rifts: example from Karoo-Ferrar LIP

ARTO LUTTINEN

*Finnish Museum of Natural History*

11:15 Investigating feedbacks between surface processes and tectonics in rift settings using coupled geomorphological and thermo-mechanical models

ROMAIN BEUCHER

*University of Bergen*

11:30 Long-term coupling and feedbacks between surface processes and tectonics during rifting

THOMAS THEUNISSEN

*University of Bergen*

11:45 Preferential development of extension-orthogonal basins in oblique continental rifts

GUILLAUME DUCLAUX

*University of Bergen***S10.4 Mafic-ultramafic intrusions and related ore deposits: Petrology and origin**

10:00–12:00 in lecture hall B123

Conveners: TAPIO HALKOAHO, HANNU MAKKONEN

10:00 **KEYNOTE Mafic-ultramafic intrusions and related Ni-Cu-PGE deposits in the northern part of the Fennoscandian Shield**

EERO HANSKI

*Oulu Mining School*

10:30 Nickel sulfide deposits related to 1.88 Ga mafic-ultramafic magmatism in Fennoscandian and Canadian Shields

HANNU MAKKONEN

*Geological Survey of Finland*

10:45 Characterization and origin of dunitic rocks in the Ni-Cu sulfide-bearing Kevitsa intrusion: whole-rock and mineral compositional constrains  
KIRSI LUOLAVIRTA

11:00 Northern Fennoscandian komatiite-hosted Ni-Cu-PGE deposits: geochemistry and trace element composition of sulphides and oxides  
MARKO MOILANEN  
*University of Oulu - Oulu Mining School*

11:15 Long duration (130 Ma), mantle reservoirs (EM-1, OIB, E-MORB and N-MORB) and multistages history for PGE-bearing Paleoproterozoic layered intrusions in the N-E part of Fennoscandian Shield.  
TAMARA BAYANOVA  
*Laboratory of Geochronology and Isotope Geochemistry*

11:30 Otanmäki and Vuorokas iron-titanium-vanadium oxide deposits, Eastern Finland  
JANNE HOKKA  
*Geological Survey of Finland*

11:45 PGE reefs in the Penikat Layered Intrusion, Northern Finland  
TAPIO HALKOAHO  
*Geological Survey of Finland*

### S2.3 Geochemical and geophysical exploration methods

10:30–12:00 in lecture hall LS1

Conveners: ELENA KOZLOVSKAYA, PERTTI SARALA, PASI EILU

10:30 The Geochemical Atlas of Sweden ; element background concentrations in till  
MARTIYA SADEGHI  
*Geological Survey of Sweden*

10:45 Ultra low-impact geochemical method for greenfield exploration using snow  
PERTTI SARALA  
*Geological Survey of Finland*

11:00 Current trends in geophysical exploration for minerals  
THORKILD RASMUSSEN  
*Luleå University of Technology*

11:15 The origin of internal reflectivity within the Kevitsa intrusion  
NIINA HELLOQVIST  
*University of Helsinki*

11:30 Time-lapse seismic tomography using the data of microseismic monitoring network in Pyhäsalmi mine (Finland)  
JOUNI NEVALAINEN  
*University of Oulu, Sodankylä geophysical observatory*

### S13.7 Supercontinents through time

10:00–12:00 in lecture hall LS2

Conveners: LAURI J. PESONEN, ÅKE JOHANSSON, JOHANNA SALMINEN

10:00 The inner core nucleation of the Earth and its paleogeographic implications  
TONI VEIKKOLAINEN  
*University of Helsinki*

10:15 Unknown details of Palaeoproterozoic evolution of the Karelian Craton: new U-Pb and geochemical data for mafic dykes  
ALEXANDRA STEPANOVA  
*Institute of Geology Karelian Research Centre RAS*

10:30 Paleomagnetism of the Keuruu dyke swarm with implications for Nuna supercontinent  
ROBERT KLEIN  
*University of Helsinki, Department of Physics*

10:45 Profile sampling of the host rock of rapakivi batholiths — A novel way to map Precambrian polarity reversals  
LAURI PESONEN  
*Solid Earth Geophysics Laboratory, Dept. of Physics, PO Box 64, University of Helsinki, Finland of Helsinki.*

11:00 From Nuna to Rodinia: Stenian-Tonian paleogeography  
SERGEI PISAREVSKY  
*Curtin University of Technology*

11:15 Did the Grenville — Sveconorwegian belt go north?  
ÅKE JOHANSSON  
*Swedish Museum of Natural History*

- 11:30 Exploring the hidden Rodinia: crustal xenoliths of Vestfjella, Dronning Maud Land, Antarctica  
ILONA ROMU  
*Geological Survey of Finland*
- 11:45 Paleogeographic evolution of the late Neoproterozoic and early Phanerozoic with new paleomagnetic constraints from West African Craton  
BORIS ROBERT  
*Institut de Physique du Globe de Paris*

## Parallel session — Wednesday afternoon

**S1.1 Geohazards in the Nordic and Arctic regions**

14:00–14:30 in lecture hall E204

Conveners: PORSTEINN SÆMUNDSSON, REGINALD HERMANNSSON

- 14:00 Debris avalanches in western Norway; comparison of geological setting and release mechanisms

LENA RUBENSDOTTER

*Geological Survey of Norway (NGU)*

- 14:15 Drivers and Estimates of Terrain Suitability for Active Layer Detachment Slides and Retrogressive Thaw Slumps in the Brooks Range and Foothills of Northwest Alaska, USA

ANDREW BALSER

*Oak Ridge National Laboratory, U.S. Dept. of Energy***S11.3 Recent developments in Quaternary dating methods**

14:00–14:30 in lecture hall D102

Conveners: MARKKU OINONEN

- 14:00 Finding a good place to date

HELENA ALEXANDERSON

*Lund University*

- 14:15 Bayesian chronological tools in event reconstruction — case study of Vuoksi breakthrough

MARKKU OINONEN

*Finnish Museum of Natural History, University of Helsinki***S8.1 Palaeoclimatology: New insights from proxy data and palaeoclimate modeling**

14:00–14:30 in lecture hall CK112

Conveners: ASLAUG GEIRSDOTTIR, HANS PETER SEJRUP, HEIKKI SEPPÄ, SIIM VESKI

- 14:00 The preboreal retreat of the Iceland Ice Sheet (IIS) and Neoglacial landscape destabilization in the Central Highlands, West Iceland

SYDNEY GUNNARSON

*University of Iceland*

- 14:15 Phytoplankton response to the environmental and climatic variability in a temperate lake over the last 14,500 years in eastern Latvia

NORMUNDS STIVRINS

*Postdoctoral researcher***S13.3 The evolution and architecture of rifts and rifted passive margins: observations and modelling**

14:00–14:30 in lecture hall A111

Conveners: RITSKE HUISMANS, ARTO LUTTINEN, JARMO KOHONEN

- 14:00 A dissected central volcano at Bíggjarskor, Faroe Islands

HANS E.F. AMUNDSEN

*Norwegian University of Science and Technology (NTNU)*

- 14:15 Sedimentary rock record and rapakivi granite emplacement as components of rift basin evolution model

JARMO KOHONEN

*Geological Survey of Finland***S10.1 Petrology general**

14:00–14:30 in lecture hall B123

Conveners: TOM ANDERSEN, TAPANI RÄMÖ

- 14:00 **KEYNOTE** Enriched continental basalts from depleted mantle melts: the issue of lithospheric contamination

JUSSI S. HEINONEN

*University of Helsinki***S2.2 Fluid and melt processes in the Earth**

14:00–14:30 in lecture hall LS1

Conveners: GABRIEL BERNI, THOMAS WAGNER, ERIK JONSSON

- 14:00 Fluid migration and fluid-rock interaction during metamorphism

MATTHIAS KONRAD-SCHMOLKE

*University of Potsdam*

14:15 Coupled reaction driven deformation, strain softening and CO<sub>2</sub> metasomatism in peridotites from the Reinfjord Ultramafic complex, northern Norway  
BJØRN ESKE SØRENSEN  
*NTNU*

**S9.2 What is the Anthropocene?**

14:00–14:30 in lecture hall LS2

Conveners: MIKAEL FORTELIUS

14:00 **KEYNOTE** **The origin of the Anthropocene? Homo-induced collapse of East African carnivore guild, 2 mya.**  
LARS WERDELIN  
*Swedish Museum of Natural History*

## Parallel session — Wednesday evening

**S1.5 Nuclear waste disposal**

16:00–17:30 in lecture hall E204

Conveners: ELINA SAHLSTEDT, JUHA KARHU

16:00 **KEYNOTE** **Glacial meltwater in the bedrock - identification and reactions**EVA-LENA TULLBORG  
*Terralogica AB*

16:30 The effects of the glaciation for deep geological disposal of spent nuclear fuel in crystalline shield rock settings.

ANNE LEHTINEN  
*Posiva Oy*

16:45 Deep groundwater evolution in Outokumpu, eastern Finland — from meteoric water to saline gas rich fluid

RIIKKA KIETÄVÄINEN  
*Geological Survey of Finland*

17:00 Microscale variation in stable isotope composition of fracture minerals — a key to subsurface processes

ELINA SAHLSTEDT  
*University of Helsinki*

17:15 Modelling of Single Tunnel Crosscutting Fractures in the underground rock characterisation facility ONKALO, Olkiluoto, SW Finland

NICKLAS NORDBÄCK  
*Geological Survey of Finland***S11.1 Glacial geology — processes, deposits and landforms**

16:00–17:00 in lecture hall D102

Conveners: JAN PIOTROWSKI, MARK JOHNSON, ANNE HORMES

16:00 Holocene glacier extent and ELA reconstructions of paleoglaciers in Sarek National Park, northern Sweden

CARL REGNÉLL  
*Department of Earth Sciences, University of Gothenburg*

16:15 Glacial sequence stratigraphy reveal the Weichselian glacial history of the SE sector of the Eurasian Ice Sheet

MATTI RÄSÄNEN  
*University of Turku*

16:30 Spatial changes in distribution of suspended matter from the tidewater glacier in Hansbukta, Hornsund Fjord (Spitsbergen)

JOANNA ĆWIAKALA  
*Institute of Geophysics, Polish Academy of Sciences - Centre for Polar Studies KNOW (Leading National Research Centre)*

16:45 Combining terrestrial and marine glacial archives — a geomorphological map of Nordenskiöldbreen forefield, Svalbard

LIS ALLAART  
*University Centre in Svalbard/Norwegian University of Science and Technology***S15.2 LIDAR in geology**

16:00–17:00 in lecture hall CK112

Conveners: ANTTI OJALA, JUKKA-PEKKA PALMU

16:00 **KEYNOTE** **Distribution and annual-origin of De Geer moraines in Sweden with insights from LiDAR**MARK JOHNSON  
*University of Gothenburg*

16:30 Occurrence of De Geer moraines in Finland based on LiDAR DEM

ANTTI E.K. OJALA  
*Geological Survey of Finland*

16:45 The aeolian dunes of Bonåsheden, central Sweden: a geomorphological, geophysical and geochronological case study

MARTIN BERNHARDSON  
*Lund University*

**S5.2 Archean-Proterozoic transition**

16:00–17:15 in lecture hall A111

CONVENERS: ANDREY BEKKER, EERO HANSKI, PETER SORJONEN-WARD

- 16:00 Longevity of Archean oceanic environments — insights from the Ilomantsi greenstone belt

PETER SORJONEN-WARD

*Geological Survey of Finland*

- 16:15 High-grade metamorphism of the Archean to Palaeoproterozoic gneiss complex in Vesterålen, North Norway

ANE K. ENGVIK

*Geological Survey of Norway*

- 16:30 Age and Sm-Nd isotopes of Palaeoproterozoic mafic rocks in Finland — evidence for rifting stages and magma sources

HANNU HUHMA

*Geological Survey of Finland*

- 16:45 Paleoproterozoic spherulitic layers in Zatonaga Formation, Karelia: new data from OnZap1

SIGRID SOOMER

*University of Tartu*

- 17:00 Petrography and the composition of apatite in the Paleoproterozoic Pilgijärvi Sedimentary Formation

TIMMU KREITSMANN

*University of Tartu*

**S10.1 Petrology general**

16:00–17:00 in lecture hall B123

CONVENERS: TOM ANDERSEN, TAPANI RÄMÖ

- 16:00 Mesoproterozoic diabase in Death Valley, California

TAPANI RÄMÖ

*University of Helsinki*

- 16:15 The Pushtashan ophiolite: New Evidences for Iraq Zagros Suture Zone, Kurdistan Region, NE Iraq

SABAH ISMAEL

*Applied Geology Department / University of Kirkuk*

- 16:30 Magmatic age of the Norra Kärr alkaline complex determined by U–Pb and Lu–Hf isotopes of metasomatic zircon in fenite

AXEL SJÖQVIST

*University of Gothenburg*

16:45 Pilanesberg, South Africa: The “forgotten” alkaline complex  
TOM ANDERSEN  
*Department of Geosciences, University of Oslo*

### S2.2 Fluid and melt processes in the Earth

16:00–17:00 in lecture hall LS1

Conveners: GABRIEL BERNI, THOMAS WAGNER, ERIK JONSSON

16:00 Fluid inclusion LA-ICPMS analysis of ore fluids from the Pampalo orogenic gold deposit, Eastern Finland  
TOBIAS FUSSWINKEL  
*University of Helsinki*

16:15 Au-rich fluid inclusions in gold-bearing quartz from the Kola superdeep borehole (SG-3)  
VSEVOLOD PROKOFIEV  
*IGEM RAS*

16:30 Using altered enclaves in the identification of subseafloor replacement processes in VMS systems  
MARCELLO IMAÑA  
*Luleå University of Technology*

16:45 Age and Mo mineralisation in the Phnom Baseth granite, Cambodia  
JEREMY WOODARD  
*University of KwaZulu Natal, Westville (Durban), South Africa*

### S9.2 What is the Anthropocene?

16:00–17:30 in lecture hall LS2

Conveners: MIKAEL FORTELIUS

16:00 A Tale of Ice and Campfires: Changes in the carnivoran guild of Britain during the Quaternary period influenced by hominids and climate change  
LAURA SÄILÄ  
*Department of Geosciences and Geography, University of Helsinki*

16:15 The chemical composition of the atmosphere in the Anthropocene  
FRODE STORDAL  
*University of Oslo, Department of Geosciences*

16:30 Duality of Anthropocene  
JUSSI ERONEN  
*University of Helsinki, Dept. Geosciences & Geography*

16:45 The Anthropocene; a formal stratigraphical unit, an informal concept, or an interval of Holocene time?  
PHILIP GIBBARD  
*University of Cambridge, Department of Geography*

17:00 A Geologic Turn - Deep Time and Deep Futures in contemporary art  
ERICH BERGER  
*Bioartsociety Finland*

17:15 Summary  
NILS CHRISTIAN STENSETH  
*University of Oslo, Faculty of Mathematics and Natural Sciences, Centre for Ecological and Evolutionary Synthesis*



## Parallel session — Thursday morning 1

**S1.6 Weathering and Alteration processes of Rocks and Minerals**

8:15–10:00 in lecture hall E204

Conveners: HENNING DYPVIK, VESA PEURANIEMI

**8:15 KEYNOTE Altered basement rocks as sediment source and oil reservoir - the southern Utsira High, Norwegian North Sea**RONALD SØRLIE  
*Lundin Norway***8:45 Inventory and characteristics of known saprolite locations in Norway**ANNINA MARGRETH  
*Norges geologiske undersøkelse***9:00 Deep weathering and mineral exploration in Norway**ODLEIV OLESEN  
*Geological Survey of Norway***9:15 Saprolites as mineral resources and significance in geochemical exploration**VESA PEURANIEMI  
*University of Oulu***9:30 Aluminum phosphate — sulfate minerals as indicator of Neoproterozoic Baltic paleosol paleoenvironment**ILZE VIRCAVA  
*Tartu University***9:45 Earth Mars Analogues - Linking experimental and Martian clays**CHRISTIAN SÆTRE  
*University of Oslo***S5.2 Archean-Proterozoic transition**

8:30–10:00 in lecture hall D102

Conveners: ANDREY BEKKER, EERO HANSKI, PETER SORJONEN-WARD

**8:30 KEYNOTE Paleoproterozoic carbon isotope excursion: updating the evidence from the Fennoscandian Shield**JUHA KARHU  
*University of Helsinki***9:00 Global to continental-scale glaciations and their sedimentary record during the Archean-Proterozoic transition**KARI STRAND  
*University of Oulu***9:15 Palaeoproterozoic Earth history: a proposed revision**TONY PRAVE  
*University of St Andrews***9:30 Resolving history of the early Paleoproterozoic time**ANDREY BEKKER  
*University of California, Riverside***9:45 Mo and Os as indicators of atmospheric oxygenation: evidence from Paleoproterozoic black shales at Talvivaara, eastern Finland**ASKO KONTINEN  
*Geological Survey of Finland***S15.2 LIDAR in geology**

9:00–10:00 in lecture hall CK112

Conveners: ANTTI OJALA, JUKKA-PEKKA PALMU

**9:00 Structural geology of the Naamivitikko and Riikonkumpu postglacial fault scarps in Finnish Lapland**JUSSI MATTILA  
*Posiva Oy***9:15 Pattern recognition of mass-flow deposits from airborne LiDAR**MAARIT MIDDLETON  
*Geological Survey of Finland***9:30 Timing of paleoseismicity in western Finnish Lapland**RAIMO SUTINEN  
*Geological Survey of Finland***9:45 LiDAR-based interpretation of deglacial dynamics in SW Finland**JONI MÄKINEN  
*University of Turku*

**S3.2 Higher education in geosciences: Experiences, practices and development**

8:30–10:00 in lecture hall A111

Conveners: KIRSTI KORRKA-NIEMI, MIA KOTILAINEN, EILA VARJO

8:30 The role of misconceptions in the development of a reliable geological knowledge. ? statistical analysis of the alternative ideas of Earth Science Bachelor students at Uppsala University.

MAGNUS HELLQVIST

*Department of Earth Sciences*

8:45 GTK Academy for the maintenance of high-grade professional geological survey

PERTTI SARALA

*Geological Survey of Finland*

9:00 Educating towards expertise — self-regulated learning methods in geology

MIA KOTILAINEN

*Department of Geosciences and Geography, University of Helsinki*

9:15 Experiences of teaching in the Turkana Basin Fieldschool, northern Kenya

MIKAEL FORTELIUS

*University of Helsinki & University of Oslo*

9:30 New Master's program in Solid Earth Geophysics at the University of Helsinki: Lessons from one year of operation

EMILIA KOIVISTO

*Department of Geosciences and Geography, University of Helsinki*

9:45 Applied geophysics at Oulu Mining School: challenges and solutions

ELENA KOZLOVSKAYA

*University of Oulu*

**S10.3 Recent developments in metamorphic geology**

9:00–10:00 in lecture hall B123

Conveners: PENTTI HÖLTTÄ, FRANCIS CHOPIN

9:00 **KEYNOTE** Continental Crustal Growth and Consolidation of Crust in Accretionary and Collisional Orogens: Trans-Euroasian Paleozoic System

KAREL SCHULMANN

*Czech Geological Survey*

9:30 Thermodynamics, isochemical and pseudobinary systems: applications to some practical problems including the atmospheric CO<sub>2</sub> budget

SEPPO LEINONEN

*Geologian tutkimuskeskus*

9:45 Leucosome distribution method and geochemical melt modelling in Masku migmatites, SW Finland

ANNA SAUKKO

*Åbo Akademi University*

**S2.4 Precambrian metallogeny**

8:30–10:00 in lecture hall LS1

Conveners: PASI EILU, PER WEIHED

8:30 **KEYNOTE** Precambrian orogens and their hypozonal orogenic gold ores

JOCHEN KOLB

*Geological Survey of Denmark and Greenland*

9:00 Palokas Prospect: An Exciting new Gold Discovery in the Peräpohja Schist Belt, Finland

NICK COOK

*Mawson Resources*

9:15 Tourmaline geochemistry and B-isotopes from the Palokas Au-mineralization, Peräpohja Belt, Northern Finland

JUKKA-PEKKA RANTA

*University of Oulu*

9:30 Re-Os and U-Pb geochronology of the Au-U mineralization at Rompas, Peräpohja Schist Belt

FERENC MOLNÁR

*Geological Survey of Finland*

9:45 In-situ U-Pb of hydrothermal phosphates by LA-ICP-MS: Dating episodic mineralisation along the Kiistala Shear Zone, Central Lapland Greenstone Belt  
ALEXANDER MIDDLETON  
*Geological Survey of Finland*

### S7.1 Mineralogy

8:30–10:00 in lecture hall LS2

Conveners: OLAV EKLUND, MARKKU LEHTINEN

8:30 Reconciling modal mineralogy and chemical compositions of a sample  
MEHDI PARIAN  
*Luleå Tekniska Universitet*

8:45 The sulphide ores in the Alvdal-Tynset region, SE Norwegian Caledonides  
MAREN GALGUFTEN LUNSAETER  
*The Arctic University of Tromsø*

9:00 Origin of gem and ore minerals obtained in gold sluicing in Finnish Lapland  
PEKKA TUISKU  
*University of Oulu*

9:15 Effects of Microstructures and Mineralogical Variables to the Thermal Shock Resistance of Carbonate Soapstone  
ANNE HUHTA  
*University of Oulu*

9:30 The mineralogical characteristics that influence the functionality of “The ÅA Route” - carbonation method  
SONJA LAVIKKO  
*Åbo Akademi University*

9:45 FennoFlake: a project to find flake graphite ores in the Fennoscandian shield and utilize graphite  
OLAV "JOFFI" EKLUND  
*Åbo Akademi University*

## Parallel session — Thursday morning 2

### S1.2 Hydrogeology

10:30–12:00 in lecture hall E204

CONVENERS: KIRSTI KORRKA-NIEMI, JARKKO OKKONEN, TAINA NYSTÉN

10:30 A 3D-model of the Uppsala esker

EVA JIRNER

*Geological survey of Sweden*

10:45 Groundwater vulnerability assessment of shallow low-lying coastal aquifer in south Finland

SAMRIT LUOMA

*Geological Survey of Finland*

11:00 Infrared imaging in assessing ground and surface water resources related to mining development sites, northern Finland

ANNE RAUTIO

*University of Helsinki, Department of Geosciences and Geography*

11:15 Acidity and geochemistry of coarse-grained acid sulfate soil materials in western Finland

STEFAN MATTBÄCK

*Åbo Akademi University*

11:30 Adaptation measures for securing good quality and quantity in Finnish groundwater resources

JANNE JUVONEN

*Finnish Environment Institute*

11:45 Groundwater Checklist - Metadata tool for groundwater protection and interaction

SIRKKU TUOMINEN

*SGS*

### S11.2 Glacial history of Scandinavia

10:30–12:00 in lecture hall D102

CONVENERS: JUHA PEKKA LUNKKA, ANTTI OJALA

10:30 **KEYNOTE** The Scandinavian Ice Sheet - History and dynamics

EILIV LARSEN

*Geological Survey of Norway*

11:00 A new Middle Pleistocene interglacial occurrence in Copenhagen, Denmark

OLE BENNIKE

*Geological Survey of Denmark and Greenland*

11:15 Early Weichselian glacial history in western Finland

JUHA PEKKA LUNKKA

*University of Oulu*

11:30 OSL dating of Weichselian ice-free periods at Skorgenes, western Norway

JOHANNA ANJAR

*National Laboratory for Age Determination, NTNU University Museum*

11:45 Sequential development of Jutulhogget canyon, southern Norway

RANNVEIG ØVREVIK SKOGLUND

*Dep. of Geography, University of Bergen*

### S9.1 Life-Earth Processes in Deep Time

10:30–12:00 in lecture hall CK112

CONVENERS: BJÖRN KRÖGER, AIVO LEPLAND

10:30 **KEYNOTE** Tracing the Evolution of Oxygen on the Archean Earth

KURT KONHAUSER

*University of Alberta*

11:00 The Ediacaran succession and fauna of the Digermulen Peninsula, northern Norway

JAN OVE EBBESTAD

*Museum of Evolution, Uppsala University*

11:15 Local environmental controls on microbial Fe(II)-oxidation in seafloor hydrothermal deposits

KAREN CECILIE JOHANNESSEN

*University of Bergen*

11:30 Microbiological research on the Nornhraun lava field

ANU HYNNINEN

*University of Turku*

- 11:45 Origin of rod and dumbbell shaped phosphate precipitates in Namibian shelf sediments  
 KAAREL MÄND  
*University of Tartu, Department of Geology*

**S13.5 Impact cratering as a geological process**

10:30–12:00 in lecture hall A111

- CONVENERS: STEPHANIE WERNER, ARGO JOELEHT, LAURI J. PESONEN
- 10:30 Postimpact crater sedimentation in marine-target impact structures.  
 HENNING DYPVIK  
*University of Oslo*
- 10:45 The Lockne–Målingen doublet impacts, the result of a binary asteroid from the 470 Ma Main Asteroid Belt Event  
 ERIK STURKELL  
*University of Gothenburg*
- 11:00 Comparing methods to estimate the decay rate of fracturing away from impact centers  
 LAURI PESONEN  
*Solid Earth Geophysics Laboratory, Dept. of Physics, PO Box 64, University of Helsinki, Finland of Helsinki.*
- 11:15 Impact cratering model of the Chelyabinsk meteoroid formation  
 EVGENIYA PETROVA  
*Ural Federal University, Physical Technological Institute, FMPK*
- 11:30 Post-Impact Modification of Craters on Titan by Aeolian and Fluvial Processes : Lessons from Earth Analogs  
 RALPH LORENZ  
*JHU Applied Physics Laboratory*
- 11:45 ASPECT CubeSat mission to a binary asteroid  
 TOMAS KOHOUT  
*Department of Physics, University of Helsinki*

**S10.2 Chronicles of petrological processes: In-situ geochemical studies of minerals and melts**

10:30–12:00 in lecture hall B123

- CONVENERS: JUSSI HEINONEN, VALENTIN TROLL, YANN LAHAYE, HUGH O'BRIEN
- 10:30 **KEYNOTE** Novel isotopic and geochemical applications of Secondary ion mass spectrometry  
 MARTIN WHITEHOUSE  
*Swedish Museum of Natural History*
- 11:00 **KEYNOTE** Laser ablation Rb/Sr dating by on-line chemical separation in a reaction cell  
 THOMAS ZACK  
*University of Gothenburg*
- 11:30 Augite and enstatite standards for SIMS oxygen isotope analysis and their application to Merapi volcano, Sunda arc, Indonesia  
 FRANCES DEEGAN  
*Uppsala University*
- 11:45 Composition and evolution of plume melts in the lower crust; Seiland Igneous Province  
 THOMAS GRANT  
*Norwegian University of Science and Technology (NTNU)*

**S2.4 Precambrian metallogeny**

10:30–12:00 in lecture hall LS1

- CONVENERS: PASI EILU, PER WEIHED
- 10:30 Poly-phase structural controls on ore deposits in northern Sweden  
 TOBIAS BAUER  
*Luleå University of Technology*
- 10:45 Base Metal Zoning in the Pyhäsalmi Volcanogenic Massive Sulfide Deposit  
 JUHO LAITALA  
*Pyhäsalmi Mine Oy*
- 11:00 Regional scale prospectivity analysis of Outokumpu mineral district  
 SOILE AATOS  
*Member of Geological Society of Finland*
- 11:15 Can polymetallic mineralizations in Hiekkapohja, Central Finland be part of a one porphyritic system?  
 ESA HEILIMO  
*Geological Survey of Finland*

11:30 The Circum-Arctic Mineral Resource Project  
ROGVALD BOYD  
*Geological Survey of Norway*

11:45 The Barents project  
ILDIKO ANTAL LUNDIN  
*Geological Survey of Sweden*

**S13.4 Imaging and modelling geological structures from microscopic to orogen scales**

10:30–12:00 in lecture hall LS2

Conveners: MOHAMMAD SAYAB, PIETARI SKYTTÄ, JUSSI MATTILA

10:30 **KEYNOTE** **Imaging rock deformation on multiple scales: advances in better understanding heterogeneous deformation**  
ULRICH RILLER  
*University of Hamburg*

11:00 Seismic investigations in the central Swedish Caledonides  
PETER HEDIN  
*Uppsala University*

11:15 Exposed and blind, multiphase, mafic dykes in the Caledonides of northern Finnmark revealed by a new high-resolution aeromagnetic dataset  
AZIZ NASUTI  
*Geological Survey of Norway (NGU)*

11:30 Trialing the anisotropy of magnetic susceptibility (AMS) to determine the West Spitsbergen Fold-and-Thrust Belt Palaeostress pattern  
KATARZYNA DUDZISZ  
*Institute of Geophysics Polish Academy of Sciences - Centre for Polar Studies*

11:45 The Scandian folds on the Paleozoic sedimentary cover of Estonia  
ÜLO SÕSTRA  
*Estonian Geological Society*

## Parallel session — Thursday afternoon

**S1.7 Environmental geology**

14:00–14:30 in lecture hall E204

Conveners: VELI-PEKKA SALONEN, TIMO TARKKAINEN, PETER ÖSTERHOLM, ARTO ITKONEN

14:00 Sources and controls of organic carbon in subarctic lakes across the Fennoscandian tree line

MARTTIINA RANTALA

*University of Helsinki, Department of Geosciences and Geography*

14:15 Speciation matters: views on iron and sulfur chemistry in geothermal waters, Iceland

HANNA KAASALAINEN

*University of Iceland*

**S11.2 Glacial history of Scandinavia**

14:00–14:30 in lecture hall D102

Conveners: JUHA PEKKA LUNKKA, ANTTI OJALA

14:00 Deglaciation of the southwestern Scandinavian Ice Sheet using <sup>10</sup>Be dating

JOHN INGE SVENDSEN

*University of Bergen and Bjerknes Center of Climate Research*

14:15 Extent and timing of the Late Weichselian Scandinavian ice-sheet maximum and the following deglaciation in northern Atndalen, east-central southern Norway

SVEIN OLAF DAHL

*Department of Geography, University of Bergen*

**S5.4 Challenges in isotope dating of Precambrian terrains**

14:00–14:30 in lecture hall CK112

Conveners: HANNU HUUMA, MARTIN WHITEHOUSE

14:00 **KEYNOTE** Isotope dating from a Nordic perspective — past, present and some thoughts about the future

STEFAN CLAESSON

*Swedish Museum of Natural History*

**S1.4 Geoenergy**

14:00–14:30 in lecture hall A111

Conveners: SIGNHILD GEHLIN, TEPPU AROLA

14:00 **KEYNOTE** Geoenergy in the Nordic Countries

SIGNHILD GEHLIN

*Svenskt Geoenergicentrum*

**S10.2 Chronicles of petrological processes: In-situ geochemical studies of minerals and melts**

14:00–14:30 in lecture hall B123

Conveners: JUSSI HEINONEN, VALENTIN TROLL, YANN LAHAYE, HUGH O'BRIEN

14:00 A novel approach to in-situ rutile thermochronology

ELLEN KOIJMAN

*Swedish Museum of Natural History*

14:15 Nano-powder tablets of mineral standards as matrix-matched reference materials for Rb-Sr dating

ANDREAS KARLSSON

*University of Gothenburg*

**S13.2 Dynamics and evolution of the lithosphere from Archean to present**

14:00–14:30 in lecture hall LS1

Conveners: DAVID WHIPP, GIAMPIERO IAFFALDANO

14:00 **KEYNOTE** Plate Tectonics: Past and Present

TROND TORSVIK

*CEED (University of Oslo)*

**S13.4 Imaging and modelling geological structures from microscopic to orogen scales**

14:00–14:30 in lecture hall LS2

Conveners: MOHAMMAD SAYAB, PIETARI SKYTTÄ, JUSSI MATTILA

14:00 **KEYNOTE** Rock mechanics characteristics of fault zones and their effect for designing underground facilities

ERIK JOHANSSON

*Saario & Riekkola Oy*

## Parallel session — Thursday evening

**S1.7 Environmental geology**

16:00–17:00 in lecture hall E204

Conveners: VELI-PEKKA SALONEN, TIMO TARVAINEIN, PETER ÖSTERHOLM, ARTO ITKONEN

16:00 Geochemistry in soil and humus, central Norway

MALIN ANDERSSON

*Geological Survey of Norway*

16:15 Current applications in using geochemical baselines

JAANA JARVA

*Geological Survey of Finland*

16:30 The first arsenic guidelines for aggregate production were established in Finland

KIRSTI LOUKOLA-RUSKEENIEMI

*Geological Survey of Finland*

16:45 Acid Sulfate Soils in Finland - mapping and environmental risks

PETER EDÉN

*Geological Survey of Finland GTK***S11.2 Glacial history of Scandinavia**

16:00–17:15 in lecture hall D102

Conveners: JUHA PEKKA LUNKKA, ANTTI OJALA

16:00 Dynamics of and controls on post-Younger Dryas retreat of a Bothnian Sea ice stream

SARAH GREENWOOD

*Department of Geological Sciences, Stockholm University*

16:15 What really happened during Salpausselkä formation

KEIJO NENONEN

*Geological Society of Finland*

16:30 Fluctuations of the Scandinavian Ice Sheet during Bølling-Younger Dryas were very different in Western Norway compared with Sweden-Finland

JAN MANGERUD

*University of Bergen*

16:45 Dating the collapse of the Scandinavian Ice Sheet using CH<sub>4</sub>-derived carbonate crusts from the Barents and Norwegian Seas

AIVO LEPLAND

*Geological Survey of Norway*

17:00 Jan Mayen - The Pleistocene-Holocene glacial history of an active volcanic island

ASTRID LYSÅ

*Geological Survey of Norway***S5.4 Challenges in isotope dating of Precambrian terrains**

16:00–17:00 in lecture hall CK112

Conveners: HANNU HUUMA, MARTIN WHITEHOUSE

16:00 Re–Os and U–Pb geochronology — complementary systems

JUDITH L HANNAH

*AIRIE Program, Colorado State University and CEED-University of Oslo*

16:15 Dating the hidden Archaean bedrock of Kimberly South Africa

CAROLINE LUNDELL

*University of Gothenburg*

16:30 A new U–Pb baddeleyite age for the Ottfjället dolerite dyke swarm in the Scandinavian Caledonides — a minimum age for late Neoproterozoic glaciation in Baltica

RISTO KUMPULAINEN

*Dept Geol. Sci., Stockholm University*

16:45 The Varangerian/Marinoan glaciation in Scandinavia - new age constraints

JOHAN PETTER NYSTUEN

*Geological Society of Norway***S1.4 Geoenergy**

16:00–17:30 in lecture hall A111

Conveners: SIGNHILD GEHLIN, TEPPA AROLA

16:00 Groundwater as an energy resource in Finland

TEPPA AROLA

*Golder Associates Oy*



16:15 ORMEL- Optimal utilization of ground water for heating and cooling in Melhus and Elverum  
 SONDRÉ GJENGEDAL  
*NTNU (Norges Tekniske- Naturvitenskapelige Universitet)*

16:30 Seasonal storage of heat and cold in the bedrock.  
 SVEN ÅKE LARSON  
*Terralogica AB*

16:45 Energy systems based on closed loop boreholes in sedimentary areas - development of tools and best practices  
 CLAUD DITLEFSEN  
*Geological Survey of Denmark and Greenland*

17:00 Detecting and quantifying the influence of natural convection on a thermal response test carried out in a groundwater-filled borehole heat exchanger  
 KIMMO KORHONEN  
*Geological Survey of Finland*

### **S10.2 Chronicles of petrological processes: In-situ geochemical studies of minerals and melts**

16:00–17:00 in lecture hall B123

CONVENERS: JUSSI HEINONEN, VALENTIN TROLL, YANN LAHAYE, HUGH O'BRIEN

16:00 In-situ Sr isotope of plagioclase and its implication in the study of mafic layered intrusions  
 SHENGHONG YANG  
*Oulu Mining School, University of Oulu*

16:15 Micro drill sampling in in situ mineral analysis  
 AKU HEINONEN  
*Department of Geosciences and Geography, University of Helsinki*

16:30 Aillikite and Kimberlite Dike Emplacement as a Climax of Long-lived Magmatism in West Greenland  
 MATTHIJS SMIT  
*University of British Columbia*

16:45 Reconstructing the plumbing system of Krakatau volcano  
 VALENTIN TROLL  
*Uppsala University*

### **S13.2 Dynamics and evolution of the lithosphere from Archean to present**

16:00–17:30 in lecture hall LS1

CONVENERS: DAVID WHIPP, GIAMPIERO IAFFALDANO

16:00 Garnet: a key to unraveling Earth's dynamic lithosphere  
 MATTHIJS SMIT  
*University of British Columbia*

16:15 Orogen-parallel mass transport along the arcuate Himalayan front into Nanga Parbat and the western Himalayan syntaxis  
 DAVID WHIPP  
*University of Helsinki*

16:30 Rheological behaviour on the crust of the northern Fennoscandian shield  
 KARI MOISIO  
*OMS/University of Oulu*

16:45 Structural and geochronological studies on the crustal-scale Pajala deformation zone  
 STEFAN LUTH  
*SGU*

17:00 Evolution of the Crustal Structure of the Svecofennian Orogen  
 ANNAKAISA KORJA  
*University of Helsinki*

17:15 Crustal conductors in a complex accretionary Svecofennian orogen in Fennoscandia  
 TOIVO KORJA  
*Geophysical Society of Finland*

### **S13.4 Imaging and modelling geological structures from microscopic to orogen scales**

16:00–17:15 in lecture hall LS2

CONVENERS: MOHAMMAD SAYAB, PIETARI SKYTTÄ, JUSSI MATTILA

16:00 Seismic images providing glimpse into the deep geology of Pyhäsalmi mining district in Finland  
 SUVI HEINONEN  
*Geological Survey of Finland*

- 16:15 Detail scale in situ fracture modelling of excavation damage zone  
NOORA KOITTOLA  
*Posiva Oy*
- 16:30 Deformation phases delineated by AMS in high-grade migmatites, Olkiluoto, SW Finland  
FREDRIK KARELL  
*Geological Survey of Finland*
- 16:45 The tectono-metamorphic evolution of basement rocks as revealed by combining optical, 3D neutron diffraction and x-rays synchrotron microstructural analyses  
MICHELE ZUCALI  
*Università degli Studi di Milano*
- 17:00 Characterizing ore textures by combining synchrotron-based X-ray 3-D nanotomography and LA-ICP-MS analyses: Insights from the Suurikuusikko orogenic gold deposit, Finland  
MUHAMMAD SAYAB  
*Geological Survey of Finland*

## Parallel session — Friday morning 1

**S2.1 Critical metals — petrology, geochemistry and ore geology**

8:30–10:00 in lecture hall E204

Conveners: LAURA LAURI, HÅVARD GAUTNEB

**8:30 KEYNOTE Studies on mineralogy and beneficiation of REE ores**

JASON YANG

*Geological Survey of Finland*

9:00 Transport properties of Nb and Ta in hydrothermal fluids: thermodynamic analysis of hydroxo- and fluoride complexes over a wide range of temperatures and pressures

NIKOLAY AKINFIEV

*IGEM RAS*

9:15 REE mineralisation in Sweden: 222 years of discovery?

ERIK JONSSON

*Geological Survey of Sweden; Uppsala University*

9:30 Critical raw material potential in Finland

LAURA S LAURI

*Geological Survey of Finland GTK*

9:45 Quantifying the resource potential of selected end-of life products for five critical metals

JUSSI POKKI

*Geological Survey of Finland***S6.1 Marine geology**

9:15–10:00 in lecture hall D102

Conveners: THOMAS ANDRÉN, MARTIN JAKOBSSON

9:15 Marine base maps: Making seabed sediment mapping relevant for all

SIGRID ELVENES

*The Geological Survey of Norway (NGU)*

9:30 Large scale seafloor classification based on sediment quality guidelines

HENRY VALLIUS

*Geological Survey of Finland*

9:45 Societal needs and marine geological mapping in Finland - case Pyhäjoki

JYRKI HÄMÄLÄINEN

*Geological Survey of Finland***S3.1 Geoscience outreach**

9:15–10:00 in lecture hall CK112

Conveners: TONI EEROLA, ARI BROZINSKI

**9:15 KEYNOTE Geodiversity - A strategic concept in geological outreach**

LARS ERIKSTAD

*NINA*

9:45 ProGEO - The European Association for the Conservation of the Geological Heritage

TAPIO KANANOJA

*Geological survey of Finland***S5.1 Archean of the Fennoscandian shield: From bits and pieces towards a bigger picture**

8:30–10:00 in lecture hall A111

Conveners: PERTTU MIKKOLA

**8:30 KEYNOTE New insights into the geological evolution of the Archean Norrbotten province, Fennoscandian shield**

LAURA S LAURI

*Geological Survey of Finland GTK*

9:00 Archean evolution of Volgo-Uralia — isotopic constraints

STEFAN CLAESSON

*Swedish Museum of Natural History*

9:15 Chronostratigraphic aspects of the Archean Suomussalmi-Kuhmo-Tipasjärvi greenstone complex

ELINA LEHTONEN

*Finnish Museum of Natural History*

9:30 Archean Belomorian collisional orogen: new data and implication for supercontinent reconstruction

ALEXANDER SLABUNOV

*Institute of Geology, Karelian RC RAS*

9:45 Deeper meaning of the compositionally diverse Neoproterozoic magmatism in the Karelia Province?  
PERTTU MIKKOLA  
*Geological Survey of Finland*

### S10.5 Precambrian granitic systems of Fennoscandia: From genesis to emplacement

9:00–10:00 in lecture hall B123

Conveners: AKU HEINONEN, TAPANI RÄMÖ

9:00 Formation mechanism and age of the Särki-lahti garnet-cordierite leucogranite, SE Finland  
HANNU MÄKITIE  
*Geological Survey of Finland*

9:15 Rapakivi texture in the Wiborg batholith  
KIRSI LARJAMO  
*University of Helsinki*

9:30 Zircon U-Pb ages and  $\delta^{18}\text{O}$  values from syenites and topaz granites of the Suomeniemi batholith  
EINARI SUIKKANEN  
*University of Helsinki*

9:45 Polybaric crystallization of the Ahvenisto anorthosite  
HELI KIVISAARI  
*University of Helsinki*

### S15.4 Nordic collaboration

9:30–10:00 in lecture hall LS1

Conveners: TAPANI RÄMÖ

9:30 NordVulk: Nordic Collaboration in Volcanology and Related Fields  
RIKKE PEDERSEN  
*Nordic Volcanological Center, University of Iceland*

### S13.6 Interactions between climate, erosion and tectonics

8:45–10:00 in lecture hall LS2

Conveners: ANU KAAKINEN, DAVID WHIPP

8:45 A field perspective on the role of creep processes for development of high altitude low relief surfaces  
IVAR BERTHLING  
*Department of Geography, Norwegian University of Science and Technology*

9:00 Glacial striations from the Varangerian glaciation in South Norway  
ROY H. GABRIELSEN  
*Department of geoscience, University of Oslo*

9:15 Tectonic controls of the eolian deposits in Chinese Loess Plateau  
BIN WANG  
*Shaanxi Normal University*

9:30 Variations in the Provenance of the Late Neogene Red Clay in Northern China  
YUAN SHANG  
*University of Helsinki*

9:45 Dust trajectory changes over the Loess Plateau due to regional mountain uplift  
HUI TANG  
*University of Oslo*

## Parallel session — Friday morning 2

**S2.1 Critical metals — petrology, geochemistry and ore geology**

10:30–12:00 in lecture hall E204

Conveners: LAURA LAURI, HÅVARD GAUTNEB

- 10:30 Critical metals in the mines and dumps of W Bergslagen, Sweden  
KARIN HÖGDAHL  
*Uppsala University*
- 10:45 Mineralogy and geochemistry of the apatite vein-type Mushgia Khudag REE-deposit in southern Gobi, Mongolia  
AKSELI TORPPA  
*Geological Survey of Finland*
- 11:00 Scandium deposits and potential in Finland  
MARJAANA AHVEN  
*University of Helsinki*
- 11:15 300 million years of indium-forming processes in A-type igneous environments in the Fennoscandian Shield  
KRISTER SUNDBLAD  
*University of Turku*
- 11:30 Graphite deposits of Norway; a review  
HÅVARD GAUTNEB  
*Geological Survey of Norway*
- 11:45 The Nunasvaara graphite deposit, northern Sweden: New geochemical and U-Pb zircon age results for the host greenstones  
EDWARD LYNCH  
*Geological Survey of Sweden*

**S6.1 Marine geology**

10:30–12:00 in lecture hall D102

Conveners: THOMAS ANDRÉN, MARTIN JAKOBSSON

- 10:30 Geo-biointeractions in a fragmented seafloor area, the Eastern Gulf of Finland  
ANU KASKELA  
*Geological Survey of Finland*

- 10:45 Paleohighlights of IODP Expedition 347, Baltic Sea Paleoenvironment  
THOMAS ANDRÉN  
*School of Natural Science, Technology and Environmental Studies*
- 11:00 Unconformities in the stratigraphic division of strata in a formerly glaciated semi-enclosed basin, the Baltic Sea  
JOONAS VIRTASALO  
*Geological Survey of Finland*
- 11:15 Holocene sedimentation processes in the Ångermanälven River estuary  
OUTI HYTTINEN  
*University of Helsinki*
- 11:30 Preliminary results of seabed investigations in the Baltic Sea and the Gulf of Finland  
STEN SUUROJA  
*Geological Survey of Estonia*
- 11:45 Radocarbon dating of Baltic Sea sediments  
THOMAS ANDRÉN  
*School of Natural Science, Technology and Environmental Studies*

**S3.1 Geoscience outreach**

10:30–12:00 in lecture hall CK112

Conveners: TONI EEROLA, ARI BROZINSKI

- 10:30 The Making of a county - geoheritage mapping in Nordland, Northern Norway  
ANNA BERGENGREN  
*Geological Survey of Norway and Trollfjell Geopark*
- 10:45 Geoheritage - the future potential of Geological Surveys  
SVEN LUNDQVIST  
*Geological Survey of Sweden*
- 11:00 The Geological Narrative  
ARI BROZINSKI  
*Åbo Akademi*
- 11:15 Geoparks promotes geological heritage  
JARI NENONEN  
*Geological Survey of Finland*

- 11:30 Playing with dimension stones: A geological city walk at the New Performance Turku Festival, Finland 2014  
TONI EEROLA  
*Geological Survey of Finland*

### S5.3 Proterozoic orogens

10:30–12:00 in lecture hall A111

Conveners: MIKKO NIRONEN, SVETLANA BOGDANOVA, STEFFEN BERGH

- 10:30 **KEYNOTE** **Paleoproterozoic collisional history of northern Fennoscandia**  
RAIMO LAHTINEN  
*University of Helsinki*
- 11:00 Gravitational Spreading of the Central Part of the Svecofennian Orogen  
KAISA NIKKILÄ  
*University of Helsinki*
- 11:15 The Central Russian fold belt: Paleoproterozoic boundary of Fennoscandia and Volgo-Sarmatia, the East European Craton  
ALEXANDER SAMSONOV  
*Institute of geology of ore deposits, petrography, mineralogy and geochemistry of Russian Academy of Sciences (IGEM RAS)*
- 11:30 The Precambrian crust in the Baltic Sea region  
EVGENIA SALIN  
*University of Turku*
- 11:45 The Danopolonian orogeny: rotation of Baltica between 1.55 and 1.40 Ga  
SVETLANA BOGDANOVA  
*Lund University*

### S4.1 Drilling projects

10:30–12:15 in lecture hall B123

Conveners: ILMO KUKKONEN, MARIA ASK

- 10:30 **KEYNOTE** **The Collisional Orogeny in the Scandinavian Caledonides (COSC) project: investigating mountain building through drilling of a Paleozoic orogen**  
THÉO BERTHET  
*Uppsala University*

- 11:00 Hydrogeologic testing and sampling at the COSC-1 borehole  
LASSE AHONEN  
*Geological Survey of Finland*

- 11:15 Orientation of in-situ horizontal stress in Outokumpu, Finland  
MARIA ASK  
*Luleå University of Technology*

- 11:30 Helsinki University Kumpula Campus Drill Hole Project  
ILMO KUKKONEN  
*Department of Physics, University of Helsinki*

- 11:45 Project DAFNE: Deep drilling in the Pärvie postglacial fault system  
MARIA ASK  
*Luleå University of Technology*

### S15.1 Applied 3D and 4D modelling in geosciences

10:30–12:00 in lecture hall LS1

Conveners: TOBIAS BAUER, TERO NIIRANEN

- 10:30 **KEYNOTE** **The significance of recognizing the structural setting within the context of geological 3D-modelling**  
PIETARI SKYTTÄ  
*University of Turku*
- 11:00 2D and 3D Resistivity Models From Magnetotelluric Measurements North East of Kiruna, Sweden  
MEHRDAD BASTANI  
*Geological Survey of Sweden*
- 11:15 3D-Norge: a new project to build a nationwide 3d bedrock map of Norway  
IAIN HENDERSON  
*Geological Survey of Norway*
- 11:30 Porosity, Permeability, Thermal Properties of clastic rocks. A case study in Stenlille Structure, Denmark.  
LISA PASQUINELLI  
*DTU BYG-Department of Civil Engineering*

11:45 Regional-scale 3D temperature distribution beneath the northern North Sea and adjacent areas of the continent according to lithosphere-scale 3D thermal modelling  
YURIY MAYSTRENKO  
*Geological Survey of Norway (NGU)*

**S13.1 Burial, uplift and exhumation of Scandinavia and surrounding regions: Timing, magnitude and mechanisms**

10:30–12:00 in lecture hall LS2

CONVENERS: PETER JAPSEN, OLA FREDIN, SOFIE GRADMANN

10:30 **KEYNOTE** **The Norwegian strandflat: Insights into an old weathering front**  
MARCO BRÖNNER  
*Geological Survey of Norway*

11:00 The Scandinavian highlands and Miocene to Pliocene sea levels  
FRIDTJOF RIIS  
*Norwegian Petroleum Directorate*

11:15 Uplift and faulting of the Utsira High basement: evidence from low-T thermochronology  
ANNA KSIENZYK  
*University of Bergen*

11:30 Burial and exhumation history of southernmost Norway estimated from apatite fission-track analysis data and geological constraints  
PETER JAPSEN  
*GEUS, Geol. Surv. DK and Greenland*

11:45 Uplift Record in Hydrocarbons and Sulphides in South Norway  
HOLLY STEIN  
*AIRIE Program, Colorado State University and CEED-University of Oslo*

## Parallel session — Friday afternoon

**S1.3 Mining and the environment: Towards socially and environmentally acceptable mining**

14:00–14:30 in lecture hall E204

Conveners: VELI-PEKKA SALONEN, PÄIVI KAUPPILA

14:00 Characterizing the Aijala copper mine tailings by diverse mineralogical methods

MARJALEENA LEHTONEN

*Geological Survey of Finland*

14:15 Seepage water quality and prediction of waste rock effluents

TEEMU KARLSSON

*Geologia.fi / GTK***S13.8 Volcanology**

14:00–14:30 in lecture hall D102

Conveners: HEIDI SOOSALU, ERIK STURKELL

14:00 **KEYNOTE** The role of volatiles in the formation of basaltic to kimberlitic maar-diatreme volcanoes, and its wider implications

HANNES MATTSSON

*ETH Zurich***S15.3 Arctic research**

14:00–14:30 in lecture hall CK112

Conveners: ANNE LEHTINEN, JON ENGSTRÖM

14:00 **KEYNOTE** Monitoring the Greenland ice sheet

DIRK VAN AS

*GEUS***S5.3 Proterozoic orogens**

14:00–14:30 in lecture hall A111

Conveners: MIKKO NIRONEN, SVETLANA BOGDANOVA, STEFFEN BERGH

14:00 Tracing Proterozoic mantle Hf-isotope depletion through coupled zircon U–Pb and Lu–Hf isotopes

ANDREAS PETERSSON

*Lund University*

14:15 1.90–1.88 Ga magmatism of southern Svecofennia: geochemical and Sm–Nd isotopic data from southern Finland

JAAKKO KARA

*University of Turku, Department of Geography and Geology***S12.1 Sedimentology**

14:00–14:30 in lecture hall B123

Conveners: KARI STRAND, MARTIN JAKOBSSON, JAN SVERRE LABERG, MATTHIAS FORWICK

14:00 On the evolution of glaciated continental margins

JAN SVERRE LABERG

*University of Tromsø*

14:15 Last glacial ice sheet dynamics and deglaciation on Svalbard inferred from fjord records

MATTHIAS FORWICK

*University of Tromsø - The Arctic University of Norway***S15.1 Applied 3D and 4D modelling in geosciences**

14:00–14:30 in lecture hall LS1

Conveners: TOBIAS BAUER, TERO NIIRANEN

14:00 3D petrographic imaging and diagenetic modelling of reservoir formations

ORHAN MAHMIC

*University of Oslo*

14:15 Talsinkifix — new challenges for engineering geologists

OSSI IKÄVALKO

*Geological Survey of Finland*



**S13.1 Burial, uplift and exhumation of Scandinavia and surrounding regions: Timing, magnitude and mechanisms**

14:00–14:30 in lecture hall LS2

Conveners: PETER JAPSEN, OLA FREDIN, SOFIE GRADMANN

14:00 Phanerozoic denudation across the Kola Peninsula

ADRIAN HALL

*Department of Physical Geography, University of Stockholm*

14:15 Mass-balance of an Induan (Early Triassic) Fennoscandian-derived sedimentary fan in the Barents Sea: Implications for early Triassic landscape and exhumation

CHRISTIAN HAUG EIDE

*University of Bergen*

## Parallel session — Friday evening

### S1.3 Mining and the environment: Towards socially and environmentally acceptable mining

15:00–16:00 in lecture hall E204

CONVENERS: VELI-PEKKA SALONEN, PÄIVI KAUPPILA

15:00 Mobilization of heavy metals in submarine mine tailings

INGEBORG OKLAND

*Centre for Geobiology/ Department of Earth Science*

15:15 Mine Closure Wiki

PÄIVI KAUPPILA

*Geological Survey of Finland*

15:30 Developing tools for the integration of mining with other land uses

MIRA MARKOVAARA-KOIVISTO

*Geological Survey of Finland*

15:45 Stakeholder engagement practiced by the Geological Survey of Finland in its mineral potential mapping in Southern Finland

TONI EEROLA

*Geological Survey of Finland*

### S13.8 Volcanology

15:00–16:00 in lecture hall D102

CONVENERS: HEIDI SOOSALU, ERIK STURKELL

15:00 Episodic propagation of the 2014 Bárðarbunga-Holuhraun dyke intrusion, Iceland

HEIDI SOOSALU

*Geological Survey of Estonia*

15:15 Volcano-tectonic interplay at the Askja volcanic system, Iceland: Finite element modeling constrained by geodetic measurements

MD. TARIQUL ISLAM

*Department of Earth Sciences, University of Gothenburg, P.O. Box 460, 405 30 Gothenburg, Sweden*

15:30  $^{40}\text{Ar}/^{39}\text{Ar}$  dating basaltic melt segregations in Reykjanes Peninsula, SW Iceland

PAAVO NIKKOLA

*Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland*

15:45 Multi-disciplinary approaches to studying volcanic plumbing systems — a Nordic case study

STEFFI BURCHARDT

*Uppsala Universitet*

### S15.3 Arctic research

15:00–16:00 in lecture hall CK112

CONVENERS: ANNE LEHTINEN, JON ENGSTRÖM

15:00 Groundwater flow and solute transport modelling in coupled permafrost-hydrogeological systems

ANDREW FRAMPTON

*Stockholm University*

15:15 Electromagnetic study of deep permafrost in Central West Greenland

HEIKKI VANHALA

*Geological survey of Finland*

15:30 Geological description of the DH-GAP04 borehole, Kangerlussuaq, Central West Greenland

JON ENGSTRÖM

*Geological Survey of Finland*

15:45 Hydrogeological and hydrogeochemical bedrock conditions under an ice sheet, Kangerlussuaq, Central West Greenland

JAN-OLOF SELROOS

*SKB*

**S5.3 Proterozoic orogens**

15:00–15:30 in lecture hall A111

Conveners: MIKKO NIRONEN, SVETLANA BOGDANOVA, STEFFEN BERGH

15:00 Is mafic magmatism a heat source for the high temperature metamorphism in southern Finland?

MARKKU VÄISÄNEN  
*University of Turku*

15:15 News of the Mauri sandstones

JUSSI LEVEINEN  
*Aalto University*

**S12.1 Sedimentology**

15:00–15:45 in lecture hall B123

Conveners: KARI STRAND, MARTIN JAKOBSSON, JAN SVERRE LABERG, MATTHIAS FORWICK

15:00 Provenance analysis of the Late Glacial — Holocene SW Barents Sea sediments

EKATERINA KAPARULINA  
*Thule Institute, University of Oulu*

15:15 Reservoir Quality of Jurassic Sandstones within the Johan Castberg Field in the Barents Sea.

ABDUL JABBAR  
*University of Oslo*

15:30 Palaeogeography of the main carbonate reservoir of the Barentshavet Sea, the Late Carboniferous-Early Permian Gipsdalen Grou.

GEIR ELVEBAKK  
*Geo-Moski AS*

**S13.1 Burial, uplift and exhumation of Scandinavia and surrounding regions: Timing, magnitude and mechanisms**

15:00–16:15 in lecture hall LS2

Conveners: PETER JAPSEN, OLA FREDIN, SOFIE GRADMANN

15:00 Burial stress and burial strain

IDA LYKKE FABRICIUS  
*Technical University of Denmark*

15:15 3D Stress Modelling of a Neotectonically Active Area in Northwestern Norway

SOFIE GRADMANN  
*NGU - Geological Survey of Norway*

15:30 Process-oriented gravity modelling of the Northern Scandes

JÖRG EBBING  
*Department of Geosciences, Kiel University*

15:45 Isostatic and dynamic support of high passive margin topography in southwestern Scandinavia

VIVI KATHRINE PEDERSEN  
*University of Bergen*

16:00 “For the mountains may be removed and the hills may shake...”

SUSANNE BUTTER  
*Geological Survey of Norway*

## Poster session 1

### S1.1 Geohazards in the Nordic and Arctic regions

Development of an empirical tool to predict rock-slope dam heights of future rock slope failures

VEGARD UTSTØL JAKOBSEN

*Norwegian University of Science and Technology*

The rock slope instability at Tytefjellet in Vindafjord, Norway. Morphologic and structural characterization.

ØYVIND REM

*Norwegian University of Science and Technology (NTNU)*

Determining snow avalanches, debris flows and rock fall runout distances on an active colluvial fan. Innfjorddalen, Norway

SILJE ØREN SKEI

*Geological survey of Norway, Norwegian University of Science and Technology*

Slush flow thresholds for regional early warning in Norway

GAUTE BRUNSTAD ØYEHAUG

*Norwegian Water Resources and Energy Directorate, NVE and University of Oslo, UiO*

### S1.3 Mining and the environment: Towards socially and environmentally acceptable mining

Monitoring of mining impact on natural waters using isotopic tracers (S, U, and Sr) — a pilot study from Talvivaara, northeastern Finland

YANN LAHAYE

*Geological Survey of Finland*

Mining environments — GTK's isotope analytical facilities on dissolved elements in water

IRMELI MÄNTTÄRI

*Geological Survey of Finland (GTK)*

### S1.5 Nuclear waste disposal

New 3D modelling approaches in the study of Palmottu fracture patterns

EEVALIISA LAINE

*Geological Survey of Finland*

Measurement and monitoring of geological repository boreholes using terrestrial laser scanner and photogrammetry

JOHANNA SAVUNEN

*Posiva Oy*

### S2.2 Fluid and melt processes in the Earth

Hydrothermal alteration and sources of fluids in the Juomasuo Au-Co deposit, Kuusamo Schist Belt, Finland

MIKAEL VASILOPOULOS

*Oulu Mining School, University of Oulu*

### S5.2 Archean-Proterozoic transition

Neoarchaean(?) and Palaeoproterozoic tectonometamorphic events affecting the basement-cover sequence on Ringvassøy, West Troms Basement Complex.

PAUL ARMITAGE

*North Atlantic Minerals Ltd*

Mantle source of the 2.44-2.50 Ga mantle plume-related magmatism in the Fennoscandian Shield: evidence from Os, Nd and Sr isotope compositions of the Monchepluton and Kemi intrusions.

SHENGHONG YANG

*Oulu Mining School, University of Oulu*

### S7.1 Mineralogy

Overview of lithium pegmatite exploration in the Kaustinen area

TIMO AHTOLA

*Geological Survey of Finland*

The crystal structure of blödite under extreme conditions and its implications to planetary mineralogy

TONCI BALIC-ZUNIC

*University of Copenhagen*

Flake graphite occurrences in a high-grade metamorphic region in Sortland (NW Norway)

JENNY PALOSAARI

*Åbo Akademi University*

Mineralogy and applications of Sokli vermiculite

MIRADIJE RAMA

*Åbo Akademi*

Synthetic ikaite precipitation simulating conditions in Ikka Fjord, SW Greenland

GABRIELLE STOCKMANN

*Stockholm University*

### **S8.1 Palaeoclimatology: New insights from proxy data and palaeoclimate modeling**

7500 Years of Pine Tree-Ring  $\delta^{13}\text{C}$  Values from Norther Finland

LAURA ARPPE

*Finnish Museum of Natural History*

Dinoflagellate cysts as a sea-ice proxy — new insights from the Hudson Bay system

MAIJA HEIKKILÄ

*University of Helsinki*

Sokli: a hotspot for climate change research in the North Atlantic region

KARIN HELMENS

*University of Stockholm*

Drivers of regional and local boreal forest dynamics during the Holocene

NIINA KUOSMANEN

*Department of Geosciences and Geography, University of Helsinki*

Re-coring Lake Kråkenes: a high resolution lake archive of palaeohydrological variability

DAVID MAAS

*GFZ Potsdam*

Parameter correlations in paleoclimatics - PIXE, PIGE and RBS

SARIANNA SALMINEN

*Department of Geography and Geology, University of Turku*

Major Cooling Intersecting Peak Eemian Interglacial Warmth in Northern Europe

SAKARI SALONEN

*University of Helsinki*

Climate signals in tree-rings from the Norwegian Stave Churches

HELENE LÖVSTRAND SVARVA

*NTNU University Museum*

From eutrophic towards hypertrophic - the story of southern Finnish lakes

MIRA TAMMELIN

*University of Turku*

Plant macrofossil evidence for an early onset of the Holocene summer thermal maximum in northernmost Europe

MINNA VÄLIRANTA

*University of Helsinki*

### **S9.1 Life-Earth Processes in Deep Time**

The Ordovician reefs of Baltica

BJÖRN KRÖGER

*University of Helsinki*

Magnetostratigraphic framework for the late Miocene mammalian fossils in Maragheh, NW Iran

MOHAMMAD PAKNIA

*Department of Geology and Geography, University of Helsinki*

Ancient ecosystems of crystalline bedrock fractures

LOTTA PURKAMO

*VTT Technical Research Centre of Finland*

### **S9.2 What is the Anthropocene?**

Co-occurrence of pliopithecoid and hominoid primates in the fossil record: an ecometric analysis

LEENA SUKSELAINEN

*University of Helsinki*

**S10.1 Petrology general**

The stability of wöhlerite in agpaitic nepheline syenite: The effect of oxygen fugacity

TOM ANDERSEN

*Department of Geosciences, University of Oslo*

Naujakasite revisited

TOM ANDERSEN

*Department of Geosciences, University of Oslo*

Stability of hydrothermal tourmaline: insights from phase equilibria experiments in the system MgO-(±FeO)-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O-NaCl-B<sub>2</sub>O<sub>3</sub> at 400-650 °C and 3 kbar

HENRIK KALLIOMÄKI

*University of Helsinki*

A general model for carbonatite petrogenesis in shallow alkaline intrusions

HANNES MATTSSON

*ETH Zurich*

**S10.2 Chronicles of petrological processes: In-situ geochemical studies of minerals and melts**

Chemical evolution of the Luumäki gem beryl pegmatite: Constraints from EPMA and LA-ICPMS mineral composition data

RADOSLAW MICHALLIK

*University of Helsinki*

Magmatic fractionation and episodic fluid exsolution of the Kymi topaz granite stock, SE Finland: Insights from biotite major and trace element chemistry

GABRIEL VALENTIM BERNI

*University of Helsinki*

**S10.3 Recent developments in metamorphic geology**

Metamorphic map of Finland

PENTTI HÖLTTÄ

*Geological Survey of Finland*

<sup>40</sup>Ar/<sup>39</sup>Ar thermochronology of low-temperature alteration in a flood basalt pile during burial metamorphism

MORTEN S. RIISHUUS

*Nordic Volcanological Center, University of Iceland*

**S10.4 Mafic-ultramafic intrusions and related ore deposits: Petrology and origin**

The Rein fjord Ultramafic complex; Petrology and Geochemistry

KIM RUNE B. GRANNES

*Norwegian University of Science and Technology*

Chalcophile element geochemistry of komatiites and basalts in the Archean greenstone belts of Russian Karelian

FANGFANG GUO

*University of Oulu*

The origin of internal reflectivity within the Kevitsa intrusion

NIINA HELLQVIST

*University of Helsinki*

The Hunt for Platinum Group Elements in the Rein fjord Intrusive Complex

EVEN NIKOLAISEN

*Norwegian University of Science and Technology*

Pt-Os geochronology constraints of a Cu-Pt-rich ore body in the Jinchuan intrusion, China: dating hydrothermal overprinting and the final emplacement of the deposit

SHENGHONG YANG

*Oulu Mining School, University of Oulu*

**S11.1 Glacial geology — processes, deposits and landforms**

Microtextural and heavy mineral constraints on the oscillations of the late Pleistocene Scandinavian Ice Sheet

NINNA IMMONEN

*University of Oulu*

Provenance of glacial sediments by detrital geochronology from Kapp Ekholm, Svalbard

FILIP JOHANSSON

*University of Gothenburg*

Glacial landscapes carved by subglacial meltwater erosion under the Scandinavian Ice Sheet

JAN A. PIOTROWSKI

*Department of Geoscience, Aarhus University*

Internal structure and drainage conduits in a cold Svalbard glacier

JAN A. PIOTROWSKI

*Department of Geoscience, Aarhus University*

Evolution of saltwater intrusions in coastal aquifers during the past and the future

JAN A. PIOTROWSKI

*Department of Geoscience, Aarhus University*

Thickness of superficial deposits in Finland

OLLI SALLASMAA

*Geological Survey of Finland*

### S11.2 Glacial history of Scandinavia

DATED-2: updates to the Eurasian ice sheet chronology and time-slice reconstructions

RICHARD GYLLENCREUTZ

*Department of geological sciences, Stockholm University*

Lake Nordlaguna, Jan Mayen: the potential for a palaeoclimate record from the island

EILIV LARSEN

*Geological Survey of Norway*

### S11.3 Recent developments in Quaternary dating methods

Cosmogenic surface exposure dating with  $^{36}\text{Cl}$  on Jan Mayen

JOHANNA ANJAR

*National Laboratory for Age Determination, NTNU University Museum*

Quantifying the Past Present and Future at the Laboratory of Chronology

KARI ESKOLA

*Helsinki University, Laboratory of Chronology*

Askja 1875 tephra in lake sediment in Southern Finland

MAARIT KALLIOKOSKI

*Department of Geography and Geology, University of Turku*

Trondheim radiocarbon laboratory — performance results and future plans

HELENE LØVSTRAND SVARVA

*NTNU University Museum*

### S13.2 Dynamics and evolution of the lithosphere from Archean to present

Monazite and Zircon Dating of the plagiogranites in the Mawat Ophiolite Complex, NE Iraq.

HEIDER AL HUMADI

*Turku University*

Consistent top-to-the-foreland directed deformation from floor to roof in the Seve Nappe Complex (SNC), Jämtland, Sweden

HAGEN BENDER

*Stockholm University*

Structural framework of Paleoproterozoic rocks northeast of Kiruna, Sweden

SUSANNE GRIGULL

*Geological Survey of Sweden*

Controls on continental strain partitioning above an oblique subduction zone, Northern Andes

JORINA SCHÜTT

*University of Helsinki*

Basement deformation during continental collision: a modelling example of the Swedish central Caledonides.

RÉMI VACHON

*Uppsala University*

The rock matrix: formation and evolution of rocks in polyphase metamorphic basements

MICHELE ZUCALI

*Università degli Studi di Milano*

### S13.5 Impact cratering as a geological process

Deep subcrater shock effects in large terrestrial impact structures

ADAM ANDREAS GARDE

*Geological Survey of Denmark and Greenland*

Söderfjärden impact crater, new results and new drilling plan

SATU HIETALA

*Geological Survey of Finland*

Reflection seismics of the Dobeles impact crater, Latvia

ARGO JÖELEHT

*University of Tartu, Department of Geology*

Shock-darkening in ordinary chondrites: impact modelling

JULIEN MOREAU

*University of Helsinki*

Reflectance spectra of meteorites and asteroids – new results and applications?

LAURI PESONEN

*Solid Earth Geophysics Laboratory, Dept. of Physics, PO Box 64, University of Helsinki, Finland of Helsinki.*

Geological overview of the Ritland impact structure

FRIDTJOF RIIS

*Norwegian Petroleum Directorate*

Inverted Structure of Suevites at Bosumtwi Crater: Implications to Mixing of Outer Suevites

RUDOLF VÄLJA

*University of Tartu*

On the Scaling of Small Impact Craters on the Moon

STEPHANIE WERNER

*CEED - University of Oslo*

### **S13.7 Supercontinents through time**

Geomagnetic Field at the Mesoproterozoic - Geocentric Axial Dipole?

ROBERT KLEIN

*University of Helsinki, Department of Physics*

Testing the core of the Proterozoic Supercontinent Nuna

JOHANNA SALMINEN

*University of Helsinki*

### **S15.2 LIDAR in geology**

LiDAR-based geomorphological mapping and Quaternary stratigraphy in the Sodankylä region, northern Finland

PETER JOHANSSON

*Geological Survey of Finland*

Characterization of Riikonkumpu fault scarp in Kitilä

ASKO KÄPYAHO

*Geological Survey of Finland*

Appearance of PGFs in Finland – case Lauhavuori

JUKKA-PEKKA PALMU

*Geological Survey of Finland*

Distribution of the fine-grained sediments in Helsinki metropolitan area, Finland

MAARIT SARESMA

*Geological Survey of Finland*



## Poster session 2

### S1.2 Hydrogeology

Bank storage affected aquifer along the river Kiti-  
nen in Sodankylä, Northern Finland

SUSANNE ÅBERG

*Department of Geosciences and Geography, Uni-  
versity of Helsinki*

Understanding groundwater-surface water exchange  
as a tool for groundwater management.

PETER HOWETT

*University of Helsinki*

Integration of conventional method and transition  
probability geostatistics for the evaluation of aquifer  
heterogeneity

SAMRIT LUOMA

*Geological Survey of Finland*

### S1.4 Geoenergy

CO<sub>2</sub> storage potential of the Norwegian Continental  
Shelf

MAREN BJØRHEIM

*Norwegian Petroleum Directorate*

Physical- and geochemical properties of core sam-  
ples from the Swedish part of the southern Baltic  
Sea: Implications for CO<sub>2</sub> storage

EHSAN ELHAMI

*Division of Geoscience and Environmental engi-  
neering*

Mapping of CO<sub>2</sub> Storage Possibilities on the Nor-  
wegian Continental Shelf

JASMINKA MUJEZINOVIC

*Norwegian Petroleum Directorate*

### S1.6 Weathering and Alteration processes of Rocks and Minerals

Geochemical changes in a podzolic forest soil  
caused by mechanical site preparation

ANTTI-JUSSI LINDROOS

*Natural Resources Institute Finland*

Deep weathering patterns on the Fennoscandian  
shield in northern Finland

PERTTI SARALA

*Geological Survey of Finland*

Neoproterozoic weathering crust of Baltic Basin

PEETER SOMELAR

*University of Tartu, Department of Geology*

### S1.7 Environmental geology

Acid Sulfate Soils in Northern Europe. A prelimi-  
nary overview

PETER EDÉN

*Geological Survey of Finland GTK*

Tracing the carbon cycle in river systems using the  
isotopic composition of dissolved inorganic carbon

PAULA NIINIKOSKI

*University of Helsinki*

Extraction of Natural Stone in Finland - The Best  
Environmental Practices (BEP)

ILONA ROMU

*Geological Survey of Finland*

Acid sulphate soils along the coast of northern Swe-  
den

GUSTAV SOHLENIUS

*Geological Survey of Sweden*

Comparison on humus and soil geochemical base-  
lines in Southern Finland

TIMO TARVAINEN

*Geological Survey of Finland*

### S2.1 Critical metals — petrology, geochemistry and ore geology

REE mineralisation in the Olserum area, SE Swe-  
den

STEFAN ANDERSSON

*University of Helsinki*

Petrography, geochemistry and P-, Nb-, and REE-mineralizations in the Kaulus region, Sokli carbonatite complex, Finland

LAURA S LAURI

*Geological Survey of Finland GTK*

Thermal and hydrothermal influence of rapakivi igneous activity on Late Svecofennian granites in SE Finland

KRISTER SUNDBLAD

*University of Turku*

### **S2.3 Geochemical and geophysical exploration methods**

The use of geophysical methods in assessment of natural stone prospects

PAAVO HÄRMÄ

*Geological Survey of Finland*

Delineating structures hosting REE-bearing apatite iron oxide (Sweden) and apatite-rich carbonatite-alkaline deposits (Finland) through systematic geophysical and geological investigations

ALIREZA MALEHMIR

*Uppsala University*

Geochemistry of the hydrothermally altered rocks in Orijarvi, SW Finland

ALEKSI RATSULA

*University of Turku*

### **S2.4 Precambrian metallogeny**

Magnetic properties for characterization and quantification of magnetite and hematite in apatite iron-oxide deposits at Blötberget, central Sweden

ANDREAS BJÖRK

*Department of Earth Sciences, Uppsala University*

Assessment of orogenic gold resources in Finland

PASI EILU

*Geological Survey of Finland*

Towards a structural framework for apatite-iron oxide deposits in the Grängesberg-Blötberget area, Bergslagen, Sweden

SARA EKLÖF

*Uppsala University*

Mineral chemistry, spectroscopy and parageneses of oxyborates in metamorphosed Fe-Mn oxide deposits, Bergslagen, Sweden

ZACHARIAS ENHOLM

*Department of Earth Sciences, Uppsala University*

Phyllic alteration-related Cu-Au mineralisation at Raitevarri, Norway

JANI JÄSBERG

*University of Turku*

Te-Se-Au-Ag-Bi-rich polymetallic vein mineralisation south of Glava, SW Sweden

ERIK JONSSON

*Geological Survey of Sweden; Uppsala University*

Major and trace element analysis of sphalerites from W Bergslagen, Sweden

ARISTEIDIS KRITIKOS

*Uppsala University*

Petrophysics revealing alteration zones of ore deposits

SATU MERTANEN

*Geological Survey of Finland*

The Palaeoproterozoic Vannareid VMS occurrence in the northern Fennoscandian Shield

JUHANI OJALA

*GTK (Geological Survey of Finland)*

Metallogeny of the Precambrian West Troms Basement Complex, northern Norway

HANNE-KRISTIN PAULSEN

*Arctic University of Norway*

Trace element composition of Fe-oxides from Cu-Fe mineralization in the Paleoproterozoic Lätäseno Schist Belt, Finnish Lapland

ANTONIN RICHARD

*Univ. Lorraine - GeoRessources - Nancy*

Mineralogy and geochemistry of indium-bearing polymetallic veins in the Sarvixviken area, Lovisa, Finland

MIRA VALKAMA

*University of Turku, Department of Geography and Geology*

**S3.1 Geoscience outreach**

Coming to terms with geodiversity in Norwegian nature management

ANNA BERGENGREN

*Geological Survey of Norway and Trollfjell Geopark*

Aspiring Trollfjell geopark — Geology and Landscape at Sør-Helgeland and Leka, central Norway

ANNA BERGENGREN

*Geological Survey of Norway and Trollfjell Geopark*

**S3.2 Higher education in geosciences: Experiences, practices and development**

Helping geology students to learn without teachers present

HELENA ALEXANDERSON

*Lund University*

International Earth Science Olympiad: inspiring a new generation of geoscientists

ANN MARI HUSÅS

*Geological Society of Norway*

Does University Entrance Exam Type Predict Student-material ?

EILA VARJO

*University of Turku*

**S5.1 Archean of the Fennoscandian shield: From bits and pieces towards a bigger picture**

Magnetotellurics in Northern Finland

UULA AUTIO

*Oulu Mining School, University of Oulu*

**S5.3 Proterozoic orogens**

Sveconorwegian albitites, Bamble Sector, S-Norway — new U/Pb geochronological and stable O-isotopic data

ANNE K. ENGVIK

*Geological Survey of Norway*

U-Pb SIMS dating of granitoids from eastern Blekinge, southern Sweden

ÅKE JOHANSSON

*Swedish Museum of Natural History*

Titanite and zircon U-Pb ages from West Uusimaa complex, Finland, and implications to titanite geochronology

MATTI KURHILA

*University of Helsinki*

New bedrock geological map and database of Finland 1:1 000 000

MIKKO NIRONEN

*Geological Survey of Finland*

1.86 Ga granites in the Salo area, SW Finland

HEIDI PENTTINEN

*University of Turku*

Remnants of pre 1650 Ma sediments in the Western Gneiss Complex, Norway

TORKIL S. RØHR

*Geological Survey of Norway (NGU)*

The 1.83-1.80 Ga volcano sedimentary sequence in southern Lithuania: origin, evolution and correlation with south-central Sweden

LAURYNAS ŠILIAUSKAS

*Institute of Geology and Geography, Nature Research centre*

Trans-Baltic Palaeoproterozoic correlations as a key to the Svecofennian orogeny

GRAZINA SKRIDLAITE

*Institute of Geology and Geography, Nature Research Centre*

**S5.4 Challenges in isotope dating of Precambrian terrains**

Precise U-Pb (ID-TIMS) and SHRIMP-II ages on single zircon and Nd-Sr signatures from Achaean TTG and high aluminum gneisses on the Fennoscandian Shield

TAMARA BAYANOVA

*Laboratory of Geochronology and Isotope Geochemistry*

**S6.1 Marine geology**

Physical properties of glacial sediments from the Landsort Deep

RAISA ALATARVAS

*University of Helsinki*

Long-term trends in coastal hypoxia in the Archipelago Sea of Finland — is it a natural phenomenon?

SAMI JOKINEN

*Department of Geography and Geology, University of Turku*

Seabed substrates and sedimentation rates of the European Seas — EMODnet Geology

AARNO KOTILAINEN

*Geological Survey of Finland*

Seabed sediment grain size prediction using multi-beam backscatter data and spatial regression models

GILL SCOTT

*INFOMAR, Geological Survey of Ireland*

Iron and manganese in coastal sediments of the Gulf of Finland: relevance for methane dynamics

ROSA TIIHONEN

*The Department of Geosciences and Geography, University of Helsinki*

#### **S10.5 Precambrian granitic systems of Fennoscandia: From genesis to emplacement**

Net-veined and mafic pillow structures in the 1,64 Ga Ahvenisto complex, southeastern Finland.

RIIKKA FRED

*University of Helsinki*

The age of the Wiborg batholith

AKU HEINONEN

*Department of Geosciences and Geography, University of Helsinki*

Age of the late stage magmatic phases of the Ahvenisto rapakivi granite batholith

SARI LUKKARI

*Geological Survey of Finland*

Three stages to form and stabilize an arc-collisional batholith — an example from the Svecofennian orogen

KAISA NIKKILÄ

*University of Helsinki*

#### **S12.1 Sedimentology**

The Early to Middle Cenozoic paleoenvironment and sediment yield of the southwestern Barents Sea margin

AMANDO LASABUDA

*Research Centre for Arctic Petroleum Exploration (ARCEX), University of Tromsø, Norway*

#### **S13.4 Imaging and modelling geological structures from microscopic to orogen scales**

Prediction of Zones of Weakness – from ground to tunnel

TUIJA ELMINEN

*Geological Survey of Finland*

Use of terrestrial laser scan data in detailed geological structure mapping: a case study from Vekara, SW-Finland

JUSSI KINNUNEN

*University of Turku*

Characterization and 3D -modelling of the brittle structures in Westmetro tunnels

MIRVA LAINE

*University of Turku*

#### **S13.6 Interactions between climate, erosion and tectonics**

First magnetostratigraphic time frame for the fossiliferous late Eocene – early Oligocene sequence at Ulanatal, Inner Mongolia, China

ANU KAAKINEN

*University of Helsinki*

Noble gas geochronology: new tools for constraining the landscape evolution of Scandinavia

ROELANT VAN DER LELIJ

*NGU*

A fluvial facies in the Mesoproterozoic Dala sandstone. Preliminary results from the Moberget quarry, west-central Sweden.

LINDA M. WICKSTRÖM

*Geological Survey of Sweden*

**S13.8 Volcanology**

Explosive volcanism in Iceland between 8000 and 60.000 years as expressed by tephra layer frequency in marine sediments

ESTHER RUTH GUDMUNDSDÓTTIR

*Institute of Earth Sciences, University of Iceland*

Tephra in the effusive Bárðarbunga 2014-2015 eruption, Iceland

ESTHER RUTH GUDMUNDSDÓTTIR

*Institute of Earth Sciences, University of Iceland*

Askja 1875 tephra in lake sediment in Southern Finland

MAARIT KALLIOKOSKI

*Department of Geography and Geology, University of Turku*

Origin of the Lake Natron Footprint tuff, northern Tanzania

HANNES MATTSSON

*ETH Zurich*

**S15.1 Applied 3D and 4D modelling in geosciences**

Kersilö database and its applications within the ice divide zone of Finnish Lapland

ANNIKA ÅBERG

*Department of Geosciences and Geography, University of Helsinki*

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## **4 Abstracts**

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HELSINKI



## S1.1 Geohazards in the Nordic and Arctic regions

ORAL

### What did trigger the rockslide in the Askja caldera on the 21st of July 2014?

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On the 21st of July 2014 a large rockslide occurred in the Askja Caldera in the northeastern highlands of Iceland. This rockslide is the largest rockslide which has occurred in Iceland since the settlement of the island more than 1100 years ago. The slide was initiated in the southeastern rim of the caldera and fell into the 220 m deep Öskjuvatn Lake, causing a 20-30 m high displacement wave in the lake. Earth tremors were observed in nearby seismic stations giving the exact time of the slide at 23:24. At around 23:27 a white plume rose up from the site. The scar of the rockslide is about 900 m wide and about 350 m above the surface of the lake, at 1056 m a.s.l. The movement of the slide is a rotational slide, but the location of the lower boundary is presently not known. It is estimated that the size of the slide is between 15-30 million m<sup>3</sup>. The runout length is 3100 m and the fall height 500 m. During the last 3 decades the volcano has been deflating at a rate from 7 cm/yr, down to a 2-3 cm/yr in recent years. Indications of movements prior to the slide obtained from photographs show that slow movement of the slide mass had already begun few years before the slide. It is likely that thick snow cover and rapid melting the days before the slide may have initiated the slide.

ORAL

### Lime stabilisation of soil in the Vinge urban development area, Denmark

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Vinge is the name of the largest urban development area in Denmark, covering 370 hectares and planned housing for 20,000 residents. Construction started in the spring of 2015 and during the next few decades the town will emerge. An important aim of the Vinge development is to be sustainable, e.g. by reducing CO<sub>2</sub> emissions and raw material consumption. An obvious solution is to minimise soil redistribution over large distances and instead reuse the soil in the construction projects on-site. Lime stabilisation is a well-known technique for improving clay soil properties with respect to construction; however, there is currently disagreement on whether this technique would be suitable for the Vinge soil (predominantly clay till). The aim of this project is therefore to test whether it would be possible to reuse the removed soil in construction projects on-site by applying lime stabilisation. In this project we have made initial classification tests of the soil, proctor tests in order to test the optimal water content, CBR (California bearing ratio) tests and unconfined compression tests. Furthermore pH and mineralogical aspects were investigated on both natural and lime-stabilised soils.

#### References:

- www.byenvinge.dk  
 Bell, F.G. 1996 Lime stabilization of clay minerals and soils, Engineering geology 42, pp. 223-237.

## ORAL

**Permafrost in steep slopes in Norway**

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The warming and degradation of mountain permafrost within alpine areas is an important process influencing the stability of steep slopes and rock faces. A more systematic approach to evaluate both the potential spatial distribution of steep rock faces in permafrost in Norway, and the thermal regime of those along has recently been launched.

To better estimate the thermal state of permafrost in steep rock walls in Norway, five temperature loggers were already installed in 2009 and 2010 (Hipp et al., 2014), measuring the near-surface rock wall temperatures in vertical rock faces. Surface temperatures in rock walls in Norway are on average higher than the ambient air temperature, about 1°C in shaded faces to more than 3°C in the other aspects. In 2015, we installed 15 additional rock wall loggers in both southern and northern Norway.

To address the thermal regime in entire rock faces a 2D transient thermal model has been developed. As forcing, we have used temperature and snow data interpolated from meteorological observations to the study sites. The analysis demonstrate how steep slopes with no or limited snow act as a cooling area, influencing the thermal regime of adjacent areas such as mountain plateaus etc. The spatial distribution of potential steep slopes in permafrost is evaluated by combining a high-resolution digital elevation model with gridded temperature data ("seNorge"). This analysis shows a widespread abundance of rock faces in permafrost in Norway.

The presentation provides an concept and overview about the topic, along with first results from temperature observations, thermal and spatial distribution modelling of steep permafrost slopes.

**References:**

Hipp, T., Etzelmüller, B., and Westermann, S., 2014, Permafrost in Alpine Rock Faces from Jotunheimen and Hurrungane, Southern Norway: Permafrost and Periglacial Processes, v. 25, no. 1, p. 1-13.

Myhra, K. S., Westermann, S., and Etzelmüller, B., in press, Modelled distribution and temporal evolution of permafrost in steep rock walls along a latitudinal transect in Norway by Cryo-Grid 2D: Permafrost and Periglacial Processes.

## ORAL

**Contaminated area instability – the example of Ångerman River, northern Sweden**

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Industrially utilized river basins are frequently exposed to contaminants originating from polluting activities. However, the physical instability, and risk of mass movement mobilisation of contaminated soil into rivers have only received little attention. In this study, we present a GIS-based method to produce a regional overview of where and how contaminated areas are at risk of being exposed to slope instability. A five kilometre buffer along the Ångerman River was used as a case study, exemplifying the method performance in a case where the slope instability is not known, but where more generally available land-cover data exist. A landslide susceptibility-index was created through calculating statistical correlations between land-cover parameters and landslide scars. These data were then used to study the degree and distribution of overlap between contaminated sites and unstable ground. A contaminated area instability risk classification was produced integrating mass movement probability and the contamination risk classification used by the Swedish environmental protection agency. Our results indicate that mass movement can be tied mainly to a slope gradient  $\geq 16^\circ$ , a proximity to the river that is  $< 500\text{m}$ , a distance of  $< 500$  meters from roads, concave surface curvature, and sand- and silt soils. 46 (22%) of all considered contaminated sites are located within areas with a non-negligible risk of mass movements, of which a majority, 30 sites (14%) are situated on ground with a low or moderate risk. 3 sites with a class 2 contamination risk (the 2nd highest class) are located on ground with a very high risk of mass movement.

ORAL

### The influence of steep rock walls on the thermal regime of talus slopes

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Talus slopes are common features in high mountain environments, and comprises the transition between steep rock walls and the lower valley bottom in periglacial areas. In mountain permafrost areas, the talus slopes may accumulate ice, developing rock glaciers or other flow features, which are important indicative landforms for present and former permafrost distribution and thus climate conditions.

As talus slopes often consists of coarse, frictional material, non-conductive heat flow may dominate the energy balance in such systems. However, also conductive processes from steep, snow free rock faces may influence the thermal regime especially in the rooting zone of talus slopes.

In this presentation we show this influence, by applying a 2D heat conductivity model, CryoGrid 2D (Myhra et al., 2015), to simulate the ground thermal regime in a talus slope situated below a steep rock wall. Our results indicate that, under certain conditions, thermal gradients across the top of the talus slope and the lower part of the steep rock wall contribute to formation and existence of ice in talus slopes situated below steep rock walls. This process has wide implication both for frost weathering in the sensible transition zone between rock wall and talus material, and the development of dynamic flow systems such as rock glaciers.

#### References:

Myhra KS, Westermann S, Etzelmüller B.(in press), Modelled distribution and temporal evolution of permafrost in steep rock walls along a latitudinal transect in Norway by CryoGrid 2D. *Permafrost and Periglacial Processes*

ORAL

### Wind wave climate of west Spitsbergen - seasonal variability and extreme events

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The ocean of western shore of Spitsbergen Island, Svalbard archipelago, is a subject of numerous research considering current, temperature or salinity patterns, but little to none of scientists attention was given to wind wave climate of the region. Direct off shore measurements of wave action have not been published so far, and satellite altimetry observations are sparse, lacking proper frequency needed in analysis of phenomenon as dynamic as wind waves.

Earth is facing the climate change, which is observable in variety of studies. Changes in ocean or atmospheric circulation and also quantity of sea and shore ice have direct influence on wave environment and vice versa. Intensification of wave action influence on coastal zones poses a threat to man made structures (e.g. shipping infrastructure, housing and also scientific installations) positioned in close proximity of the sea shore.

What we propose is wave environment analysis based on NOAA Wave Watch 3 (NWW3) and Wave Prediction Model (WAM) hindcast data. With information about common wave patterns, wave action intensity and frequency of extreme events occurrence we expect to deliver reliable boundary conditions for future marine and coast-related research of western Spitsbergen.

ORAL

### The origins of large, coastal, paleo-landslides in central Sweden

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Numerous large landslides, generally greater than one km in either length or width, have been recently discovered with the aid of LiDAR imagery. The presence of old landslides can indicate current instability. To assess the potential hazard associated with such landslides, it is necessary to understand the geology of the sites and the conditions that led to the landslides. Even apparently relic landslides may present hazards under changing climatic conditions.

Four such landslides were selected for study including a combination of, geomorphic, stratigraphic, and geotechnical investigations. All of these landslides occurred below the post-glacial marine limit and in settings that involve sand or gravel overlain by fine-grained sediments. Given the geologic settings, these landslides may be related to 1) sensitive clays, 2) hydrologic conditions, or 3) paleo-seismicity, each of which presents a different risk factor.

Results of the geomorphic investigation indicate the landslides are long runout features suggestive of a submarine origin. This, coupled with well-preserved and apparently not wave washed scarps, indicates that these landslides occurred at their respective shorelines. Thus, they are early Holocene in age. Preliminary stratigraphic results from an ongoing drilling campaign indicate that sliding occurred along the tops of confined aquifers. At the time of the landslides, the recharge areas of the aquifers would have been recently emerged above sea level. We hypothesize that these upland recharge areas were critical in generating water pressures significant enough to destabilize the coastlines and near-shore areas. At some locations, loading of the slopes with several meters of littoral sand would have also contributed to increased pore pressures in the confined aquifers.

ORAL

### Ages of rock-avalanche deposits allow tracing the decay of the Scandinavian ice sheet

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We have mapped rock-avalanche deposits in western and northern Norway and dated several by means of cosmogenic nuclide dating. Rock avalanches that deposited in ice-free valleys have pristine morphologies with a lobate form and a carapace of large angular boulders comprising only the lithology of the failed slope. The deposits of rock avalanches on decaying ice bodies are more difficult to recognize as the typical lobate form is missing by deposits are only preserved in end moraines or on valley slopes higher than the ice body at time of failure. However, those deposits have similar sedimentologic characteristics, with angular boulders comprising only lithology of the failed slope. Rock-avalanche deposits in moaines are characterized by boulder accumulations with a small amount of fines as those got washed out by the melting ice (Schleier et al. 2015). Our results indicate that valleys on islands in the Barents sea have been ice-free by 13.5 kyr, slopes were ice-free in outer fjord regions in northern Norway by 12 kyr, and slopes in inner fjord regions by 10-11 kyr. In western Norway, the Innerdalen valley still had a 350-m-thick valley glacier at 14.1 kyr while a first age suggests that the Innfjorddalen valley was ice free at that time. Multiple rock avalanches with pristine morphology distributed throughout the inner fjords and valleys in western Norway indicate that most valleys became essential ice free between 12 and 10 kyr. This includes valleys like Bøyadalen in Fjærlandsfjord that are close to today's existing ice fields. Our data match well with models of the Scandinavian ice sheet (Hughes et al., 2015) and show the fast reply of rock slopes on decaying ice sheets.

## References:

Hughes, A.L., Gyllencreutz, R., Mangerud, J., and Svendsen, J.I., 2015, The last Eurasian ice sheets—a chronological database and timeslice reconstruction, 1: Boreas.

Schleier, M., Hermanns, R.L., Rohn, J., and Gosse, J. C., 2015, Diagnostic characteristics and paleodynamics of supraglacial rock avalanches, Innerdalen, Western Norway: *Geomorphology*, v. 245, p. 23-39.

ORAL

### Debris avalanches in Norway; comparison of geological setting and release mechanism

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Debris avalanches are a type of rapid gravitational process that widens along the flow path and therefore often becomes very destructive in the wide outrun area. This avalanche type is not common in Norway, but recent events have sparked the need to understand them better. One important aspect is the geological and climatic setting, affecting release mechanisms and enabling predictions of future events. We aim also to define release mechanisms and factors causing the widening avalanche path, thus pinpointing geologic characteristics that may be mapped over larger areas.

Four debris avalanches are investigated, situated in Møre and Romsdal county, North western Norway. We have focused on the meteorological preconditions, process of initiation and factors along the avalanche path that might contribute to the widening of the track.

Various topographic and meteorological analyses were used. Digital terrain models were analyzed for angle of slope, fluvial flow paths and convexity of slope, in several directions. We compared data on daily precipitation and rainfall intensity before and during the events.

Release is found to be linked to meteorological pattern in combination with geology at each release area. The stratigraphy often including layers of weathered bedrock or till cover, as well as denser, more finegrained units. The widening of the avalanche paths seems to be related to slope sections with shallow soils together with smooth and compact bedrock surfaces in the flow path and slightly convex slope profile.

ORAL

### Drivers and Estimates of Terrain Suitability for Active Layer Detachment Slides and Retrogressive Thaw Slumps in the Brooks Range and Foothills of Northwest Alaska, USA

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Active layer detachment sliding and retrogressive thaw slumping are key modes of upland permafrost degradation linked with climate trends, ecosystem impacts, and permafrost carbon release. In the Brooks Range of northwest Alaska, they are widespread, with distribution associated with multiple landscape properties. Co-varying terrain properties, including surficial geology, topography, geomorphology, vegetation and hydrology, are key drivers of permafrost landscape characteristics. However, these inter-relationships as drivers of terrain suitability for active layer detachment (ALD) and retrogressive thaw slump (RTS) processes are poorly understood in this region. We empirically tested and refined a hypothetical model of terrain factors driving ALD and RTS terrain suitability, then generated terrain suitability estimates across the region. Terrain data were examined against locations of 2,492 ALDs and 805 RTSs using structural equation modelling and integrated terrain unit analysis. Factors significant for model fit substantially constrained region-wide terrain suitability estimates, suggesting that omission of relevant factors leads to broad overestimation of terrain suitability. Mapped estimates of terrain suitability were used to quantify and describe suitable landscape settings. 51% of the region is estimated suitable terrain for retrogressive thaw slumps, compared with 35% for active layer detachment slides, and 29% of the region estimated suitable for both.

## POSTER

### Development of an empirical tool to predict rockslide dam heights of future rock slope failures

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This work is part of a method development project at the Geological Survey of Norway to evaluate the consequences of potential rockslides in Norway. In particular we develop here a tool to assess dam height and therefore the consequences related to valley impoundment, with related upriver and potential outburst flooding. Seventy-two landslide dams were identified in southwestern Norway by searching for landslides bodies impounding water bodies using aerial photographs. Each identified dam was characterized by depositional process, showing that 46% were formed by rock falls, 53% by rock avalanches and 1% by debris flows. The majority of dams are stable, constituting 39%, 18% of all dams have failed partially or nearly entirely, the remaining dams are either eroded or filled in. The identified dams were classified according to Hermanns et al., 2011. The two-dimensional classification show that 65% of all dams were formed by singular landslide events that cross the valley entirely, 11% by singular events that only partially dammed the valley, while 6% of the dams are composed of several landslide events. The remaining dams are composed of larger landslide events that form multiple lakes in a valley, or several valleys. Furthermore the Dimensionless Blockage Index describing the relation of dam-volume/dam-height versus size of drainage system was used to assess dam stability. Results show that the Norwegian dams follow with  $DBI < 2.3$  for stable dams and  $DBI > 3.0$  for unstable dams, a similar trend as dams elsewhere on Earth. Likelihood of dam longevity thus relates to a decrease of the DBI.

We will use this rockslide dam inventory to establish empirical relationships relating the rockslide volume, expected shape, width and length of the rockslide deposits, and the valley width to the rockslide dam height. These relationships will be integrated in a tool for dam height prediction of future rockslide dams in Norway.

## References:

Hermanns, R. L., Hewitt, K., Strom, A., Evans, S. G., Dunning, S. A., & Scarascia-Mugnozza, G. (2011). The classification of rockslide dams *Natural and Artificial Rockslide Dams* (pp. 581-593): Springer.

## POSTER

### The rock slope instability at Tytefjellet in Vindafjord, Norway. Morphologic and structural characterization.

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The Tytefjell unstable rock slope is located on the west side of Vindafjord, Rogaland (Southwestern Norway). Tytefjell lies on a ENE-facing slope composed of phyllites. The unstable slope extends in W-E direction from the top of the slope at 500 m above sea level down to the fjord over a distance of 1.2 km and 2.5 km N-S resulting in an area of 3 km<sup>2</sup>. The unstable rock slope shows high rockfall activity at the frontal limit in the northern sector. Two bigger rockfall events have occurred there in the last 15 years. In 1999, a rockfall resulted in a displacement wave that caused damage on a boat and equipment lying at a fish farm 450 meters from the impact area. A smaller event occurred two years later

The rock-slope deformation at Tytefjell is characterized by a prominent 2 to 15-meter-wide, N-S oriented back crack that extends approx. 700 meters along the upper limit of the instability. Lenses of graphite with a thickness up to 0.5 meters are identified along the N dipping foliation at most locations. In the northern sector rock deformation increases towards east along two pronounced lineaments, and results in areas with higher degree of fracturing closer to the fjord.

The structural analysis revealed four steep joint sets: J1 striking SSW-NNE, J2 striking NNW-SSE, J3 striking E-W and J5 striking N-S, and in addition J4 with an average orientation of 063/43. The metamorphic foliation scatters between N and E dipping with an average orientation of 003/21. Measured crack orientation on the DEM indicates that opening mainly follows J1, J2, J4 and J5.

Future goals of this study is to perform a hazard assessment of the site following the Norwegian system for hazard and risk classification for unstable rock slopes.

## POSTER

### Determining snow avalanches, debris flows and rock fall runout distances on an active colluvial fan. Innfjordalen, Norway

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Colluvial fans are built up by slope processes (Blikra, 1998). Those processes are often discussed separately, while the real picture shows a complex system with several interlinked processes occurring in the same area. The main goal of this master thesis is to understand how slope processes interact and how that interaction conditions run-out distances. The study area is located near Gråfonnfjellet (1475 m.s.l), in the east slope of Innfjordalen. The glacially shaped valley with alpine mountains has a north-south orientation. Mean annual precipitation is 1500 mm, and the area lies within the Western Gneiss Region of Norway. Generations of snow avalanches, debris flows, landslides and rock falls have over time built up a 1.5 km<sup>2</sup> large convex fan, lying on top of detachment area of several landslides (Schleier, 2013).

#### References:

Blikra, L., H. & Nemeč, W. (1998). Postglacial colluvium in western Norway: depositional processes, facies and paleoclimatic record. *Sedimentology*, 45, 909-959.

Schleier, M., Hermann, R., & Rohn, J. (2013). Spatial distribution of rockslide deposits and their morphological features suggest timing and palaeo-environmental conditions for rock slope failures in Innerdalen and Innfjordalen, Møre og Romsdal County, Western Norway. *Italian Journal of Engineering Geology and Environment*.

## POSTER

### Slush flow thresholds for regional early warning in Norway

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<sup>2</sup>Norwegian Water Resources and Energy Directorate

Slush flows constitute a significant hazard in Norway. Therefore, the recently established national early warning system (EWS) operated by the

Norwegian Water resources and Energy Directorate (NVE) also issue regional warnings for these situations. Slush flows occurs when the snow pack becomes water saturated and the initiation slope is usually between 5 and 30 degrees. The triggering mechanism of slush flows is closer to that of debris flows than snow avalanches. The Norwegian regional slush flow assessment is based on weather forecasts and information about hydro-meteorological conditions that are derived from real-time measurements, model simulations and forecasts assembled as nationwide thematic maps and time-series data available at [www.xgeo.no](http://www.xgeo.no). In addition, real-time observations on the snow cover constitute essential input. The snow pack observations are distributed through the webtool [www.regobs.no](http://www.regobs.no) and contains information on exposed snow types such as depth hoar, fresh snow on frozen ground and coarse-grained snow. As opposite to debris flows, where the soil properties are stable over time, the dynamic snowpack properties are an additional challenge. This study aims at improving the evaluation basis by establishing thresholds for the initiation of slush flows. The methodological steps will be analysis of a dataset of 70 historical slush flow events by extracting hydro-meteorological simulated and observed data for each event and initiation area. The observational data have gaps in corresponding snow types, and these will be filled by applying the Crocus snow-pack model to simulate the missing data. Classification trees and multivariate analyses is used to investigate slush flow thresholds at a regional level. Warnings are issued at three awareness levels that reflects the potential danger: yellow, orange and red, while green is equal to generally safe conditions. The daily evaluation of the slush flow hazard resulting from comprehensive expert judgement of the available data and simulations are published on the web portal [www.varsom.no](http://www.varsom.no).

## S1.2 Hydrogeology

ORAL

### A 3D-model of the Uppsala esker

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<sup>4</sup>Akvanovium

<sup>5</sup>Uppsala Vatten

**Introduction.** In 2013 Uppsala Vatten initiated a strategic study of the Uppsala Esker in order to investigate the esker's continued viability as the main water supply for the City of Uppsala. This study includes the development of a digital database and a 3-D mathematical groundwater model. As a basis for the mathematical modelling, a conceptual hydrogeological model was developed of the relevant stretch of the esker and its catchment (c. 300 km<sup>2</sup>), see Figure 1.

The geological strata and its geometry are key components of the conceptual model which must to be transferred to the mathematical model. This was accomplished by constructing a 3-D geological model using the *Subsurface Viewer MX* software, with subsequent *ArcGIS* transformation in order to create continuous layers for input to the *Feflow* mathematical groundwater model.

**Development of the geological model.** The digital data used for the geological modelling include c. 1200 borehole logs, published geological maps and sections, geophysical profiles, topographical maps and a digital terrain model (resampled to 25 m resolution). All data were simplified to a general vertical sequence of seven classes: bedrock, till, glaciofluvial sediment, silt and clay, outwash sand, organic soil and fill.

Borehole data were connected in almost 200 cross-sections, taking into account all the geological background information, including geophysical profiles. After review and approval by hydrogeological experts, the sections were used to define 3-D geological units based on the simplified stratigraphic model. The units and the sections are modelled in the software to create a block model. In the final model, "synthetic" cross-sections can be generated anywhere and the top and base of each unit can be exported into grids.

**Acknowledgements.** The presented work has been performed as a cooperation between Uppsala Vatten and Swedish Geological Survey within the framework of Uppsala Vatten's project "Funktionsanalys Uppsalaåsen".

ORAL

### Groundwater vulnerability assessment of shallow low-lying coastal aquifer in south Finland

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A shallow, unconfined, low-lying coastal aquifer in southern Finland surrounded by the Baltic Sea is vulnerable to changes of groundwater recharge, sea level rise and human activities. Groundwater intrinsic vulnerability assessments were performed for the Hanko aquifer area, south Finland by utilising the integration of 3D geological modelling, groundwater flow modelling and the ArcGIS mapping platform. Three intrinsic vulnerability mapping methods: modified SINTACS, AVI and GALDIT were applied and compared. The rating classification of SINTACS was modified based on the superficial deposit map of Finland to be most suitable for the aquifers deposit from glaciations and deglaciations depositional environments.

The results indicate that groundwater vulnerability in Hanko aquifer to the contaminations from sources on the ground surface and seawater intrusion have greatly affected by the seasonal variations of groundwater recharge and relative changes in seaward groundwater discharge. The potential of high groundwater vulnerability to contaminations from anthropogenic sources on the ground surface occurs during high groundwater recharge after the snowmelt, while the high vulnerability to seawater intrusion could take place during low groundwater recharge in the dry season. In Hanko, AVI gives a higher vulnerability index than SINTACS, while GALDIT provides more insight of the groundwater vulnerability to seawater intrusion of the coastal aquifer, particular the areas that have low hydraulic gradient and cannot be identified by SINTACS or AVI.



The methods described can be used as a guideline for the groundwater intrinsic vulnerability assessment for glacial and deglacial deposits to the contamination from anthropogenic sources and sea-water intrusion in the other aquifer areas with similar physical characteristics.

ORAL

### Infrared imaging in assessing ground and surface water resources related to mining development sites, northern Finland

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Environmental issues play an increasingly important role in planning large-scale mining activities. Potential impacts are often related to groundwater and surface water systems, which may be inadequately understood and assessed. This is true especially in Lapland, northern Finland, where subsurface and surface water reserves and their hydraulic connections have rarely been studied.

However, the mining development sites occasionally host complicated aquifer systems with notable connections to natural surface water bodies. There are aquifers related to fluvial and glaciofluvial sands and gravels, which have observed to feed sensitive groundwater dependent ecosystems e.g. wetlands or rivers bearing critical spawning grounds for the sea trout (*Salmo trutta trutta*), an endangered species.

According stable isotopic composition ( $\delta D$ ,  $\delta^{18}O$ ) of waters and low altitude aerial infrared (AIR) surveys (helicopter and drone), surface water bodies studied are dominantly fed by groundwater. AIR was found to be a highly applicable method to identify thermal anomalies as potential groundwater discharge areas into the rivers and wetlands, to identify potential thermal refugees and to record spatially continuous patterns of river water temperatures.

This study revealed that GW–SW interactions are far more common phenomenon in our study sites than has thus far been acknowledged and should be taken into account in environmental assessment and managing critical thermal habitats in rivers and wetlands. Hydrogeological background information is

crucial in planning and siting essential mining facilities such as tailings storage areas. This research provided new insights into the water management in subarctic environments, and the results can be used to secure and sustain the groundwater dependent ecosystems in the future.

ORAL

### Acidity and geochemistry of coarse-grained acid sulfate soil materials in western Finland

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Discharge from fine-grained acid sulfate (a.s.) soils with total sulfur > 0.2% is commonly associated with acidic metal-rich runoff, with metal-loads exceeding the Finnish mining environments and the combined Finnish industry. These soils currently pose one of the largest threats to water-bodies in the coastal areas of Finland and it is estimated that over one-third of the coastal waters are negatively affected by a.s. soil runoff. It has previously been considered that a.s. soils in Finland were limited to fine-grained soil materials, capable of producing large amounts of acidity and a low pH (< 4.0) if oxidized. Recently it has been found, that some coarse-grained materials ( $d_{50\%} > 63\mu m$ ) also display severe drops in pH upon oxidation in laboratory conditions. These materials are attractive for sand and gravel excavation which, in some cases, result in sand-pit lakes and discharge with unusually low pH-values (c. 3.5) and high metal concentrations, which may pose a threat to the groundwater and drinking water supplies.

In the current study we show that even though the acidity and sulfur content (0.01–0.1%) is low, the coarse-grained soil materials are still capable of lowering the pH below 4.0 (values as low as 2.0 have previously been recorded) upon oxidation, due to poor buffering capacity. The titratable incubation acidity of the soil samples correlate directly with the sulfur content, which suggest that sulfide oxidation is the main cause for the acidity. The origin of the sulfides is not clear, but it is suggested that they have formed in situ, due to reduction of sulfate in the beach sand deposits.

ORAL

### Adaptation measures for securing good quality and quantity in Finnish groundwater resources

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A nationwide Finnish program to monitor and evaluate the changes in groundwater levels has been functioning since the 1970's. Groundwater quality has been monitored and assessed in a parallel program since the early 90's. This priceless monitoring data has been used to characterize the mean seasonal groundwater level variation patterns in Finland into four different hydrogeological regimes. The mean annual variations during the past decades under natural conditions have been used to model the effects of climate change, which is an essential mean for further developing adaptation measures to ensure adequacy of groundwater as a water resource, as groundwater reservoirs or artificial groundwater provide 66 percent of the national water supply when only the largest cities use surface water. Five million Finns have access to the water distribution network and the daily use is in average 130 liter/person.

Even though Finland has in worldwide comparison abundant water resources compared to the population density, the supply and demand of naturally occurring groundwater does not meet in the long run when projected with the population growth projections in the near decades. Other key impact factors that can jeopardize the quality and availability of groundwater resources due to climate change are more frequent and severe weather conditions: storms, heavy rainfall, flooding, and droughts. Precautionary adaptation measures for water supply facilities include risk assessment, preparedness plans for water supply facilities, the planning of flood control and conservation of groundwater basins. In a larger scale, national challenges in preserving good quality and quantity of groundwater have been recognized with the help of monitoring results and include: agricultural loads as well as forestry loads, domestic wastewater in areas outside sewerage networks, harmful impacts of hydrological engineering and water-level regulation, and containing the

effects of soil and bedrock specific characteristics. Different measures have been applied and are being further developed to diminish these effects.

ORAL

### Groundwater Checklist – Metadata tool for groundwater protection and interaction

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Groundwater pollution prohibition (Environmental Protection Act and Water Act) covers all groundwater. The aim of Groundwater Checklist is to enhance the groundwater protection, prevent groundwater contamination and ease the groundwater risk management.

Groundwater Checklist is a documentation and communication tool for companies, government agencies and consultants. The checklist includes information of hydrogeological structure and interaction of groundwater and surface water, managing the groundwater flow pattern and transport of contaminants. Main documents are the metadata table and the table of methods.

Groundwater Checklist improves document management, clarifies the basis of conclusions and helps finding suitable research methods. It introduces various suitable ways to acquire the needed groundwater information. With the Checklist, companies can assemble and present all groundwater studies that have been done in their project together with all the methods that have been used and also document the investigations that are planned to be made in the future. The Checklist can be used as an advisory list to ensure that all the important knowledge of groundwater issues has been appropriately investigated.

Groundwater Checklist can be employed in all stages of an industrial facility's life cycle. The Checklist is applicable to groundwater at risk by any human activities.

## POSTER

### Bank storage affected aquifer along the river Kitinen in Sodankylä, Northern Finland

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Water management in mining projects has long been discussed but the properties and extent of associated aquifers are usually inadequately known. The aim of this PhD study is to carry on targeted hydrogeological research connected to planning of possible future mining sites in Northern Finland. The study site presented here is in Sodankylä, Northern Finland where AA Sakatti Oy has a prominent ore showing in Viiankiaapa mire, which belongs to the Natura 2000 network.

There are groundwater table measurements from 30 observation wells locating in the western part of the Viiankiaapa mire as well as continuous on-line record from 17 automatic stations measuring groundwater table and temperature since April 2012. Hydraulic conductivities of the sediments were evaluated from slug-test ( $n = 12$ ) and grain size analyzes ( $n = 14$ ). Water table data of river Kitinen, mire and groundwater, as well as DEM was combined in ArcGis to study flow directions and interactions between surface and groundwater bodies.

Groundwater temperature is in summer about 2-5 °C and in late autumn 4-8 °C which is almost reversed in comparison to air temperature, thus alluding the recharge rate. Groundwater flow direction in the main study area, western part of Viiankiaapa mire, is mainly from east to west but it changes gradually towards more NE-SW direction within the times of spring thaw (snowmelt). Near the river Kitinen annual groundwater level fluctuations are more prominent than farther away from the river. River Kitinen has flooded since historical times but the construction of the power plants in 1967-2001 and regulation of the river by Kelukoski Oy has diminished the intensity of floods. Regulation also caused 2-5 m rise of the river level and many wells in the banks sunk into river.

Viiankiaapa has clear flark and string pattern reflecting surface water flow directions, which are in

the study area mainly towards river Kitinen. Hydraulic conductivities are lower in the banks of river Kitinen than in the sandy layers beneath the Viiankiaapa mire. The sand-till-gravel formation in the banks of river Kitinen hosts a bank storage system where floodwaters recharge. It is possible that the bank storage influences to the biodiversity values of the mire, as well.

## POSTER

### Groundwater/surface water interactions as a management issue for groundwater extraction: a detailed hydrogeological model approach, Hyvinkäänkylä, Finland.

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The municipality of Hyvinkää, southern Finland supplies water to ~46,000 people from groundwater directly pumped from aquifers or surface waters artificially recharged through them. The aquifers are a part of a complex glacial system of eskers, moraines and glacial-lacustrine sediments, which cover a large part of the study site and through which groundwater is channelled towards the extraction wells. In order to optimise the management and protection of these waters and to determine which groundwater routes are affecting the supply most of all, a detailed geological model was built using various indirect and direct methods. Then, along with measured hydraulic conductivities, groundwater elevations, stream flow measurements and simulated recharge values a flow model was adapted from the geological model and calibrated using MODFLOW. The water budget could determine which of three likely scenarios is true. Either the flow paths dominate from the north or south through the esker system or along the river valley itself through buried highly conductive sediments. The study also incorporated an infra-red imaging field technique to identify areas of groundwater/surface water interaction i.e. areas along the river where groundwaters discharges.

## POSTER

### Integration of conventional method and transition probability geostatistics for the evaluation of aquifer heterogeneity

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Under the EU Groundwater Directive (2006/118/EF), groundwater body should be identified and protected. Groundwater resources management and protection need information of geological and hydrogeological characteristics of the aquifer. For the aquifer vulnerability assessment, the hydraulic conductivity and the distribution of the protective layer of fine-grained sediments are important parameters in most of the vulnerability assessment methods. The First Salpausselkä ice-marginal formation in Hanko cape, southern Finland, case study area consists of glacial gravel, sand, till and clay, together with postglacial littoral gravel, sand and clay. The complexity of the sedimentation during Weichselian glaciation and deglaciation makes details characterisation of the aquifer heterogeneity in the First Salpausselkä ice-marginal formation difficult. This study presents the results of the integration of conventional and transition probability geostatistics methods to construct 3D geological model and evaluate heterogeneity of shallow aquifer in Hanko, to provide a geological framework for groundwater flow model and groundwater vulnerability assessment. In conventional method, the aquifer characteristic was identified utilizing great variety of data. These include gravimetric survey, ground penetrating radar survey (GPR), sedimentological as well as hydrogeological data. The transition probability geostatistical method (TPROGS) was used to estimate the aquifer heterogeneity, especially in area that lack of sedimentological and hydrogeological data. The distributions of five hydrofacies (gravel, sand, fine sand, silt and clay) were determined based on sediment descriptions from 220 drilled wells and sedimentological information from 1022 m of GPR survey lines under the geological framework identified from the conventional method. Based on those results, the distribution of the protective layer of

fine-grained sediments and also aquifer hydraulic conductivity were able to predict.

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## S1.3 Mining and the environment: Towards socially and environmentally acceptable mining

ORAL

### Characterizing the Aijala copper mine tailings by diverse mineralogical methods

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A vertical sampling profile (0-80 cm) of the unremediated, weathered Aijala copper mine (1949-1974) tailings has been characterized by diverse mineralogical methods. The sample material was analysed by X-ray diffraction, traditional and field emission scanning electron microscopes, QEM-SCAN and electron microprobe. The aim was to investigate the mineralogical evolution of the tailings profile, including compositional changes, elemental deportment, weathering processes and formation of secondary minerals and a hard pan detected at the depth of 30-35 cm during the sampling. One important aspect was to study the alteration of sulphide minerals as a function of time, and to obtain information on the long-term behaviour of tailings.

The results obtained by different analytical methods demonstrate that the texture, modal mineralogy and the degree of alteration change dramatically throughout the tailings profile as a result of 35 years of tailings weathering. Acidity produced by the sulphide oxidation has depleted carbonates in the profile, and they are only found at the deepest, water-saturated level of the profile. Gypsum, formed as a secondary mineral, is abundant through the profile, except for the deepest and the surface layers. Chlorite dominates the main mineralogy. The weathering degree of sulphides and the formation of their alteration products, Fe-hydroxide (goethite), Fe-sulphates and jarosite, increases gradually towards the surface. Above the hard pan layer the sulphide minerals are extremely rare, and, if present, heavily altered. The hard pan layer acts as a dividing range for several other minerals. Goethite and serpentine are present only below the hard pan, whereas jarosite is found at and above it.

The complementary setup of the mineralogical instruments used in this study proved to be efficient in characterizing the tailings. The methodology provides a good toolbox for future work dealing with environmental impact assessments and estimations of secondary raw material potential of tailings materials.

ORAL

### Seepage water quality and prediction of waste rock effluents

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The wastes and waste facilities are usually the most prominent sources of pollution at a mine site. To predict the long term behaviour of disposed waste material and to successfully close a waste facility, a proper characterisation is needed.

The objective of this study was to review ore deposit geology and to determine waste rock geochemistry and mineralogy to study their relation to the actual seepage water quality. For the prediction of the acid production potential (APP) of the waste rocks, suitability of the most commonly used tests (modified acid base accounting (ABA), net acid generation (NAG), calculated ABA) was evaluated. Dissolution of metals and metalloids during *Aqua Regia* extraction, NAG test and two-stage shake-flask test was investigated to assess mobility of contaminants during the long term waste rock storage, and to evaluate performance of the different prediction methods.

Differences were observed between the various methods predicting APP and the actual acidity of the seepage waters. The study indicated that the laboratory tests were principally too pessimistic compared with the real situation at the mine sites. For the APP prediction, the use of several different methods, as well as mineralogical data, is recommended.

According to the leachability results, the *Aqua Regia* extraction had the best correspondence with the actual seepage water quality in predicting which elements will be present in the effluents, although it overestimated the presence of some individual elements, such as Cu and Cr. In general, performance of the NAG test leachate was reasonable, but it underestimated the metals in some cases. The shake flask test was observed to be the most unsuitable for

the effluent quality prediction, because of the weak solvent used in the test (water) and the too short reaction time for the crystalline waste rock material.

The results obtained from the *Aqua Regia* extraction and NAG test leachate can be used to predict the elements that will appear as elevated concentrations in the effluents, considering that the concentrations are only approximate, not exact. Elevated concentrations in any of the evaluated leaching tests indicate a possibility of increased element loads in the seepages.

ORAL

### Mobilization of heavy metals in submarine mine tailings

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Submarine mine-tailing disposal (STD) is considered as an alternative for land based tailings disposal for near-coast mining operations in Norway, and is also used in some other countries. However, also STDs have some environmental issues, such as smothering of benthic fauna and, potentially, leaking of heavy metals and chemicals used in the beneficiation processes from the tailings. The ongoing biogeochemical processes in STD, and which role they play in mobilization and/or immobilization of heavy metals are not well understood.

The Ballangsfjord, northern Norway, has two STDs. The sulphide-quartz dominated Ballangsløira deposit contains tailings from a Cu, Zn and S mine, while the olivine rich Fornesodden deposit has tailings from a Ni mine. In this study we investigate the sediment and porewater geochemistry and the microbial communities of sediment cores collected from the two different tailing deposits and from the background sediment in the fjord.

Both porewater geochemistry and microbial community profiles differ between the two tailing deposits, and between the tailings and the background sediment. In the background sediment, SO<sub>4</sub> decreased from 28 to 19 mM from the top of the core to 140 cm depth. Moreover, the abundance of

Deltaproteobacteria was positively correlated with sulphate concentration and decreased from 18% – 6% of the microbial community in the same depth interval. Sulphate reduction was not apparent from the porewater chemistry in the mine tailings. However, the coexistence of putative sulphide oxidizers and sulphate reducers suggests that sulphate reduction might be ongoing, but masked by sulphide oxidation. Ni, and to a lesser degree Co, was present in the porewater from both tailings. The porewater from the sulphide-rich tailings also contained Zn and lesser amounts of Cu and Pb. Sequential extraction of the mine tailings revealed the presence of heavy metals both in the fraction representing loosely-bound and carbonate-bound metals and in the fraction representing Fe and Mn oxide-bound metals. The porewater geochemistry and sequential extraction data suggest that heavy metal are mobilized and redistributed in the tailing deposits. To what degree the heavy metals are leached to the seawater is, however, not clear.

ORAL

### Mine Closure Wiki

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Mine closure is one of the key issues in the development of sustainable mining. Once mines close they leave behind mineral waste material facilities and open spaces (ground workings) that may have long-term impacts on the environment, if not closed properly. Successful closure requires wide knowledge on suitable closure technologies and related research methods as well as on the site-specific factors affecting selection of proper closure technologies. To reach the best results, planning of mine closure should start as early as possible - ideally during the mine feasibility study, before mining operations begin.

The Mine Closure Wiki databank (GTK 2015) was developed to provide comprehensive guidance

on mine closure to reduce the environmental, societal and economic impacts of mine closure and to facilitate smoother closure planning and permitting. It was published by the Geological Survey of Finland (GTK) and the Technical Research Centre of Finland (VTT) in October, 2015 as part of Closeure; a Tekes funded Green Mining Project.

The Mine Closure Wiki presents an overall description of the best practices and legislation pertinent to closure, provides systematic evaluation of the key methods and technologies of closure, and benchmarks national and international case studies on the performance of closure technologies. It also presents the results of mine closure related research and development (R&D) carried out during the Closedure project, such as the research on the performance of wetlands in treating mine waste effluents in Nordic conditions. Mine Closure Wiki is intended as an every-day tool for mining operators, authorities, consultants and researchers for the planning, permitting, executing and monitoring of mine closure.

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ORAL

### Developing tools for the integration of mining with other land uses

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Increase in mining and mineral exploration activities has created challenges in land-use planning. In our research, we provide spatial tools to improve the proactivity in decision making and strengthen the prerequisites for companies in gaining a social license to operate.

One of the tools is the "Mining Potential Tool" which interlinks spatial and temporal information to provide an estimate of the possible future mining activities and related time-scales in a studied area. This tool consist of map layers that are constructed by analysing the following data: 1) mineral exploration activities (e.g., TUKES 2015), 2) mineral deposit data (e.g., FODD 2015), and 3) mineral

prospectivity mapping (e.g., Nykänen et al. 2008). The map layers are intended to give the municipal authorities and citizens a spatial information about the time-scales and uncertainties related to mineral exploration and mine projects. The layers can also be used in analysing overlap with other land-use types and locating the potential future conflicts of interests.

This research is part of the joint project GovAda between the University of Lapland, Geological Survey of Finland and Natural Resources Institute Finland funded by the Academy of Finland. It brings together researchers with different backgrounds and expertise with an aim to gain deeper understanding over the land-use planning problematics. The GovAda project will provide a variety of tools for proactive planning and strengthen the possibilities of the decision makers to better prepare for the changing societal environment.

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ORAL

### Stakeholder engagement practiced by the Geological Survey of Finland in its mineral potential mapping in Southern Finland

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A good company-community relationship is important in earning a social license to operate (SLO) in mining. Communication and stakeholder engagement are part of the social corporate responsibility (CSR) and they should be started already at the very beginning of mineral exploration. Here we present a methodology of stakeholder engagement used by the Geological Survey of Finland (GTK) in its mineral potential mapping in Southern Finland.

The GTK's stakeholders in local communities are landowners, residents, media, schools and the municipality representatives. Direct contacts in the field, press releases, and conferences, as well as

open and public meetings and lectures are the approaches to engage with these groups. Leaflets informing about the upcoming field work and associated contact information are delivered to local people or in their mailboxes.

The stakeholder engagement is performed by geologists and assistants working at the region. This activity has been practiced and developed since the early 2000s. So far the stakeholder engagement has not been a systematic or standardized activity, but largely a polite and respectful approach towards the local communities. However, since the new mining act requires informing the landowners, and because public resistance towards mining activities is growing in Finland, such approaches and methodologies were recently systematized and standardized in the GTK's updated field work manual. It was made by reflecting the local conditions and stakeholder groups in different regions.

Several on-going social science projects that study, develop, and promote CSR of mining offer possibilities for cross-disciplinary cooperation between geologists and sociologists. Cooperation could involve studying the impact of GTK's stakeholder engagement in order to receive feedback to develop and improve the social performance of its field activities. Nevertheless, the GTK's stakeholder engagement has until now been a very productive and effective activity in Southern Finland, resulting in SLO.

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**POSTER**

**Monitoring of mining impact on natural waters using isotopic tracers (S, U, and Sr) – a pilot study from Talvivaara, northeastern Finland**

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This study aimed to identify the possible effects of the acidic, metal-bearing waste water leakage from the gypsum pond on natural waters at the Talvivaara mining area, northeastern Finland by using and testing the applicability of isotopic tracers. As a pilot study, only a few mining related water samples

and samples from nearby surface- and groundwaters were selected for S, U, and Sr isotope analyses.

For S and U isotope analysis, S was eluted using cation exchange resin and U using TRU-Spec resin. Sr was eluted using Dionex ICS-3000 ion chromatography system. The isotope ratios were measured using MC-ICPMS at the Geological Survey of Finland, Espoo.

From the available restricted isotope data, we can conclude that especially in case of S and U isotopes, it was not always clear whether the mining waste waters were leaked into the surrounding lakes or, whether the isotope signatures were (partially) controlled by natural redox processes. In this case, Sr isotopes showed clearly the influence of the mining processes (chemicals and their effects) to nearby lakes and one shallow groundwater sample. For identifying bedrock ground water flow paths, the sample set was insufficient.

Since individual isotopic systems may solve different type of questions, it is essential to familiarize well to surrounding geology and all the mining processes before making the sampling plan and selecting the used isotope systems. It would also be essential to select enough mining process related samples and background samples to solve possible natural trends and finally discriminate them from the mining waste water pollutions.

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**POSTER**

**Mining environments – GTK's isotope analytical facilities on dissolved elements in water**

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The Geological Survey of Finland (GTK) has been developing methods for the use of new isotopic tracers to monitor the impact of mine water discharge on natural waters, to pinpoint hydraulic connections and interactions within mine environments, as well as to detect possible natural trends and discriminate them from the impacts of mine water.

In addition to traditional water isotopes (O and H), S, Li, Mg, Pb, Sr and U isotopes can be now analysed. Analytical methods for Fe, Cu, Zn and



B isotopes are currently under development. While all other elements may be isolated using ion chromatography or conventional column methods, only S is isolated using solely conventional methods.

The isotope ratios of the purified elemental fractions are then measured using MC-ICPMS (*multicollector inductively coupled plasma mass spectrometer*) and/or TIMS (*thermal ionization mass spectrometer*).

In general U and S isotopes indicate changing redox conditions. Mg and Li are sensitive to weathering and they show slight fractionation between the mineral and the water phase. Here, the effect of runoff on the isotope ratios may be important. The more traditional Sr and Pb systems trace natural and anthropogenic sources eg. (minerals, soils, chemicals).

The current pilot studies show evidence for mixing of mine waters in recipient surface waters and thereafter introduction of polluted surface waters into ground water. Sr isotopes have been extremely useful to separate the contamination related to the mining process from the natural signature.

## S1.4 Geoenergy

### KEYNOTE

#### Geoenergy in the Nordic Countries

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Conditions are highly favorable for geoenergy applications in the Nordic countries. The climate with relatively cold winters and warm summers, as well as the dominating crystalline rock and high groundwater levels, offer excellent geoenergy opportunities. Sweden was one of the pioneering countries in developing geoenergy technology in the 1970's and 80's, and still holds a position among the world top three geoenergy countries. During the last decade geoenergy use has increased significantly also in Norway and Finland. The geological conditions in Denmark are less favorable for geoenergy, yet there has been an increase in the market in recent years.

This presentation gives an overview of the conditions, market and development of geoenergy technology and applications in the Nordic countries, and relates to the overall geoenergy development in the world.

### ORAL

#### Groundwater as an energy resource in Finland

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Groundwater can be seen as an option for renewable energy utilisation. Finland has multiple groundwater reservoirs that are easily exploitable, but groundwater energy is not commonly used for renewable energy production.

Three different scale research were made to provide a reliable assessment of the groundwater energy potential in Finland. Firstly, the national groundwater energy potential of Finnish classified aquifers was mapped. Secondly, the urbanisation effect on the peak heating and peak cooling power of groundwater was investigated, and finally, the long-term groundwater energy potential was modelled

for three different building complexes. Hydrological and thermogeological data were used together with accurate data on the energy demands of buildings. The heating and cooling power of groundwater was calculated based on the groundwater flux, temperature and heat capacity and the efficiency of the heat transfer system. The power producible from groundwater was compared with the heating and cooling demands of buildings to calculate the concrete groundwater energy potential.

Approximately 20% to 40% of annually constructed residential buildings could be heated utilising groundwater from classified aquifers that already are under urban land use in Finland. Urbanisation increases the heating energy potential of groundwater. The average groundwater temperature was 3 to 4 °C higher in city centres than in rural areas. Approximately 50% to 60% more peak heating power could be utilised from urbanised compared with rural areas. Groundwater maintained its long term heating and cooling potential during 50 years of modelled operation in an area where the natural groundwater temperature is 4.9 °C. Our results demonstrate that groundwater can be effectively utilised down to a temperature of 4 °C.

Groundwater can form a significant local renewable energy resource in Finland. Groundwater energy utilisation should be noted as one easily exploitable option to increase the use of renewable energy resources. Accurate information on hydro- and thermogeology together with the energy demands of buildings is essential for successful system operation.

### ORAL

#### ORMEL- Optimal utilization of ground water for heating and cooling in Melhus and Elverum

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Ground source heat is a renewable energy source that has a potential for more use in Norway. In the ORMEL-project the municipalities of Melhus and Elverum are evaluating their potential for ground water extraction for heating and cooling purposes. The aim of this evaluation is to identify the

heat extraction potential by mapping the aquifers beneath the city centers. Local heating and cooling demand in buildings and industry will also be mapped, as well as gathering operational data from existing production plants. Based on the totality of this investigation, the use of ground source heat can then be optimized.

The ground source heat is extracted from the ground by pumping ground water through a heat pump. As the ground water is used directly as a heat transfer medium, the flow properties of the aquifers have to be mapped extensively. The aquifers will be mapped in detail with both geophysical and traditional methods. The project started in 2015 and this year 2D- resistivity, ground penetrating radar (GPR), establishment of test wells, well capacity tests, water analysis and sediment analysis will be carried out. Analysis of operational data from existing plants will also be started this year.

The sites have some wells operating with varying degree of efficiency and success. Often the well design is not modified to fit the local geological conditions. Typical problems tend to be clogging of the heat exchanger and infiltration wells. This seems to be caused by both precipitation of iron oxides and sand production from the production well. Results from the ongoing investigation will be presented.

ORAL

### Seasonal storage of heat and cold in the bedrock

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Storage is a critical issue when discussing the possibility to use heat and cold produced intermittently. For example in temperate climate zones the sun produces heat enough during summer to cover the demand for a year but it needs to be stored to next winter. In a similar way the cold during winter is needed to cool buildings during summer time.

We use the rock mass itself as a storage /e.g. Hellström & Larson 2001/, the HYDROCK concept. Existing fractures or new fractures artificially created are used in the bedrock as flow-paths for the heat and cold carrier (water). The fracture surfaces serve as heat exchangers and the bedrock is loaded and unloaded to suite the energy needs. The way to do this is discussed.

### References:

Hellström, G., Larson, S.Å., 2001: Seasonal thermal energy storage – the HYDROCK concept. Bull. Eng. Geol. Env., 60:145-156.

ORAL

### Energy systems based on closed loop boreholes - development of tools and best practices

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Shallow geothermal energy is a renewable energy source, where the low enthalpy heat in the shallow subsurface can be exploited using borehole heat exchangers in a combination with heat pumps. Despite the energy saving and CO<sub>2</sub> emission reduction potential of the technology, the utilisation of shallow geothermal energy in Denmark is relatively limited compared to e.g. the other Nordic countries (Røgen et al. 2015). A recently completed Danish development and demonstration project has compiled knowledge, tools and best practices for closed loop boreholes combined with detailed mapping of thermal properties of shallow Danish sediments as well as 3D modelling of heat and groundwater flow. Furthermore a WEB application to estimate thermal conductivities in new project areas from existing borehole data has been developed (Ditlefsen et al. 2014). Results and recommendations from the project will be presented and discussed.

### References:

Ditlefsen, C., Sørensen, I., Slott, M. & Hansen, M. 2014: Estimation of thermal conductivity from existing soil descriptions. Geological Survey of Denmark and Greenland, Bulletin 31, 55-58.

Røgen B, Ditlefsen, C, Vangkilde-Pedersen, T, Nielsen L. H. and Mahler, A 2015: Geothermal Energy Use, 2015: Country Update for Denmark. Proceedings World Geothermal Congress 2015. Melbourne, Australia, 19-25 April 2015

## ORAL

### Detecting and quantifying the influence of natural convection on a thermal response test carried out in a groundwater-filled borehole heat exchanger

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In Finland and Scandinavia, borehole heat exchangers (BHEs) do not require grouting because they are typically located almost entirely in hard crystalline bedrock. The space between the heat collector pipes and the borehole wall in such BHEs is naturally filled with groundwater that is a fluid capable of convecting heat. The occurrence of natural convection in the borehole water of a BHE was investigated using data from a thermal response test (TRT) carried out in a groundwater-filled BHE constructed in Southern Finland. The TRT was first evaluated using the conventional infinite line source method which yielded a borehole thermal resistance estimate that was significantly lower than the estimates obtained using analytical expressions and finite element model simulations only taking into account conductive heat transfer. This discrepancy was interpreted as an indication of the occurrence of natural convection in the borehole water of the BHE during the TRT. Then, the finite element models were fitted to the TRT data keeping the groundwater thermal conductivity as a free parameter. Using the best-fit effective groundwater thermal conductivity values, the influence of natural convection on the TRT was estimated to be 63-71% depending on the locations of the heat collector pipes. According to the results, natural convection is a factor that is likely to significantly enhance the total heat transfer taking place during TRTs carried out in groundwater-filled BHEs.

## POSTER

### CO<sub>2</sub> storage potential of the Norwegian Continental Shelf

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The studies indicate that there is sufficient storage potential in the Norwegian Sea and southern Barents Sea for CO<sub>2</sub> from local sources (industry and associated with natural gas). In the North Sea, the storage potential is much larger than the CO<sub>2</sub> volumes associated with natural gas and the volumes emitted from Norwegian point sources.

The work is based on an extensive database of exploration wells, 2D and 3D seismic data. Main objectives were to facilitate selection of sites which are suited for future CO<sub>2</sub> sequestration projects and to document the total storage capacity of Norwegian sectors of the North Sea, the Norwegian Sea and the southern Barents Sea.

In order to avoid conflict of interests with the petroleum industry, studies of CO<sub>2</sub> injection into saline aquifers were mainly restricted to areas where the generation and migration of hydrocarbons is considered to be limited.

To improve the estimates of storage efficiency, we constructed geomodels and reservoir simulation models for several traps and aquifer geometries. Learning from these models, we evaluated the storage efficiency for other possible sites which were studied by geological mapping only.

The CO<sub>2</sub> storage atlas is now available as StoryMap and as an interactive Map. This application gives you the possibility to explore the assessment result, and is also suited for mobile devices. The Factmaps information is synchronised with the NPD's databases on a daily basis.

## POSTER

### Physical- and geochemical properties of core samples from the Swedish part of the southern Baltic Sea: Implications for CO<sub>2</sub> storage

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Feasibility studies of CO<sub>2</sub> storage in Sweden has been conducted based on the geological and geophysical data from the southern Baltic Sea (e.g. Juhlin et al., 2013). Suitable formations for CO<sub>2</sub> storage may exist below southern Gotland and Skåne, with good aquifer properties for storage and suitable caprock.

We present detailed results from a series of measurements conducted on core samples consisting of Cambrian sandstone (potential reservoir rock) and Ordovician limestone (potential caprock). The core samples are provided by Geological Survey of Sweden (SGU) and were collected from 146-586 m depth. The experiments consist of petrophysical properties measurements (density, porosity, permeability, thermal conductivity and P-wave velocity) and chemical analysis.

The two rock types reveal contrasting properties, for example density and P-wave velocity is  $2.36 \pm 0.13$  gr/cm<sup>3</sup> and  $3.13 \pm 1.00$  km/s, respectively, for the sandstone (reservoir rock) while significantly higher values were obtained for the limestone (caprock),  $2.58 \pm 0.08$  gr/cm<sup>3</sup> and  $6.09 \pm 0.24$  km/s respectively.

The objective of this study is to evaluate the interrelationships between the obtained petrophysical and geochemical properties from southern Swedish Baltic Sea to better understand the implications of the evaluated properties for CO<sub>2</sub> storage in Sweden.

#### References:

Juhlin C, Ask M, Bjelm L, Elhami E, Erlström M, Joodaki S, Lazor P, Lorenz H, Niemi A, Rosberg JE, Sopher D. Potential for CO<sub>2</sub> storage in Swedish bedrock: SwedSTORECO<sub>2</sub> - Phase 1. Final Report; 2013. p.1-125.

## POSTER

### Mapping of CO<sub>2</sub> Storage Possibilities on the Norwegian Continental Shelf

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The Norwegian Petroleum Directorate (NPD) at the request of the Ministry of Petroleum and Energy has mapped and evaluated possible storage sites on the Norwegian Continental Shelf (NCS). The main objectives have been to identify safe and effective areas for long-term storage of CO<sub>2</sub>. Comprehensive work is published in four CO<sub>2</sub> Storage Atlases (Hal-land et al.2011-214).

The study is established on detailed work on all relevant geological formations and hydrocarbon fields on the NCS. Aquifers and structures have been characterized in terms of capacity, injectivity and safe CO<sub>2</sub> storage. Three case studies along the NCS will be presented at 32<sup>nd</sup> Nordic Geological Winter Meeting in Helsinki 2016.

The largest storage capacities are situated in the mature part of the North Sea. The Utsira - Skade aquifer is the biggest aquifer in the North Sea. The reservoir simulation study shows that approximately 170 Mt of CO<sub>2</sub> can be injected within the aquifer. In the Norwegian Sea, the CO<sub>2</sub> storage potential is located on the Trøndelag Platform, east of the petroleum province. The aquifers in the southeastern part of the Norwegian Sea have a consistent dip of 1-2° from the Norwegian coast to the basal areas. In places, where permeable beds occurring along the dip slope there is a risk that CO<sub>2</sub> injected down dip can migrate upwards where the aquifer is truncated by the Quaternary glacial sediments. Based on simulation results about 400 mill tons CO<sub>2</sub> (8 mill tons/year over 50 years) can be stored in the Garn - Ile aquifer in the Froan Basin. The area in the Barents Sea for CO<sub>2</sub> storage is situated in the southwestern part of the Barents Sea. The main target for CO<sub>2</sub> storage in the Barents Sea is the Stø Formation, which has excellent reservoir properties, with a thickness of 130m in the well 7125/1-1 (Bjarmeland Platform). The storage capacity with respect to CO<sub>2</sub> in the southern Bjarmeland platform aquifer is calculated to 176 Mt.

## S1.5 Nuclear waste disposal

### KEYNOTE

#### Glacial meltwater in the bedrock – identification and reactions

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More than 10 sites have been investigated by SKB (Svensk Kärnbränslehantering AB) and Posiva Oy over the years, to find a suitable site for a repository for spent nuclear fuel in Sweden and Finland, respectively. At all these sites groundwater has been sampled from different depth in the crystalline bedrock and analysed for chemistry and isotopic composition cf. /SKB, 2008 a, b; Posiva 2013 and references within these reports/. In most of the sites presence of groundwater with lower  $\delta^{18}\text{O}$  than present recharge has been identified.  $^{14}\text{C}$  supports a possible glacial meltwater origin for components in these waters, although the proportion of the glacial water as well as the depth to which it has penetrated varies among the sites. Hydrogeological models support that during deglaciation meltwater can reach to substantial depth in the bedrock and the down-ward flow can be very fast. It has even been suggested that oxygenated water may possibly be transported to great depth. The impact on the hydrogeochemical system in the bedrock (e.g. mineral dissolution/ precipitation) as result of intrusions of glacial meltwater will be discussed as well as how confident we are in the identification of the glacial meltwater and especially its relation to the last deglaciation.

#### References:

Posiva 2013: Olkiluoto Site Description 2011, Posiva report 11-02.

SKB 2008a: Bedrock hydrogeochemistry Forsmark. Site descriptive modelling SDM-site Forsmark. Report SKB R-08-47.

SKB 2008b: Bedrock hydrogeochemistry Laxemar Site descriptive modelling SDM-site Laxemar. Report SKB R-08-93.

### ORAL

#### The effects of the glaciation for deep geological disposal of spent nuclear fuel in crystalline shield rock settings.

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Deep geological disposal (DGR) of nuclear waste requires a multidisciplinary and iterative approach used to develop an overall understanding of the long term performance of the repository and its surroundings. Features, events and processes that could potentially affect the safety of the repository system are identified and possible releases to the environment are assessed, as well as the consequences of such potential releases.

Given the long time span covered by safety assessments of DGRs for nuclear waste (100,000 years up to one million years), scientific information and knowledge on processes related to cold climate conditions and future glaciations are required. To achieve the required increase of understanding, Greenland Analogue Project (GAP) was initiated. The primary aims of the GAP were to enhance scientific understanding of glacial processes and their influence on both surface and subsurface environments relevant to the performance of deep geological repositories for spent nuclear fuel in crystalline shield rock settings.

The Greenland Ice Sheet (GrIS) was selected by the GAP as a natural analogue for glaciation processes expected to reoccur in Fennoscandia and Canada over DGR safety-relevant time frames.

ORAL

### Deep groundwater evolution in Outokumpu, eastern Finland –from meteoric water to saline gas rich fluid

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The Outokumpu Deep Drill Hole spans 2.5 km of 2 billion year old bedrock within the Fennoscandian Shield in eastern Finland. Groundwater at the site is characterised by abundant dissolved salts dominated by Ca, Na, and Cl, (TDS up to 70 g/L) and gases (up to 1.1 L/l water) of which CH<sub>4</sub>, N<sub>2</sub> and H<sub>2</sub> are the most abundant.

Based on the geochemical and isotopic studies, an evolution model for these groundwaters was derived. The O and H isotopic composition of water point out their origin as meteoric waters which were recharged during climatic conditions up to 10°C warmer than at present and subsequently modified at water-rock reactions. This combination produced the distinctive isotopic compositions above the meteoric water line, as well as increased the salinity and indicates residence times on the order of tens of millions of years. A further indication of very long residence times was gained from the noble gas isotopes (<sup>4</sup>He, <sup>21</sup>Ne and <sup>40</sup>Ar) which show accumulation in the groundwater due to radioactive decay of U, Th and K of the bedrock within 30 million years on average. Based on the thermodynamic calculations, CH<sub>4</sub> can be produced from graphite and H<sub>2</sub>. The process is likely on-going and potentially mediated by microorganisms.

As similar ancient groundwaters are found from the Olkiluoto nuclear waste repository site, our results have important implications for the long term safety of nuclear waste disposal. On one hand they manifest the isolation and immobility of the waters that has prevailed over millions of years. On the other hand, the results point out the complexity and vulnerability of these hydrosystems as they are being utilised. For example, the on-going process of CH<sub>4</sub> formation should be taken into account

in the studies of mobilisation of potentially hazardous compounds and microbial activity within the bedrock groundwater.

ORAL

### Microscale variation in stable isotope composition of fracture minerals – a key to subsurface processes

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The Olkiluoto site, an island located on the western coast of Finland, is the planned site for the geological disposal of nuclear waste in Finland. Stable isotope of fracture filling minerals have been used to interpret hydrogeochemical conditions of paleogroundwaters at Olkiluoto. Especially, microscale variations in stable isotope compositions of mineral phases, obtained using secondary ion mass spectrometry (SIMS), have proven to be a useful tool in interpreting hydrogeochemical conditions.

In situ analyses of sulfur isotope composition of fracture pyrite showed the influence bacterial sulfate reduction (BSR) in bedrock fractures and the complex sulfur evolution in the fractures (Sahlstedt et al., 2013). New, microscale data on carbon isotope variations, analysed in situ by SIMS, have added information on the carbon sources in the fractures. In the upper parts of the bedrock, dissolved inorganic carbon pool was supplemented by mineralisation of organic material. The organic material likely provided substrates for BSR. At the upper parts (34 m) of the bedrock, localized methanotrophic activity was detected in anomalously low  $\delta^{13}\text{C}$  values, down to -53.8 ‰. At the depths >50 m, high positive  $\delta^{13}\text{C}$  values indicate methanogenetic activity. Comparing conventional bulk isotope analyses to in situ data showed that microscale analyses were able to provide information on processes which were masked in data obtained by bulk analytical methods.

#### References:

Sahlstedt, E., Karhu, J.A., Pitkänen, P. and Whitehouse, M., 2013. Implications of sulfur isotope fractionation in fracture-filling sulfides in crystalline bedrock, Olkiluoto, Finland. *Applied Geochemistry* 32, 52-69.

## ORAL

### Modelling of Single Tunnel Crosscutting Fractures in the underground rock characterisation facility ONKALO, Olkiluoto, SW Finland

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This research focuses on Single Tunnel Crosscutting Fractures (STCF) in the ONKALO access tunnel in Olkiluoto, SW Finland. A STCF is a single fracture that cuts through the whole tunnel profile or that is at least 20 m in diameter, and is found outside known intersections of brittle deformation zones / is not a part of a brittle deformation zone. The objective of this study was to model the geometries of the STCF to gain better understanding of their size distribution, and to determine any characteristic geological properties that would improve prediction of these potentially large fractures. This work is related to Posiva's Rock Suitability Classification (RSC) system, developed for locating suitable rock volumes for repository design and construction. The aim of the classification is to avoid such features of the host rock that may be detrimental to the favourable conditions within the repository, either initially or in the long term.

The size of all the STCF fractures in ONKALO has been modelled and a minimum and maximum length recorded. Results from the modelling show that the STCF in ONKALO are normally less than 50 m in diameter, but that fractures up to 100-200 m in diameter exist. The STCF fractures follow the general trend of fracturing, but the STCF with a diameter over 50 m possess some distinctive geological characteristics. These fractures are usually characterised by an undulating, slickensided fracture surface and at least 2 mm thick mineral fillings. The occurrence of alteration, presence of water leakages or fracture fillings of quartz, epidote, graphite, or clay minerals are also typical indicators of a fracture potentially over 50 m in diameter.

#### References:

McEwen, T. (ed.), Aro, S., Kosunen, P., Mattila, J., Pere, T., Käpyaho, A. & Hellä, P. 2012. Rock Suitability Classification -

RSC 2012. Posiva Report 2012-24. ISBN 978-951-652-205-3., Eurajoki, Finland: Posiva Oy. 222 p.

Nordbäck, N., 2014. Tunnel Crosscutting Fractures (TCF) in ONKALO (chainage 0-4986). Working Report 2014-58. Posiva Oy, Eurajoki.

## POSTER

### New 3D modelling approaches in the study of Palmottu fracture patterns

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The classical Palmottu natural analogue site was used to apply three new fracture modeling tools in statistical analysis, visualizing and modeling fracture properties in 3D. The Palmottu site has been studied during an uranium exploration phase in the early 1980's and later during the Palmottu Natural Analogue Project 1994-1998. The Matlab scripts (Markovaara-Koivisto and Laine 2012) was used to cluster orientation data and to present statistical summaries and to reflect the change in degree of rock brokenness along drill holes. An intensity rose diagram was utilized to visualize interdependency of fracture properties and orientation. The FractCar Plug-in for Paradigm GOCAD was used to the model and visualize 3D fracture patterns based on the statistical analysis of fracture properties. Fracture representation was done through a Discrete Fracture Network (DFN). In addition, Multiple-point Statistics –method by ISATIS (Geovariances) based on training images was tested for fracture simulation. The resulted 3D fracture patterns were visualized and used in 3D modeling radioactive elements at Palmottu site.

#### References:

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## POSTER

## Measurement and monitoring of geological repository boreholes using terrestrial laser scanner and photogrammetry

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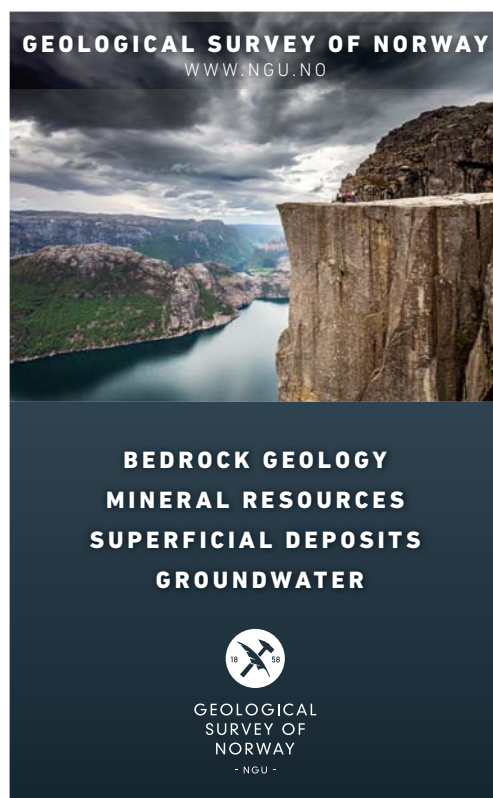
Several experiment boreholes were bored in the rock characterization facility ONKALO in order to analyze and experiment various technical aspects of the nuclear waste disposal. Among them is required an accurate measurement method to verify the strict design requirements and monitoring of the deformation of each borehole. In a 7.8 m deep borehole with a diameter of 1.75 m this has been proven challenging. The design requirements for the diameter are  $-2.5 - +25$  mm and for example for the straightness of the bottom 1:1750 mm. The present study aims at finding the most suitable technique for measuring and verifying the strict design requirements and also to develop a method for monitoring the deformation of these boreholes with high confidence and accuracy in a millimeter scale. Two different close-range measurement techniques are compared here: LiDAR and photogrammetry. Both techniques are applied using multitemporal acquisitions.

Parts of the 3D datasets are affected by an artificial distortion, with a maximum shift up to 6 mm, which is clearly above the required accuracy. The origin of this artifact is related with the data acquisition strategy. Largest distortions with LiDAR are e.g. the incidence angle, position of the scanner and rock surface moisture and color (Carrea *et al.*, 2014). For photogrammetry the greatest challenges are the setup and overlap of the images, moisture of the rock surface and georeferencing.

Up to now, the photogrammetric acquisitions have provided more accurate results than the laser scanning, but there is a range of improvement in acquisition procedures for both techniques and new acquisitions are in progress.

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## S1.6 Weathering and Alteration processes of Rocks and Minerals

### KEYNOTE

#### Altered basement rocks as sediment source and oil reservoir - the southern Utsira High, Norwegian North Sea

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The Utsira High is an intra-basinal structural high forming the eastern flank of the South Viking Graben. The Utsira is a granitic basement high located about two kilometers below the seafloor in the Norwegian North Sea. In Mid-Triassic the high was sub-aerially exposed and resulting in deep weathering of the crystalline rocks. From early Cretaceous until recent, the entire Utsira High has been submerged and covered by shallow-marine successions.

During the last few years four substantial oil discoveries have been made on and around the southern part of the Utsira high with Lundin Norway as operator; Johan Sverdrup (PL501/PL265), Edvard Grieg (Luno and Tellus, PL338), and Luno 2 (PL359).

For the first time on the Norwegian Continental Shelf, altered and fractured basement rocks have proven to act as sediment source, reservoirs and possible migration pathways for commercial hydrocarbon deposits. Following recent discoveries on the Utsira High (e.g. Edvard Grieg field), moderate reservoir properties have been observed in parts of the altered basement underlying Cretaceous oil reservoir rocks.

Hydrocarbon exploration wells drilled into the basement have encountered Silurian and Ordovician granites. On the western Utsira High the Silurian granites and caldera volcanics as well as minor Ordovician granites are the clastic source of non-marine Triassic sediments that make up the main oil reservoir of the Edvard Grieg field. In addition several wells in the area have encountered hydrocarbons in weathered and fractured granites. In well 16/1-15 (Tellus) a full scale test was perforated in the fractured and weathered basement interval, producing 650 BOPD (Barrels of oil per day).

A well-developed weathering profile was identified in cores from well 16/1-15; expressed as an upwards increase in degree of basement disintegration accompanied by an parallel increase in the amount of clay minerals.

### ORAL

#### Inventory and characteristics of known saprolite locations in Norway

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Recent hydrocarbon discoveries in crystalline basement (mainly Haugaland high) offshore Norway have sparked renewed interest in understanding the genesis, age and landscape evolution of fractured and weathered bedrock. The BASE-project, launched at NGU by integrating different research groups, addresses this problem by investigating the nature and timing of fracturing in relation to the timing and environmental conditions of saprolite formation.

The new project builds upon a previously established database of known saprolite localities extracted from a comprehensive literature review. The database gathers over 250 sites of weathering phenomena that include saprolites, tors, weathering pits, and other weathering related features. Generally two types of saprolites are identified, clayey and grussy, which commonly have been related to different weathering processes and formation times. Most saprolites are located close to the coast, with few observations in inland areas. The saprolites have mainly developed in coarse- to medium-grained, intermediate to felsic magmatic rocks and occur in regions with generally limited glacial erosion or deposits. The saprolite locations can be geographically grouped into seven distinct regions occurring mostly at elevations below 400 m asl.

Geochemical and mineralogical analyses completed on saprolites of both types from different regions reveal extensive depletion of leachable elements in the saprolites compared to fresh bedrock. Decreasing grain sizes with progressing weathering

is related to the formation of secondary clay minerals that include smectite, vermiculite, montmorillonite, illite, kaolinite and, at few locations, gibbsite. The database provides a useful tool to investigate the long-term landscape evolution in Norway.

ORAL

### Deep weathering and mineral exploration in Norway

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The remnants of deeply weathered basement on the mainland of Norway occur as accumulations of clay minerals and *grus* aggregates along structurally defined weakness zones and locally as up to c. 100 m thick continuous saprolite layers. It is suggested that glacial tills in many tracts of Norway contain significant amounts of reworked saprolite. These are places that were protected to some degree, from glacial erosion and transportation. The observed anomalously high concentrations of REEs and heavy metals such as Cr, Ni, Mo, Zn and Pb in both saprolite and overlying till can be caused by weathering processes where the major elements such as K, Na and Ca have been partly removed by leaching. Deep weathering has also been observed to be super-imposed on several copper-gold deposits in Finnmark (e.g. in Sáðgejohka and Čierte). Chalcopyrite and bornite are frequently replaced by supergene minerals such as digenite, malachite, cuperite, native copper, chrysocolla and limonite. Kaolinite deposits occur on the Varanger Peninsula in the Quaternary overburden as well as in the highly fractured bedrock. K-Ar dating in the 1970s of assumed hydrothermal clay alteration associated with Permian fluorite and sulphide vein deposits, as well as fault zones in eastern and southern Norway (e.g. at Lassedalen and Heskestad) yielded Mid and Late Triassic ages. These ages likely represent the same phase of *grus* weathering as observed offshore and do not represent hydrothermal alteration associated with the formation of the mineral deposits. K/Ar dating of clay minerals in regional fault zones provided also Late Triassic ages. XRF

analysis and mass balance calculations (degree of leaching) of bedrock in these areas commonly show a high degree of mineral alteration. We conclude that the understanding of deep weathering processes and their timing in Norway is a key to a successful mineral exploration programme in Norway.

ORAL

### Saprolites as mineral resources and significance in geochemical exploration

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Weathering transforms primary minerals into secondary phases.

Economically important mineral resources are created in weathering, as e.g. kaolin, bauxite, bentonite and sepiolite clays. Also many supergene metal deposits, as Fe, Ni and P enrichments are results of chemical weathering. This presentation gives an overview on some examples of saprolites from USA, Brasil and preglacial saprolites from Finland. Examples of kaolin deposits in Finland are Kaupinvuoma deposit in Finnish Lapland and kaolin deposits of Puolanka in Kainuu, where the saprolites are associated with N-S directed zone which at the length of 50 km hosts occasional white kaolin clay and red ferric kaolin occurrences. They are products of in situ chemical weathering of the parent rocks like arkose gneiss, meta-arenite and sericite quartzite. The weathering horizons may receive thickness of 30 meters. Sokli P-enriched weathering crust upon the 365 Ma Sokli Carbonatite Complex, hosting ca 120 Mt phosphorus ore, grade ca 13% P<sub>2</sub>O<sub>5</sub> is a good example of a world-scale supergene metal deposits. In Brasil, Minas Gerais state in particular, there are several remarkable supergene metal deposits that are weathering derivatives of alkaline rocks and carbonatites as well of chemically precipitated phoscorites. Till deposits in formerly glaciated areas can in places include a lot of metal-rich secondary phases. The knowledge of these is important when interpreting the results in geochemical exploration. Examples of this are presented from Finland.

ORAL

### Aluminum phosphate — sulfate minerals as indicator of Neoproterozoic Baltic paleosol paleoenvironment

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The aluminum phosphate-sulfate (APS) mineral solid-solutions are forming in different hydrothermal and sedimentary environments. We studied APS mineralization (< 4 wt.%) in paleosol profile developed on weathered monzogabbro-norites of Paleoproterozoic crystalline basement in northern Estonia.

APS minerals associate with kaolinite/clay matrix and are distributed in pore-space between kaolinite aggregates throughout paleosol profile. APS mineral crystallites are pseudo-rhombohedral/cubic shape with crystallite sizes <5 µm. Studied clay mineral composition change up by paleosol profile from illite, illite-smectitic to kaolinite 55 wt.% and Fe-oxyhydroxides (hematite and goethite) 25–30 wt.% rich horizon were primary mineral phases such as feldspars, biotite/mica, quartz, hematite, apatite (magmatic), anatase, zircon etc. remain strongly weathered grains. APS minerals have skeletal morphology in the upper part of paleosol (first ~1.5 m).

The APS minerals solid solutions are rich in LREE where chemical composition vary and are weathering grade dependent, for unweathered APS crystallites from lowest part of paleosol horizon estimated chemical structural formula is  $(\text{Sr}_{0.48}, \text{Ca}_{0.15}, \text{Ba}_{0.06}, \text{Ce}_{0.16}, \text{La}_{0.07}, \text{Nd}_{0.06}, \text{Pr}_{0.02})\text{Al}_3(\text{PO}_4)_{1.82}(\text{SO}_4)_{0.18}(\text{OH})_6$ .

The APS minerals precipitation, morphology and chemistry are closely related with weathering intensity and acidic and oxidizing meteoric waters/soil interaction down by profile. APS and an authigenic secondary apatite allows reconstruction of pH gradients in paleosol profile passing from acidic (pH 5) in the uppermost few meters thick section characterized by Sr-rich APS mineral solid solutions to progressively increasing pH with increasing depth down profile where secondary apatite prevails.

ORAL

### Earth Mars Analogues – Linking experimental and Martian clays

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Clay minerals were identified on Mars a decade ago by ESA's Mars Express orbiter and more recently confirmed by in situ X-ray diffraction analysis (XRD) performed by NASA's Curiosity Rover. The occurrence of clay minerals is often associated with impact craters and probably reflects aqueous alteration of impact glass. The composition of parent material and reaction fluids, time and climate are key factors controlling the formation of clay minerals. The main goal of the present project is to gain increased understanding on factors influencing weathering and alteration of minerals and amorphous phases in various hydrous regimes. Near Infrared analysis (NIR) provides the link between phyllosilicates observed on the Martian surface and during laboratory experiments. The new information gained will help in assessing observed clay minerals on Mars and their possible mode of formation e.g. climate wise.

In the project, alteration experiments are performed in reaction bombs (PARR reactors) using starting materials of different mineralogical/petrological compositions. The samples are mixed in aqueous solutions under various CO<sub>2</sub>, N<sub>2</sub> and O<sub>2</sub> partial pressures, at temperatures ranging from 120 to 200° C, and experimental running times between 3 and 6 weeks. Detailed chemical composition and mineral assemblage of starting materials and products are acquired by standard petrographical techniques, e.g. XRD, Scanning Electron Microscopy (SEM) and X-ray Fluorescence Spectroscopy (XRF). Geochemical modelling will provide in-depth understanding of the alteration reactions and stability fields of the minerals.

NIR spectra of the experimentally formed minerals will be acquired in cooperation with Université Paris Sud in order to improve mineral identification on the Martian surface both for spectra collected during the ongoing Mars Express mission and the upcoming robotic ExoMars ESA programme.

Preliminary results show dominant formation of smectite from basaltic glass, regardless of reaction temperature, time and CO<sub>2</sub>/O<sub>2</sub> pressure. More

details regarding mineral types and chemistry will be presented.

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**POSTER**
**Geochemical changes in a podzolic forest soil caused by mechanical site preparation**

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Mechanical site preparation after clear-cut of the forest stand is a normal practice in regeneration of forests. Ploughing (deep tilling) causes disturbances to the profile structure of the podzolic soil, because as a result of ploughing illuvial B as well as leached eluvial E horizons together with organic humus layer are turned upside down (so called 'tilt') onto the original soil profile located aside to the furrow. About 7 million ha of the total forest land area has been deeply tilled in Finland, and therefore it is important to increase our knowledge about the geochemical changes taking place in the exposed soil horizons in these areas. The aim of this study was to determine the changes in the total element concentrations of the podzolic soil horizons exposed to soil forming processes due to deep tilling. The changes in the total concentrations reflect the weathering processes in the soil leading to the depletion or enrichment of elements. The effects of deep tilling were studied in a boreal forest soil located in southern Finland.

Samples of the podzolic soil horizons were collected from undisturbed soil, tilt, undisturbed soil below the tilt and furrow 17 years after clear-cut of the forest stand and deep tilling of the forest soil. The total concentrations of elements were determined by x-ray fluorescence (XRF). In the topmost horizons of the furrow where the upper soil horizons (O, E, partly B) had been removed, clear weathering depletion had taken place after the exposure of the remaining B horizon to soil forming processes due to deep tilling (e.g. increase in Zr and decrease in CaO, MgO, FeO concentrations). In tilt horizons, the weathering depletion was not clear and it was found only related to the most sensitive elements (e.g. FeO). The original horizons in the tilt were

mixed due to deep tilling, and this seemed to be the main factor determining the concentrations in the tilt.

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**POSTER**
**Deep weathering patterns on the Fennoscandian shield in northern Finland**

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The nature of the regolith that existed on the shields of the Northern Hemisphere at the onset of ice sheet glaciation is poorly known. In northern Finland, a deeply weathered Late Neogene landscape is exceptionally preserved in the ice sheet divide zone. Using geochemical attribute data of a large percussion drilling dataset of the Geological Survey of Finland, we explore the weathering patterns in this unique area. We use a variant of the Weathering Index of Parker (WIP) as a proxy to assess the intensity of weathering.

The research shows that the topography of central Lapland is closely linked to its geology and structure. All these factors influence weathering patterns. Before the onset of glaciation, resistant granulate, granite, gabbro, metabasalt and quartzite hills had many fresh rock outcrops, including tors, and areas with thin (<5 m) grusses. Plains developed across less resistant biotite gneisses, greenstones and belts of alternating rock types were mainly weathered to thick (10-20 m) grusses with WIP<sub>finest</sub> values above 3000 and 4000. Beneath valley floors developed along mineralised shear and fracture zones, weathering penetrated locally to depths of >50 m and included intensely weathered kaolinitic clays with WIP<sub>finest</sub> values below 1000.

Three-part clay-gruss-saprock profiles occurred only in limited areas. In those cases, the weathering profiles reached up to 100 m in depth. Two-part gruss-saprock profiles are widespread, with saprock thicknesses of >10 m. However, incipient weathering and supergene mineralisation also extend to depths of >100 m in mineralised fracture zones.

Although the glacial erosion has been very limited (<20 m) in the ice-divide zone of northern Finland, glacial erosion and local glacial transport have

led to widespread incorporation of this saprolith material into tills. Reworked weathered material has a major influence on till geochemistry, heavy mineralogy and the fines fraction of the till matrix. Recognition of this influence is important for minerals prospecting protocols.

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**POSTER**

### **Neoproterozoic weathering crust of Baltic Basin**

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Understanding Precambrian palaeosol profiles provides important and direct evidence of the past climate (temperature, precipitation), atmospheric composition ( $p\text{CO}_2$ ,  $p\text{O}_2$ ) and (microbial)biota. The Neoproterozoic, ca 560–600 Ma old weathering crust is widespread under the Ediacaran-Phanerozoic sedimentary cover at the southern margin of the Baltic Shield, Baltic paleobasin. The palaeosol marks an unconformable contact of peneplained Palaeoproterozoic–Mesoproterozoic metamorphic-plutonic rocks and overlying unmetamorphosed Ediacaran sandstones–claystones. Palaeosol profiles were developed on apleo-Mesoproterozoic crystalline basements - rapakivi granites, sillimanite-cordierite and biotite-amphibole gneisses, amphibolites in the northern part and pyroxene and amphibole gneisses in the southern part of the area. Palaeosol is accessed in more than 100 drillcores where the thickness of the alteration profiles varies from few meters to exceptional 152 m on fractured-faulted sections of alumo-gneiss parent rocks. Palaeosol is preserved unmetamorphosed, but probably slightly modified by diagenetic illitization and uppermost part of most weathering profiles is partially eroded. Studied palaeosol profiles are characterized by three well-developed alteration zones starting from ca. 7 m thick reddish colored lateritic zone composed of kaolinite (~30-60wt %), Fe-oxyhydroxide and some residual quartz. Middle zone ca. 10-30m where the rock structures are preserved but primary minerals are replaced by secondary minerals is dominated by quartz, K-feldspar, micas, illite and

illite-smectite. In the lowermost zone, where original rock structure is still preserved and weathering can be detected only in fractures, is dominated by parent rock amphibole–plagioclase assemblage. This kind thick, well preserved lateritic kaolinite-rich weathering profile with hematite/goethite rich duricrust is similar to modern oxisols and most likely formed in warm and humid climate.

## S1.7 Environmental geology

ORAL

### Sources and controls of organic carbon in subarctic lakes across the Fennoscandian tree line

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High-latitude aquatic ecosystems are highly responsive to climate variability. Climate-induced changes in their structure and functioning are often mediated through altered carbon regime driven by landscape-scale ecosystem transformation. To investigate the dynamic catchment-lake interaction, we examined variable catchment parameters, limnological properties and surface sediment features of 31 subarctic lakes across a tree line gradient in northern Finland.

Multivariate statistical analyses were used to first identify catchment features that most strongly influence the limnology of the lakes, with a focus on dissolved organic carbon (DOC) concentrations and its colored dissolved organic matter (CDOM) fraction. Then, we investigated how the limnological characteristics were reflected in the geochemical properties of the lake sediments, including the elemental (carbon [C], nitrogen [N], C/N ratio) and isotopic ( $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ) composition of sediment organic matter.

The quantity and quality of organic carbon were identified as key variables differentiating the lakes across the tree line transect, with wetland cover as the primary catchment control on carbon concentrations and quality in the lake water. Terrestrial carbon inputs were mirrored also in the surface sediments of the lakes, yet the sediment geochemistry showed particularly strong coupling with nutrient concentrations related to high benthic production in the shallow lakes of the region. The results have implications for the responses of northern lake ecosystems to climate-mediated changes in vegetation cover and hydrology, and provide reference data

for temporal assessment of carbon dynamics in subarctic lake ecosystems.

ORAL

### Speciation matters – views on iron and sulfur chemistry in geothermal waters, Iceland

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The geochemical behaviour of elements depends largely on their speciation (i.e. the actual form). Therefore, speciation is of utmost importance in processes including water-rock-microbe interaction, scaling, and environmental pollution in aqueous environments. Iron (Fe) and sulfur (S) are particularly important in environmental geochemistry, and the transformations between their dissolved, solid and colloidal forms play a key role in the release and sequestration of many trace elements and contaminants, in mineral formation and dissolution, and their availability to biota. Both Fe and S may be present at more than one oxidation state. Thus, in order to understand the (bio)geochemical processes involving Fe and S it is not sufficient to have chemical data on the total element concentrations only, but data on the chemical species concentrations (i.e. the individual oxidation states:  $\text{SO}_4^{2-}$ ,  $\text{S}_2\text{O}_3^{2-}$ ,  $\text{S}_n\text{O}_6^{2-}$ ,  $\text{SO}_3^{2-}$ ,  $\text{H}_2\text{S}$ , Fe(II), Fe(III)) are required. It is, however, not trivial to reliably measure the species concentrations due to difficulties of preserving the speciation for later laboratory analysis.

We have studied metal and sulfur geochemistry in active geothermal systems in Iceland, with special emphasis on understanding the S and Fe reactions in geothermal fluids. Such active geothermal systems are dynamic environments characterised by steep gradients in temperature, fluid composition and oxidation state. The geothermal waters considered in this study cover temperatures ranging from ambient to  $\sim 100^\circ\text{C}$ , pH between  $<2$  to 10 and a wide range of absolute and relative Fe(II), Fe(III),  $\text{H}_2\text{S}$  and  $\text{SO}_4^{2-}$  concentrations. In order to determine species concentrations in geothermal waters, we developed and applied sampling and analysis

methods based on ion chromatography, spectrophotometry and voltammetry as well as size fractionation for geothermal waters. The analytical data on total element and species concentrations, combined with thermodynamic equilibrium constants and geochemical model calculations, were used to assess the most important reactions involving Fe and S in geothermal waters.

ORAL

### Geochemistry in soil and humus, central Norway

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A low-density (1/36 km<sup>2</sup>) study of mineral soil and humus was conducted in Central Norway to study the geochemical expression of underlying bedrock and mineral potential, to delineate regional anomalies and study the differences in the two materials. 752 samples were analysed for 53 elements in an aqua regia extraction. The four mined metal deposits in the area (Fosdalen, Skorovas, Gjersvik and Joma) were detected as the most prominent geochemical anomalies in both soil materials as well as a number of new anomalies. The results do not reveal anthropogenic contamination sources. The input of marine aerosols along the coast are clearly visible in the humus layer for Na, Se and B. The study shows that biogenic processes result in chemical differences between the two materials. Cd, Ag, S, Hg and Sb are greatly enriched in the humus layer, while Li, Th and V are 10-fold enriched in the mineral soil. Many elements, for example many major plant nutrients, show a narrow concentration range in the humus layer, which indicates a strongly regulated uptake by the plants that ultimately make up the humus layer. Some geographical differences in humus concentration can be explained by different climatic factors and thus vegetation types.

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ORAL

### Current applications in using geochemical baselines

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In Finland, geochemical surveys have been carried out since the 1930s. Today, geochemical background information is available from national and regional geochemical mapping surveys, as well as from targeted geochemical baseline surveys, from which geochemical baseline mapping of urbanized areas has had a special focus on environmental applications and land use planning. The urban geochemical baseline studies provide information on baseline concentrations for remediation projects, land extraction, land use planning and other urban functions. They also provide information for studies on the baseline status of the environment, as well as for environment impact assessment and for multi-disciplinary studies such as the protection of human health.

At present, information on geochemical baselines is mostly used in soil contamination studies. Reliable data on the geochemical baselines is of special importance in regions where the geochemical baselines may exceed the threshold values given in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007). Reliable information also enables case-specific guidelines for soil contamination assessment to be determined. If regional geochemical baseline values are available, the guideline values based on ecological risks can be modified accordingly. The recalculations of regional guideline values give tools to better assess the remediation needs as well as to choose the best available remediation technique for the area in question.

Geochemical baseline data can also be utilised for identifying and delineating areas with naturally occurring elevated concentrations of potentially harmful substances. New guidelines on the exploitation of excavated land (Ministry of the Environment, 3.7.2015) designate the classification



of excavated land as a waste or exploitative material. In principle, aggregates with elevated background concentrations, i.e. where the concentration is higher than the threshold value given in the Government Decree (214/2007), are not considered contaminated if there is plan for future use of the material. They can be exploited or placed in areas with similar or higher regional geochemical baseline concentrations.

ORAL

### The first arsenic guidelines for aggregate production were established in Finland

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Naturally occurring arsenic in bedrock and soil may cause the mobilization of As during rock aggregate production and construction activities, potentially impacting on groundwater aquifers, surface waters, and biota. Here, we present the outcome of two EU projects, RAMAS and ASROCKS. Both projects focused on the Tampere-Häme region of Southern Finland, where bedrock and soil contain more As than in other parts of Finland on average.

Over 1000 groundwater samples revealed that drilled bedrock wells may contain As-rich water in certain geological units. Naturally occurring As in bedrock and soil may also cause the mobilization of As during rock aggregate production and construction activities, potentially impacting on groundwater, surface waters, and biota.

As concentrations in aggregate products exceeded the regional background levels in some samples, but during leaching tests mobilization of As was found to be low. Risk management tools were established in cooperation with authorities, companies, and other stakeholders. The guidelines for As for the aggregate and construction industries can be applied in other countries like Sweden and Norway.

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ORAL

### Acid Sulfate Soils in Finland — mapping and environmental risks

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Sulfidic sediments have been developing in parts of the Baltic Sea during the last 8000 years. Post-glacial isostatic land uplift has brought the sediments above sea level. When these soils are drained by human activities (agriculture and forest drainage, peat mining, dredging and building), the sulfidic material will oxidise, leading to formation of sulfuric acid, leaching of acidity and metals from the soil, subsequent deterioration of watercourses and corrosion of infrastructure. The sulfidic sediments have turned into acid sulfate soils (ASS), which are a big environmental problem along the coast of Finland and worldwide. ASS also cause lots of trouble and costs in land-use related to construction and infrastructure. Dent and Pons (1995) concluded that in a global perspective "Acid Sulfate Soils are the nastiest soils in the World".

The problems related to ASS in Finland have been known for centuries, but not until 2009 did systematic mapping and (risk) classification commence on the responsibility of the Geological Survey of Finland (GTK). Until 2015 62% of the total potential 5 million hectares has been mapped. At this stage we can say that there are more acid sulfate soils in Finland than the earlier estimated maximum of 336 000 ha.

The results are published in GTK's Map services as probability maps including site descriptions and results: <http://gtkdata.gtk.fi/Hasu/index.html>.

In Finland, and also in the beginning of this mapping campaign, we have assumed that acid sulfate soils are fine-grained sediments occurring along the coast. During the mapping process it has become evident that in many places, also inland above the area once covered by the Baltic, there are also coarse-grained soils and till with low S-content (~0.01-0.1%), which are strongly acidified

when oxidised in the laboratory. There are examples where acid water from “acid sand”-pits has escaped and caused large fish kills in receiving streams. Sulfidic peat with S-contents up to 9% is also quite common. These “new findings” have raised a lot of questions and new research has to be initiated. Especially the role of black schist should be clarified.

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#### POSTER

### Acid Sulfate Soils in Northern Europe. A preliminary overview

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Acid sulfate soils (ASS) are naturally occurring soils, sediments and peats that contain iron sulfides. These soils are most commonly found in low-lying land bordering the coasts or estuarine and saline wetlands.

In an anoxic state, these materials cause no harm to the environment. However the disturbance of the sulfidic sediments, and their exposure to oxygen, leading to formation of sulphuric acid and leaching of acidity and heavy metals, has the potential to cause significant environmental and economic impacts, including fish kills and loss of biodiversity in wetlands and waterways, loss of agricultural productivity, and corrosion of concrete and steel infrastructure. The sediments have been transformed to active ASS. ASS also cause trouble and costs in land-use related to construction and infrastructure. **Acid sulfate soils have been described as the nastiest soils in the World.**

ASS currently cover approximately 17-24 million ha in coastal regions worldwide. Major occurrences are found in Africa, Australia, SE Asia and Latin America.

In Europe, the largest and most studied ASS occurrences are found in Finland and Sweden. They have originally developed / are developing mainly as fine-grained sulfidic sediments in the Baltic Sea during the last 8000 years, and have later been / are being uplifted on land by isostatic land-uplift.

Also in parts of Denmark (Jutland; North Sea), Northern Germany (both Baltic Sea and North Sea) and the Netherlands (North Sea) ASS occur, and some ASS sites have recently been described from the coast of Poland. In these countries the sulfidic sediments are mainly related to sand or peat.

In Russia ASS have been described from the eastern parts of the Gulf of Finland and on the southern shores of the White Sea they are common (N Putkinen, GTK: oral communication).

The fact that ASS exist in many regions in Northern Europe, raises the question: Do ASS also occur in the Baltic States and in Norway?

We suggest that the next step could be a multinational project, producing an ASS map of Northern Europe and ultimately some common guidelines for identification and management of ASS!

**If you have information about Acid Sulfate Soils or relevant contacts in your country or want to participate in a multinational project, please let us know!**

#### POSTER

### Tracing the carbon cycle in river systems using the isotopic composition of dissolved inorganic carbon

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It is of particular importance in fragile catchments to understand the carbon cycle within the catchment. Fragility of a catchment is increased by human activities, as well as interaction between surface and groundwater. Organic matter is one of the most important impurities in such catchments and it can cause unwanted microbial growth in the water. The stable isotopic composition of dissolved inorganic carbon (DIC) is a useful tool in studying the decomposition of organic material within a river system. In the case of the Vantaanjoki River, located in one of the most densely populated areas in southern Finland, studying the evolution of contaminants in the river system is of particular importance, because previous studies have shown the river having a considerable amount of groundwater - surface water interaction (Korkka-Niemi et al. 2012, Niinikoski et al. 2015). This increases the vulnerability of the local groundwater, which is used as a drinking water

source. Possible sources of contaminants in the area are water purification facilities, a saw mill and agricultural areas. In this study the isotopic composition of DIC was studied, along with the concentration of DIC in the river water. We were looking for traces of human induced changes in the carbon balance of the river, but also trying to establish the naturally occurring annual fluctuations in both DIC contents and isotopic composition in the river. The highest  $\delta^{13}\text{C}_{\text{DIC}}$  values were found in the summer, and the lowest ones in the spring. Similar trends have been reported in other studies and are most likely the result of naturally occurring organic material formation and decay in the river water. Locations of the water purification facilities or fields along the flow path did not show on the  $\delta^{13}\text{C}_{\text{DIC}}$  values, nor in the DIC contents of the water.

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#### POSTER

### Extraction of Natural Stone in Finland - The Best Environmental Practices (BEP)

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The extraction of natural stone differs considerably from mining and aggregate operations due to its geological environment, processes, and the volumes of quarried stone.

For granitic rocks, precision drilling, smooth blasting, diamond wire sawing, and wedging are used. Soapstone is quarried with chain saws and wheel loaders with forks. Schist is extracted with an excavator, sometimes equipped with a hydraulic hammer. For marble extraction, diamond wire saws are commonly employed.

The environmental issues in natural stone quarrying entails noise impact, dust, and vibration. Localised effects on the natural environment, surface waters and groundwater may also occur.

While managing the environmental impacts of the quarry actions, careful planning of the plant, together with utilisation of high-quality, emission-preventing techniques is crucial. Ensuring the cleanliness of the plant and continuous maintenance of machinery (such as vehicles, drilling equipment, and chain saws) are also of great importance. The methods for reducing the spread of noise and dust include emission-preventing actions, such as constructing noise barriers, and watering areas in places where dust is generated. The water discharged from the quarry should be treated in sediment ponds to remove suspended solids and nutrients. The fuels, lubricants, and other chemicals, should be handled with care and in accordance with regulations.

Effective planning including high-quality and comprehensive studies of the environmental impacts and their management for quarry operations benefit both the operators and the environment.

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#### POSTER

### Acid sulfate soils along the coast of northern Sweden

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Acid sulfate soils (AS-soils) are formed when sulfidic sediments are exposed to air, and they may affect nearby watercourses negatively by lowering the water pH and releasing high concentrations of metals such as nickel. The occurrence of AS-soils and sulfidic sediments in the coastlands of northernmost Sweden was documented to better understand which streams that may be, or have already been, negatively affected by AS-soils.

In situ measurements of pH were conducted to identify AS-soils in the field. Complementary laboratory pH measurements on field samples were done in order to examine whether some of the reduced sediments exhibited potentially acid characteristics when oxidised over a longer period of time (weeks).

Chosen samples were analysed for sulfur (S), carbon (C), metals and other elements by IPC-OES and ICP-MS.

Both AS-soils and sulfidic sediments can often be recognised in the field. The studied AS-soils are often characterised by pH levels <4.0 and vertical soil fissures covered by rust, which sometimes are associated with the yellow mineral jarosite. The sulfidic sediments in northern Sweden are often characterised by a distinct black colour and a neutral pH which after incubation in the laboratory drops to values below pH 4.

AS-soils and sulfidic sediments can be found in areas with clay and silt that have been uplifted above the sea level during the past 5 000 years due to land upheaval. AS-soils are mainly formed at sites where the groundwater level has been artificially lowered by man-made ditches. Reduced sulfidic sediments in untouched wetlands that are not exposed to air will successively be covered by layers of peat, which inhibits the development of AS-soils.

The low soil pH conditions have caused leaching of certain elements, e.g. nickel (Ni), cobalt (Co) and cadmium (Cd), from the studied AS-soils. These elements may have reached surrounding waters, and there is a correlation between drainage areas with a high proportion of AS-soils and negatively affected streams.

The correlation between the element concentrations in humus and minerogenic topsoil has been evaluated first measuring the Spearman rank correlation values; in this case the total numbers of samples and the different soil parent material, were considered too. The correlation between the element and the content of organic C was taken into account as well. Then scatter plots between the element concentrations in humus and minerogenic topsoil, and between the content of the element vs. the content of organic C, were elaborated where significant Spearman values were noticed.

In general, there was no strong positive correlation between humus and minerogenic topsoil concentrations in Southern Finland. Earlier studies have shown that there is good correlation between topsoil and subsoil concentrations suggesting a geologic origin of the distribution patterns. Concentrations in humus layer reflected better the atmospheric deposition pattern estimated from moss samples (Poikolainen et al. 2004).

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#### POSTER

### Comparison on humus and soil geochemical baselines in Southern Finland

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Geological Survey of Finland has carried out geochemical baseline mapping using topsoil, subsoil and humus samples in Southern Finland since 2002. The geochemical baseline concentration refers to both the natural geological background concentrations and the diffuse anthropogenic input of elements in soil. Humus samples reflect the interplay between atmosphere, biosphere and lithosphere. It is also used to study how (long-range) atmospheric input of elements to ecosystem accumulates over time (Salminen et al. 2004). Concentration of elements in topsoil are mostly controlled by geology but atmospheric input can affect also geochemistry of the topmost 25 cm of the mineral soil layer.

## S2.1 Critical metals — petrology, geochemistry and ore geology

### KEYNOTE

#### Studies on Mineralogy and Beneficiation of REE Ores

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Currently, the world's REO production is mainly from bastnäsite, monazite, xenotime, and the Chinese ion adsorption ores. As the demands of REE in the world are increasing other REE minerals or resources could become new REO sources in the future such as steenstrupine in Kvanefjeld deposit in Greenland, eudialyte in Norra Kärr deposit in Sweden and Kringlerne deposit in Greenland. Apatite could also be a potential REO source as the by-product in the phosphate ore processing.

Studies on mineralogy and beneficiation of the REE ores from the deposits of Kvanefjeld, Norra Kärr and Kringlerne were conducted at GTK in the EU funded project EURARE. The MLA and EPMA were used for mineralogical analyses and beneficiation laboratory bench testwork and demonstrations in pilot scale were performed. For the Kvanefjeld ore multistage flotation approaches were tested and optimized to separately obtain REE (steenstrupine) and Zn concentrates. For the Norra Kärr and Kringlerne ores wet and dry high intensity magnetic separation techniques were tested and the parameters were optimized for the enrichment of eudialyte efficiently.

In addition, case studies on mineralogy and beneficiation for the ores with complex REE mineralogy from the deposits in Finland, Norway and Mongolia, and the apatite REE ores from the phosphate deposits in Mongolia were carried out in EURARE project and the development cooperation project funded by Finland's Ministry for Foreign Affairs. Based on mineralogical analyses the beneficiation techniques of flotation, gravity concentration, magnetic separation and acid leaching were technically assessed for recovering different types of REE minerals and phases.

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### ORAL

#### Transport properties of Nb and Ta in hydrothermal fluids: thermodynamic analysis of hydroxo- and fluoride complexes over a wide range of temperatures and pressures

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Despite tantalum (Ta) and niobium (Nb) are essential metals in modern society their geochemical behaviour, especially in hydrothermal fluids is still poorly known. The goal of this study is to identify stoichiometry of Nb and Ta aqueous species and to estimate stability of their complexes' formation in a wide range of temperatures (0 – 600°C) and pressures (0.1 – 300 MPa).

The whole set of the available experimental data on Nb<sub>2</sub>O<sub>5</sub> [1, 2] and Ta<sub>2</sub>O<sub>5</sub> [3] solubility in hydrothermal HF-NaF-KF-NaOH fluids were processed by the OptimA program [4] to reveal stoichiometry of aqueous species and estimate their Gibbs free energies,  $g(T, P)$ , at given  $T, P$  point.

The estimated  $g(T, P)$  values for hydroxide and fluoride complexes were then used to generate the HKF model [5] parameters of these species by use of the OptimB [4]. As a result thermodynamic description of Nb and Ta aqueous species is available to perform various thermodynamic models of hydrothermal transport and accumulation of these metals in a wide range of temperatures (0 – 600 °C), pressures (0.1 – 300 MPa) and fluid compositions.

Acknowledgements: The study was financially supported by the RFBF grants 14-05-91750\_AF and 14-05-00424.

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## ORAL

### REE mineralisation in Sweden: 222 years of discovery?

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The increased global interest in rare earth element (REE) resources over the past few years has led to new exploration activities and on-going re-evaluation of many previously known mineralisations.

Through the discovery and subsequent publication by Finnish-Swedish chemist J. Gadolin in 1794, on the World's first known rare earth element ("yttria", from Ytterby, north of Stockholm), the history of the REE was to be interconnected with Sweden. Indeed, during the end of the 18<sup>th</sup> and the better part of the 19<sup>th</sup> century, Sweden was at the centre of REE discoveries

Over the intervening 222 years since Gadolin's publication, we have come to know a variety of genetically different types of REE mineralisations and occurrences that are relatively widely distributed over the Swedish part of the Fennoscandian shield and its cover units. In fact, the shield is one of the more promising areas in Europe for the exploration after hard-rock REE resources (cf. Goodenough *et al.* 2016). In this presentation, the spatial distribution of REE mineralisations in Sweden will be summarised and discussed, based on genetic classifications. The major types comprise primary mineralisations, encompassing intrusive as well as hydrothermal mineralised systems, whereas secondary mineralisations are represented by sediment-hosted types, including palaeoplacer deposits.

Currently, one of the most promising projects within the EU is the nepheline syenite-hosted Norra Kärr deposit in southern Sweden. Among others is the possibility of exploiting by-product REE-substituted fluorapatite and associated phosphates during mining of apatite-iron oxide ores. The recently discovered high-grade, high-HREE mineralisations in the Olserum area, SE Sweden (see presentation by S. Andersson *et al.*, this volume), may

however be hampered by the presence of radioactive elements.

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ORAL

### Critical raw material potential in Finland

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Critical raw materials as defined by the European Commission (Sb, Be, borates, Cr, Co, coking coal, fluorite, Ga, Ge, graphite, In, magnesite, Mg, Nb, phosphate rock, PGM, REE, Si metal, Ta and W) are commodities, which are needed by the EU industry, but produced elsewhere, creating a possible supply risk (EC 2014). The discovery potential of these raw materials in the bedrock of Finland has been estimated by GTK (Kihlman et al. 2014, Sarapää et al. 2015a,b). Some of the commodities are currently produced from mines (Cr, Co, PGM, phosphate rock and silica sand) and Finland also has minor refinery production of Ge from imported material. The discovery potential of borates, coking coal, fluorspar, Ga and Ge in the bedrock of Finland is estimated as low to nonexistent based on the lack of known occurrences. In and Mg are currently considered to have low potential, although the rapakivi granites may have some In potential and magnesite deposits are known in Finland. All other commodities are estimated to have moderate to good discovery potential based on the number of known occurrences and deposits and historical or current mine production. The recent investigations of GTK have revealed several new targets for REE and phosphate rock exploration in central and northern Finland. The most interesting targets comprise carbonatites (e.g., Sokli, Korttejärvi) and alkaline intrusions (Iivaara).

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ORAL

### Quantifying the resource potential of selected end-of life products for five critical metals

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The use of waste as a resource has been a topic of interest for numerous sustainability and zero waste strategies including the recently developed circular economy concept. The European Commission points out that valuable materials are leaking from European economies and Europe could benefit economically and environmentally from making better use of those resources. The European Minerals Yearbook developed by the FP7 funded project Minerals4EU (2013–2015) produced case studies that estimate the potential contribution of secondary raw materials from selected end-use products towards satisfying Europe's demand for 8 metal commodities, including 5 critical ones (Pt, Pd, Dy, In, Y). Full details of the methodology and short case studies are available at <http://minerals4eu.brgm-rec.fr/search/site/m4eu-myb>.

A significant part of the European demand for palladium (Pd) (27–81%) and platinum (Pt) (17–46%) is already covered by recycling autocatalysts from non-electric passenger vehicles. Decreasing export rates for waste cars and optimising collection could increase these percentages even further. In an ideal scenario of collection rates and recovery rates approaching 100%, the extraction of Pd from autocatalysts alone could satisfy between 41–125% of the European demand for this metal. For Pt the corresponding range is 26–73%. Dysprosium (Dy) recovered from end-of-life laptops and desktop PCs could contribute between 28–38% towards the European demand and indium (In) from end-of-life LCD TV, monitors and laptops between 15–19%. In reality however, only small parts of the European demand for Dy (<0.4%) and In (<0.2%) are covered by secondary sources due to inefficient recycling technologies and waste collection practices available.

Case studies on the selected critical metals are presented to illustrate the present and potential future contribution of secondary raw materials in strengthening Europe's security of supply.

ORAL

### Critical metals in the mines and dumps of W Bergslagen, Sweden

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Hard rock mining in the Palaeoproterozoic Bergslagen ore province in south central Sweden dates back at least 1000 years. A conservative estimate of the number of old mines and prospects in this region is about 8500, many with associated dumps. Typically, only a single metal was extracted from these operations. In some cases precious or other metals were not detected, and for a number of elements, now considered "critical", the market at the time was limited or non-existing. Hence, these occurrences represent a potential source of sought-after metals today. Here, we highlight some examples of critical metals in such dumps and mineralisations.

Increased REE concentrations occur in two iron oxide belts in western Bergslagen. The westernmost one consists of Kiruna-type apatite iron-oxide deposits (AIO). The REEY contents in the AIO mineralisations reach up to 1 wt.%. Here, REEY occur as a substitution component in fluorapatite, and in monazite-(Ce), xenotime-(Y), allanite-(Ce) and minor REE-fluorocarbonates. The other belt is the c. 100 km long REE-line, located 50 km to the east, sub-parallel to the AIO belt. The REE-line is composed of a number of magnetite-dominated skarn mineralisations. Albeit LREE-dominated some are extremely rich in total REEY, with dump samples reaching concentrations of 31 wt.%. REEY are mainly hosted by REE-silicates and fluorocarbonates. Several deposits are also enriched in Ga (200-900 ppm) and Ge (20-130 ppm). Adjacent to the REE-line, quartz-banded iron oxide (BIF) mineralisations are also enriched in REE (up to 8000 ppm REEY).

Elevated In concentrations have been known in the Filipstad district for some time (e.g. Jonsson

et al. 2013, and references therein), and additional anomalous In concentrations (>20 ppm) have now been verified in sphalerite from several sulphide mineralisations in this general area. In mostly occurs as substitutions in sphalerite or Cu sulphides, and in rare cases as roquesite (CuInS<sub>2</sub>).

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Jonsson, E., Högdahl, K., Majka, J. & Lindeberg, T. 2013. Can. Mineral. 51, 629-641.

ORAL

### Mineralogy and geochemistry of the apatite vein type Mushgia Khudag REE deposit in Gobi, Mongolia

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We have studied the mineral composition and geochemistry of the apatite vein type Mushgia Khudag REE deposit in southern Gobi, Mongolia. The rocks were studied in the field and in the laboratories of GTK Finland and CGL Mongolia by MLA, XRD, EMPA, XRF, and LA-MC-ICPMS. The studied sample material was collected during two field work periods in 2012 and 2014 for an ICI development project Chinggis II funded by the Ministry for Foreign Affairs of Finland (Yang, X. et al. 2015).

The Mushgia Khudag deposit is located in the southern parts of Gobi desert in the province of Ömnögovi some 600 km southwest of Ulaanbaatar. The REE mineralizations in the area are associated with apatite and carbonatite veins that range in width from centimetres to some tens of metres, and are genetically related to Early Cretaceous ca. 140 Ma syenite magmatism, (Munkhsengel et al., 2013). In the late stages of the igneous-hydrothermal activity the conditions of apatite crystallization were favourable for extreme enrichment of REE, leading to an average of 15% REO and the highest values reaching 21% REO in our apatite samples. To our knowledge, this is the highest content of REO reported in apatite worldwide. The average whole rock REE concentration in the studied samples is 8% of which around 97% is hosted by apatite, and the rest by monazite, monazite-(Ca), and REE-fluoro-carbonates, e.g., synchysite, and parisite.



In this work, the mineralogical and geochemical data are used along with field observations to interpret and characterize different ore forming events in the Mushgia Khudaga REE deposit. Especially, the conditions of apatite crystallization that brought about the extreme REE enrichment in this mineral are discussed.

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- Munkhtsengel, B. *et al.*, 2013. Some notes on the Lugiin Gol, Mushgia Khudak and Bayan Khoshuu alkaline complexes, Southern Mongolia. *International Journal of Geosciences* 4, 1200-1214
- Yang, X. *et al.*, 2015. Mineralogy and beneficiation of vein-type apatite rare earth element ore from Mushgia Khudag, Mongolia. In: De Lima, I.B. and Filho, W.L. (eds.) *Rare Earths Industry. Technological, Economic, and Environmental Implications*. Elsevier, Amsterdam, Netherlands, pp. 377-39

ORAL

### Scandium deposits and potential in Finland

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Scandium (atomic no. 21) is a light transition metal with good electrical conductivity and heat stabilization properties. Globally, its usage has been minor due to unstable markets as a byproduct. Current applications include Sc-Al alloys, natural light bulbs and solid oxide fuel cells, the latest being forecasted to place growing demand for a stable primary product supply. Sc is compatible in ferromagnesian minerals and is thus evenly distributed in the Earth's crust. Usually, Sc enrichment requires hydrothermal and erosional environment: typical economic deposits are in laterites or in placer sands together with REE-minerals. Other showings of Sc are related to pegmatitic vein systems, greisen, skarn and carbonatite complexes.

Sc showings in Finland are rare. In Haapaluoma pegmatites, columbite contains 0.90 wt% of Sc<sub>2</sub>O<sub>3</sub> (Haapala *et al.* 1967). Also a few grains of Sc-Y-silicate thortveitite has been described from a pegmatite in Pello (Alviola 2003).

On the contrary to the vein-type findings, a ferrodiorite intrusion in Kiviniemi, Eastern Finland, shows abnormally high and rather homogeneously distributed Sc concentrations in apatite, clinopyroxene and amphibole (940-1133 ppm, 610-1740 ppm and 103-2088 ppm of Sc<sub>2</sub>O<sub>3</sub>, respectively). Preliminary enrichment tests have been made at the

GTK Mintec and the University of Eastern Finland (UEF) facilities to evaluate the utilisation potential of the deposit. The conventional separation and flotation techniques failed to separate Sc from the silicates. Also the new extraction method with a bisphosphanate collector (at UEF) faced problems, since the high iron content of the diorite prevents the full adsorption of Sc into the collector. However, the yield can be raised up to 96 % by combining a magnetic separation with the dissolution-based bisphosphanate extraction. The collector extraction can therefore turn out to provide a new enrichment method for REE and silicate mineral type ores.

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- Haapala, I., Siivola, J. and Löfgren, A. 1967. On the Haapaluoma Sc-bearing columbite and its inclusions. *C. R. Soc. géol. Finlande*, No 39, p.95.
- Alviola, R. 2003. Pegmatiittien malmipotentialista Suomessa. *Geological Survey of Finland, archive report M 10/2003/1/85*, 5 p. (in finnish)

ORAL

### 300 million years of indium-forming processes in A-type igneous environments in the Fennoscandian Shield

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Indium has an increasing demand for liquid crystal displays, high-definition televisions and other products of modern electronic industry. Most of the indium on the global market is a by-product of zinc mining from a number of ore types. However, even if many mines in Sweden and Finland (VMS ores in the Bergslagen, Skellefte and Pyhäsalmi regions) currently are major Zn producers, they are not significant In producers. Instead, since the first indium discovery in the Fennoscandian Shield (Pitkäranta, Ladoga region, in 1910), almost all recent indium discoveries in the Precambrian of Finland and Sweden were made in veins and skarn mineralizations, in close association with 1.85-1.54 Ga anorogenic granites, none of them in current production. A review of them follows:

Moderate grades (up to 83 ppm In) have been recorded in greisen veins in A-type granites of various ages in the *Trans-scandinavian Igneous Belt*: 1.85 Ga (Gillerdrågen and Tyfors) and 1.67-1.70 Ga (Van and Norra Hålen), all located to the northwest of Bergslagen. 1.85 Ga anorogenic granites are

also responsible for the metal supply to the polymetallic ores in the Svecofennian supracrustal formations in westernmost Bergslagen (among them Getön, Hällefors, Gruvåsen and Långban), where up to 100 ppm In has been recorded.

A number of In-bearing polymetallic mineralizations occur in the western parts of the 1.64 Ga *Wiborg batholith*, SE Fin-land. High grades are recorded for the Zn-Pb-Ag-rich vein at Jungfruberger (up to 600 ppm In) and the Cu-As-Sn-rich Korsvik veins (up to 1500 ppm), the latter with In in roque-site, sphalerite and chalcopyrite (Cook et al. 2011). Indium also occurs with grades of c. 40 ppm in compact magnetite-sphalerite bodies at Getmossmalmen and Pahasaari.

Indium-rich polymetallic veins occur within and outside the 1.57 Ga *Eurajoki stock*, SW Finland, with up to 570 ppm In.

Indium is abundant (up to 600 ppm) in the Zn-rich skarn ores at Pitkäranta, along the western margin of the 1.54 Ga *Salmi batholith*. It is usually sphalerite-hosted but tiny roque-site grains occur in the Hopunvaara deposit (Valkama et al., subm.).

#### References:

Cook, N.J., Sundblad, K., Valkama, M., Nygård, R., Ciobanu, C.L., Danyushevsky, L., 2011. Indium mineralization in A-type granites in southeastern Finland... *Chemical Geology* 284, 62-73.

Valkama, M., Sundblad, K. & Cook, N.J. Geochemistry and petrology of the polymetallic skarn ores at Pitkäranta, Ladoga Karelia, Russia. Submitted to *Mineralium Deposita*.

ORAL

### Graphite deposits of Norway; a review

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There are 4 main graphite provinces in Norway and the Geolocal survey of Norway have the last 6 years conducted airborne geophysical surveys with EM, RAD and MAG. over all the potential graphite provinces of Norway.(Rodionov et al. 2013a,b & 2014)

1. The Island of Senja, here we have the Skaland graphite mine at Trælen Europes largest producer of natural graphite and the worlds richest flake graphite mine un current production. .

2. The Lofoten-Vesterålen archipelago. The new airborne geophysics indentified a number of new EM anomalies, found to be new an unknown graphite prospects. The extent of known prospects was determined with new accuracy.
3. The Holandsfjord area. The abandoned Rendalsvik mine and the nearby Nord-Værnes mine, have been investigated with mapping and ground and airborne geophysics.
4. The Bamble area of southern Norway. In this area there are large areas with supracrustal rocks with a graphite content of 2-6 %.

All the Norwegian graphite occurrences are of flake graphite type and occur in proterozoic supracrustal rocks of high amphibolite or granulite facies metamorphic conditions. In general they are deformed in a complex manner. Many of the occurrences show high, (> 15%) content of graphitic carbon.

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ORAL

### The Nunasvaara graphite deposit, northern Sweden: New geochemical and U-Pb zircon age results for the host greenstones

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The Nunasvaara graphite deposit, located in north-central Norrbotten, represents the largest known metamorphic graphite occurrence in Sweden (JORC indicated resource<sup>1</sup>: c. 5.6 Mt, 24.6% C<sub>g</sub>, 10% cut-off). Mineralization consists of disseminated to massive c. < 0.1mm graphite, within

a schist horizon that forms part of a relatively conformable, polydeformed Paleoproterozoic greenstone succession (basalts, tuffs, doleritic sills, intercalated sedimentary rocks). We present new litho-geochemical, Sm-Nd isotope and U-Pb SIMS zircon results from the Nunasvaara area that provide new petrogenetic insights into this graphite-bearing greenstone sequence.

In general, least altered basalts and doleritic sills have sub-alkaline, high-Fe tholeiite signatures, with flat to mildly LREE-enriched, chondrite-normalized REE patterns ( $\text{La/Yb}_N = 1.0$  to 3.9 and 1.4 to 4.1, respectively). Tuffaceous rocks have tholeiitic basalt to basaltic andesite compositions and similar REE systematics. U-Pb SIMS zircon dating of a doleritic sill intruding hanging wall volcanoclastic rocks has yielded a precise igneous age of  $2144 \pm 5$  Ma ( $2\sigma$ ,  $n = 10$ ). This date constrains the timing of mafic magmatism and provides a minimum age for the deposition of volcanoclastic and sedimentary material. Whole-rock  $\epsilon\text{Nd}_{(2.14 \text{ Ga})}$  values range from +1.4 to +4.0 for basalt ( $\pm 0.4$   $\epsilon$ -units;  $n = 4$ ), +0.5 to +3.8 for dolerite ( $n = 3$ ), and +2.3 to +2.9 for the basaltic tuffs ( $n = 3$ ). These data fall close to the depleted mantle evolution curve and are characteristic of 'juvenile' magmatism with a relatively short crustal residence time.

The geological and geochemical features of the Nunasvaara greenstones indicate a tholeiitic magmatic event with intermittent sedimentation at c. 2.14 Ga. The positive  $\epsilon\text{Nd}_{(2.14 \text{ Ga})}$  values suggest mafic magmas were derived from a sub-continental source region, with little contribution from the Archean Norrbotten craton (i.e., typically negative  $\epsilon\text{Nd}$  character by c. 2.14 Ga). Subsequent metamorphism, including graphitization of carbonaceous sediment, is attributed to Svecokarelian-cycle tectonothermal events.

<sup>1</sup>Talga Resources Ltd, 2012

## POSTER

### REE mineralisation in the Olserum area, SE Sweden

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Hydrothermal transport of the rare earth elements (REE) in geological fluids is essential for the formation of economic REE mineral deposits. We are investigating the hydrothermal REE mineralisation in the Olserum area, SE Sweden, which represents an unusual and possibly new type of REE deposit dominated by high-grade REE phosphates. The area is part of a larger U±REE-enriched zone in the Palaeoproterozoic, metasedimentary Västervik formation, located at the southernmost end of the Svecofennian domain. This formation is bordered by granitoids belonging to the Transscandinavian Igneous Belt.

The Olserum area consists of several mineralised subareas, currently under exploration by Tasman Metals. The main targets are the Olserum-Djupedal areas. Monazite-(Ce) and xenotime-(Y) are the main REE phases, and they mostly occurs as veins in both areas. The REE phosphates and apatite typically occur as cm-sized, fractures crystals. The fractures are infilled by gangue minerals, mainly biotite, quartz, magnetite, amphibole, cordierite, muscovite, chlorite and tourmaline (In Djupedal). In Olserum, the mineralisation is hosted within metasediments, whereas the Djupedal area is closer to the contact zone of the adjacent granite, manifested by more complex host rock relationships and diverse mineralogy. Additional REE phases, besides monazite and xenotime, are allanite-(Ce) and REE-fluorocarbonate. Allanite is apparently younger than the bulk of the xenotime and monazite, but is itself fractured and infilled by gangue minerals, including minor amounts of REE phosphates. In both areas, monazite and allanite are also hosted in biotite-magnetite schlieren in the granite. Future work will focus on obtaining mineral chemistry and

trace element data, as well as analysing fluid inclusions by LA-ICPMS, which will provide input data for thermodynamic modelling of the hydrothermal REE mineralising system.

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**POSTER**
**Petrography, geochemistry and P-, Nb-, and REE-mineralizations in the Kaulus region, Sokli carbonatite complex, Finland**

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The Kaulus study area of GTK is situated in the southern part of the Devonian Sokli carbonatite complex in northern Finland. We have studied the petrography, geochemistry and P<sub>2</sub>O<sub>5</sub>-, Nb- and REE-mineralizations in the Kaulus region. In addition, the regional lithology and the petrogenesis of the carbonatites are examined (Pynttari 2015).

The predominant rock types in the study area are carbonatite dikes that intrude fenitized tonalites, gneisses and amphibolites. No significant P<sub>2</sub>O<sub>5</sub>-, Nb- or REE-mineralizations were found in the fenites.

Metacarbonatites and metaphoscorites originally represent alkaline mafic or ultramafic rocks that have undergone carbonatization and alkali metasomatism. Metacarbonatites are enriched in P<sub>2</sub>O<sub>5</sub> (2.6–4.0 %). Metaphoscorites occasionally have elevated Nb contents (up to 1799 ppm), which may originate from magmatic phoscorite. As CO<sub>2</sub> concentrations increase in metacarbonatites, their REE-concentrations rise up to the REE-concentrations in carbonatites.

Carbonatites probably originate from metasomatized mantle at the depth of 70–80 km. Ferrocarbonatites and magnesiumcarbonatites may have acted as a source for the REE-carbonatites of magmatic Stage 5. The richest P<sub>2</sub>O<sub>5</sub>-concentrations are in calciumcarbonatites and ferrocarnatites (3.3 % and 4.4 %, respectively). The richest Nb-concentrations are found in REE-carbonatites, ferrocarnatites and calciumcarbonatites (1834 ppm, 1790 ppm and 1636 ppm, respectively). The average REO-concentration of the REE-carbonatites is 1.63 % and the maximum content is 1.94 %.

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**POSTER**
**Thermal and hydrothermal influence of rapakivi igneous activity on Late Svecofennian granites in SE Finland**

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Recent discoveries of polymetallic mineralization in the Sarv-laxviken area, south-eastern Finland, have unveiled the ore potential for rapakivi granites along the western margin of the Wiborg Batholith (Cook et al., 2011). Two kinds of mineralized systems have been recognized: 1. quartz veins with In, Cu, As, Sn and W in coarse-grained wiborgites and 2. alteration veins with Mo, Sn, As, Cu, Bi, Be in late-stage even-grained rapakivi granites (Valkama et al., *subm.*).

Exploration activities in the Svecofennian bedrock at Lill-träsket, 2 km west of Sarvlaxviken, have resulted in the discovery of an ore boulder with a 1/2 m wide greisen alteration zone (with 5 % Zn) and significant soil anomalies with respect to Zn, Cd, In, Ag, Fe, Pb, Bi and As. Intense ground magnetic anomalies match the iron rich soil anomalies, clearly indicating a very local origin of the ore boulder and the soil anomalies. This implies that wide-spread polymetallic mineralization also exists in the Late Svecofennian granites, up to one km from the rapakivi contact, which is interpreted as a result of the rapakivi igneous activity.

The polymetallic mineralizations in the Lillträsket area are located within the 10–20 km wide thermal alteration aureole along the Wiborg Batholith that Vormaa (1972) identified for the transfer of microcline into orthoclase in the Svecofennian crust. In the Lillträsket area, this thermal alteration is accompanied by wide-spread hydrothermal potassic alteration.

In order to refine Vormaa's contact aureole, further petrographic studies of the microcline-orthoclase relations are now undertaken, together with studies of the geochemistry and the Rb-Sr systematics in the Late Svecofennian granites, along a 16 km profile from the rapakivi contact towards the west.

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Cook, N.J., Sundblad, K., Valkama, M., Nygård, R., Ciobanu, C.L., Danyushevsky, L., 2011. Indium mineralization in A-type granites in southeastern Finland: insights into mineralogy and partitioning between coexisting minerals. *Chemical Geology* 284, 62-73.

Valkama, M., Sundblad, K., Nygård, R., Cook, N.J. Mineralogy and geochemistry of indium-bearing polymetallic veins in the Sarvlax-viken area, Lovisa, Finland. Submitted to *Ore Geology Reviews*.

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## S2.2 Fluid and melt processes in the Earth

ORAL

### Fluid migration and fluid-rock interaction during metamorphism

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A crucial aspect for the generation of ore deposits is an effective mass transfer through solid rocks in the deeper Earth. Element transport is most effective in a liquid phase along pathways that enable mass transfer through a solid material. Thus, quantification of fluid-mediated element transport requires knowledge about the formation of permeability, constraints on the amount of percolating fluids as well as on the extent of fluid-rock interaction. In this contribution we give an overview about the theoretical considerations of fluid migration in metamorphic rocks, show natural examples of permeability development during metamorphism and present an approach to quantify fluid-rock interaction utilising combined thermodynamic-geochemical models. Transient fluid pathways generated by metamorphic phase transitions can be used as conduits for fluid migration. On the other hand, creep mechanisms lead to plastic rock deformation, which in turn leads to compaction and closure of this transient permeability. We show natural examples of syn-metamorphic interconnected porosity associated with different types of mineral reactions that is preserved in metamorphic high pressure-low temperature rocks. Utilising focused ion beam techniques and transmission electron microscopy this porosity can be visualized and processes during fluid-rock interaction can thus be studied in situ down to sub-micron scale. A combination of thermodynamic and geochemical forward models are then used to quantify the effect of fluid-rock interaction and the amount of percolating fluids through the pore network.

ORAL

### Coupled reaction driven deformation, strain softening and CO<sub>2</sub> metasomatism in peridotites from the Rein fjord Ultramafic complex, northern Norway

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The Seiland Igneous Province (SIP) ultramafic rocks in the Rein fjord intrusion is cut locally by narrow (mm-cm) thick shearzones, containing extremely fine-grained material with a distinct shape-preferred orientation. Offset off dykes across numerous micro-faults are documented in field images in areas close to the major fault zone cutting through the area. Mineralogical changes occurs in relation to the shear zones, with increase opx and introduction of dolomite and decrease in olivine and clinopyroxene due to the reaction:

Olivine + Clinopyroxene + CO<sub>2</sub> = Dolomite + Orthopyroxene

As evidenced by coronas of orthopyroxene and dolomite between olivine and clinopyroxene in the shearzones. In addition large olivine grains proximal to the shearzones show a microstructure with subgrain walls decorated by rounded grains of dolomite and more irregular and elongated grains of orthopyroxene. Local variations in the opx/dolomite ratio suggest at least some material transport within the shearzone.

The shearzones thus gives a unique view into CO<sub>2</sub>-Metasomatism of the lower crust, but also perhaps could provide a proxy for the pressure during late stage solidification or post solidification of the magma-chamber of the SIP, something which is only available from pressure estimates of the surrounding metasediments obtained by geothermobarometry on mineral assemblages sensitive to resetting at such elevated temperatures. Moreover the shearzones provide a unique insight into the interplay between CO<sub>2</sub>-metasomatism and reaction accommodated strain softening. Experiments has shown how CO<sub>2</sub> can influence the flow laws of olivine by imposing a brittle and more localised type of deformation (Rowetta and Blasic, 1987). This is also confirmed by fractures extending into large olivine grains proximal to the shearzones.

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Rowettta and Blasic (1987): Microfracture and crack healing in experimentally deformed peridotite. *JGR*, VOL. 92, NO. B12, pages 12,902-12,910

ORAL

### Fluid inclusion LA-ICPMS analysis of ore fluids from the Pampalo orogenic gold deposit, Eastern Finland

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The late Archean Hattu schist belt, Eastern Finland, is composed of metamorphosed epiclastic and felsic volcanic rocks, intruded by tonalites and granodiorites. The schist belt hosts structurally controlled orogenic-type gold deposits, including the actively mined Pampalo deposit and many smaller prospects. The mineralization at Pampalo is characterized by gold disseminations in a felsic porphyry dike and intermediate pyroclastic rock as well as gold bearing quartz veins. Quartz occurs as euhedral crystals in boudin necks within the ore zone together with biotite, K-feldspar and calcite; as massive veins recording ductile deformation, and as tabular euhedral crystals in later vein sets related to brittle deformation. Based on structural and petrographic features, a clear time framework of different quartz veins and generations could be established. We have quantitatively determined the composition of fluid inclusions along this time sequence, combining microthermometry, quantitative Raman spectroscopy and LA-ICPMS analysis of individual fluid inclusions. This yielded the most complete multi-element dataset of fluid compositions from orogenic gold deposits worldwide.

Low salinity aqueous-carbonic fluids predominate in quartz associated with earlier boudin neck infills and veins recording ductile deformation, while the later tabular quartz crystals contain only aqueous fluids of similarly low salinities. The LA-ICPMS data reveal significant compositional differences between fluids hosted in the different quartz generations. Alkaline and alkaline earth metals as well as Sb show distinctly higher concentrations in the youngest fluids, whereas high S concentrations up to 3000 µg/g occur only in the oldest fluid types.

These also contain Au in the range of up to 0.5 µg/g, in line with recent considerations about reliable Au concentration levels in orogenic gold ore fluids (Pettko and Diamond, 2015), and well above Au concentrations in typical regional-metamorphic fluids. The early Au-bearing fluid therefore bears all the hallmarks of an ore forming fluid, while the later fluid types record the subsequent evolution of the Pampalo hydrothermal system. This provides a firm basis for reconstructing the P-T evolution and thermodynamically modelling the key factors that control formation of orogenic gold deposit.

## References:

Pettko, T. and Diamond, L.W., 2015. Fluid Inclusion Gold Concentrations: From Analysis to Implications for Hydrothermal Ore Formation. *ECROFI XXIII Extended Abstracts*, p. 29.

ORAL

### Au-rich fluid inclusions in gold-bearing quartz from the Kola superdeep borehole (SG-3)

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In the core of the Kola super-deep borehole (SG-3, 12262m depth) gold-enriched rocks of Archean age were located at depths between 9.5-11.0 km. These rocks were overprinted by Proterozoic regional epidote-amphibolite facies metamorphism at 500-650 °C and 3.5-6 kbar.

We have studied fluid inclusions (FI) in quartz from a vein, located at a depth of 9907.5m, within the gold enriched interval of the stratigraphy. The quartz contains 3 types of FIs: 1) gas inclusions of dense CO<sub>2</sub>, 2) vapour-liquid two-phase aqueous inclusions, and 3) three-phase inclusions with NaCl daughter crystals. CO<sub>2</sub> inclusions homogenized into the liquid phase at temperatures ranging from +21.2 to -6.1 °C with T<sub>m</sub>CO<sub>2</sub> from -57.1 to -58.9 °C and density of 0.76 to 0.96 g/cm<sup>3</sup>. The salinity of the water phase of vapour FI is 3.4-4.1 wt. %-eq. NaCl. Microthermometry showed that the two-phase inclusions are brines containing chlorides of Ca and Na with Te from -55 to -74 °C and

$T_{m,ice}$  from -33 to -63 °C, corresponding to salinities of 25.9 to 30.2 wt. % -eq.  $CaCl_2$ ,  $T_h$  was between 137-185 °C. Three-phase inclusions have  $T_{h,halite}$  between 231-123 °C and  $T_{h,vapour}$  107-185 °C. They also contain Na and Ca chlorides with  $T_c$  of c. -64 °C and salinities of 28.7-33.5 wt. % -eq. NaCl.

Individual FI compositions were analysed by LA-ICP MS. Elemental ratios of the 3-FI types are reasonably consistent and confirm the major cations are Na, K and Ca, with several 100's to a few thousand ppm of Fe, Cu, Zn, Pb in the higher salinity fluids. There are extremely high concentrations of Au in all FI types. In the high salinity FI's the average concentration is c. 300 ppm and as high as 1500 ppm. Thermodynamic simulations indicate such high Au concentrations correspond to a saturated solution of Au in the chloride complexes at temperatures above 500 °C. We suggest these fluids could be a precursor of "Orogenic gold fluids" which at these Au concentrations would reduce the requirements for large volumes of metamorphic fluids to form such ore deposits.

ORAL

### Using altered enclaves in the identification of seafloor replacement processes in VMS systems

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Progress in submarine hydrothermal system research has revealed that seafloor replacement in VMS systems is an important mechanism that contributes to the formation of large tonnage and/or high grade VMS deposits (Doyle and Allen 2003, Piercey, 2015).

Recognizing diagnostic features of replacement in highly deformed and metamorphosed VMS deposits can be challenging. Genetic interpretation of rock inclusion found in deformed massive ores could lead to an erroneous conclusion if their provenance is not assessed properly. Rock inclusions in massive ores can form from a variety of sources eg. tectonic enclaves, post/late VMS intrusions, exogenous detritus in clastic ores and relicts of unreplaced host rocks, with only the latter contributing critical evidence to probe a replacement origin for the ore.

This contribution presents detailed examples of using lithochemical mineralogical and mapping techniques, to infer the extent of seafloor replacement processes in the formation of the metamorphosed Pyhäsalmi and Storliden deposits which occur in the Proterozoic submarine arcs of Finland and Sweden.

The giant Pyhäsalmi deposit is inferred to have formed by combined processes that involve exhalation and replacement (Mäki et. al. 2015); whereas the small but high grade Zn-Cu Storliden deposit was originally thought to be a coarse grained hydrothermal replacement deposit based on its flat lying aspect and rock inclusions, but is now conceived as a seafloor exhalation with a minor volume of semi massive Cu ore replacing the feeder area.

### References:

Doyle, M.G. and Allen, R.L., 2003 Subsea-floor replacement in volcanic hosted massive sulphide deposits: *Ore Geology Reviews*, Vol. 23, pp. 183-222

Mäki, T., Imaña, M., Kousa, J. and Luukas, J. 2015. The Vihanti-Pyhäsalmi VMS belt in: *Mineral Deposits of Finland*, Ed. Maier, W., Lahtinen, R., and O'Brien H. pp. 507-530

Piercey, S.J., 2015 A semipermeable interface model for the genesis of seafloor replacement-type volcanogenic massive sulphide (VMS) deposits. *Economic Geology*, vol.110 pp.1655-1660

ORAL

### Age and Mo mineralisation in the Phnom Baseth granite, Cambodia

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Granitic magmatism in the Indochina Craton is largely related to tectonic activity during the Indosinian Orogen (Late Permian - Early Jurassic, ~260-190 Ma). While granitoids in the marginal areas of the craton are quite well-studied, less work has been done on granites in the interior. At Phnom Baseth, ~20km NW of Phnom Penh, Cambodia, is a small granite intrusion with 2-5 cm microcline-plagioclase-quartz phenocrysts set in a medium to fine grained (0.5-1 mm) groundmass of quartz, plagioclase, microcline, biotite and amphibole. The granite is cut by a network of 1-2 mm wide quartz veins, indicative of WNW-trending brittle fracture with a conjugate N-S fracture direction. A ~100 m



wide zone of intense hydrothermal alteration, also showing a WNW-trend, extends for at least 500 m along strike. 1-5 mm wide quartz-molybdenite-chalcopyrite-pyrite veins occur with a frequency of about one per metre within this alteration zone. Geochronological data from the granite intrusion (U-Pb zircon; Ar-Ar biotite) and the mineralisation (Re-Os molybdenite) are presented and discussed in a regional tectonic context.

SIMS U-Pb zircon analyses result in a crystallisation age of  $194.6 \pm 1.2$  Ma for the Phnom Baseth granite. Ar-Ar biotite analysis of two samples resulted in plateau ages of  $184.7 \pm 0.4$  Ma and  $188.3 \pm 0.4$  Ma. These slightly younger ages likely represent cooling of the pluton through  $\sim 300$ - $400^\circ\text{C}$ . Re-Os analysis of four molybdenite fractions resulted in an isochron age of  $95.1 \pm 3.2$  Ma. This indicates that the quartz veining and associated mineralisation is not co-magmatic.

The U-Pb crystallisation age correlates well with the latest, post-collisional stage of the Indosinian Orogen, during which the regional tectonic environment shifted from compressional to weakly extensional. Intrusion may have been controlled by strike-slip movement in the Tonle Sap region, likely reflecting an extension of the Mae Ping (Wang Chao) shear zone. Mineralising fluids infiltrated the Phnom Baseth granite during reactivation of this shear zone, caused by the collision of India with Asia during the Late Cretaceous.

#### POSTER

### Hydrothermal alteration and sources of fluids in the Juomasuo Au-Co deposit, Kuusamo Schist Belt, Finland

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The Juomasuo Au-Co deposit in the Paleoproterozoic Kuusamo Schist Belt is hosted by a volcano-sedimentary sequence, which was metamorphosed in upper greenschist-lower amphibolite facies during the Svecofennian orogeny. Our current petrographic and geochemical observations revealed that the sequence of protoliths consists of ultramafic, mafic, intermediate and felsic volcanic

rocks, as well as metasedimentary rocks and albitites. There is no strict lithological control on the mineralization. Hydrothermal alteration mineralogy was established on the basis of petrography and molar element ratios calculated from whole-rock geochemical data. Au and Co enrichments are mainly connected to sericitic (K-mica) alteration and subordinately to chlorite-biotite alteration. Local U, Mo and REE enrichments are confined to superimposing fractures. The pre-ore albitites host mineralization in their silicified parts only.

Fluid inclusion data indicate that high-salinity (>20 NaCl equiv. wt%) carbonic-aqueous fluids can be connected to early (prograde metamorphic) albitization. Low-salinity ( $\sim 5$  NaCl equiv. wt%) carbonic-aqueous fluids can be assigned to the later retrograde metamorphism. Late, low temperature aqueous fluids with salinities from 15-20 to 5 NaCl equiv. wt% also interacted with the rocks. Tourmaline (dravite) is an ubiquitous accessory mineral in albitite and is predominantly characterised by heavy B-isotope compositions (from +6 to +16 ‰  $\delta^{11}\text{B}$ ). This finding, together with the fluid inclusion salinities, supports the earlier hypothesis (Vanhanen, 2001), that parent fluids of albitization and some stages of mineralization at Juomasuo contained evaporite-related components.

This work was supported by the Academy of Finland project No. 281670 to F. Molnár.

#### References:

Vanhanen, E., 2001. Geology, mineralogy and geochemistry of the Fe-Co-Au-(U) deposits in the Paleoproterozoic Kuusamo Schist Belt, Northeastern Finland. *Geol Surv Finland Bull* 399, 230p.

## S2.3 Geochemical and geophysical exploration methods

ORAL

### The Geochemical Atlas of Sweden — element background concentrations in till

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Till reflects the underlying bedrock with its billion years old geological history and records soil-formation processes such as weathering style during variable climate conditions. The Geochemical Atlas of Sweden provides a harmonized countrywide database with modern baseline geochemical data on till from the C horizon. The work was carried out between 2011 and 2014 and has been based on till samples from the SGU archive as well as on new sampling of till conducted mainly in the mountainous areas of western Sweden.

Chemical analyses (aqua regia digestion by ICP MS) were carried out at the ALS laboratory in Luleå and at the SGU laboratory in Uppsala with strict quality control routines. As a result, 67 (element and pH) map in till were produced. 53 element maps of grazing land soil chemistry (from the GEMAS project), and 14 biogeochemical maps (based on geochemistry of aquatic plants from earlier SGU campaigns) have also been included in this project.

The interpretation of the elemental maps and associated statistics has revealed several groups of factors influencing the observed spatial trends in the geochemical patterns. The most important being bedrock geology, the presence of ore deposits, the soil type and its properties, and climate zone controlled by the latitude and altitude.

The results of this survey are available free to the public and can be used for university education, mineral exploration, environmental monitoring, in forensic studies and epidemiology as well as for policy making and spatial planning by local authorities. The geochemistry of till in northern European countries is an excellent proxy for groundwater quality assessments and risk evaluations. To allow broad use of the Atlas both on the national and international level, Swedish and English languages have been used simultaneously throughout the book.

### References:

Andersson, M., Carlsson, M., Ladenberger, A., Morris, G., Sadeghi, M., Uhlbäck, J., 2014: *Geochemical Atlas of Sweden (Geokemisk atlas över Sverige)* Sveriges Geologiska Undersökning, 210 pp.

ORAL

### Ultra low-impact geochemical method for greenfield exploration using snow

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New sample materials and geochemical analysis methods have been studied recently for mineral exploration in northern, vulnerable areas. One of the materials has been snow which covers the landscape several months each year, for example in southern parts of Finland from two to three months up to seven months in northern parts. The same situation is actual in large areas in the Northern Hemisphere, which increase the interest to use snow as a sampling media for mineral exploration.

The thickness of snow cover varies from some tens of centimeters up to one meter. Snowing periods and the snow properties are constant in a regional scale, which gives a good foundation for large and comparable geochemical exploration. Snow sampling is easy and quick, and it does not cause any environmental impacts.

Snow is composed of water coming from atmosphere. It also includes both local and long-distance components like dust, metal ions, hydrocarbons and even mineral particles. The lowest part of snow cover gives the most stable sampling media because of the longest deposition history and the coverage of the upper snow layers. In addition, the lowest layer is in contact with the ground and is influenced by the gases and heat coming from the underlying soil and bedrock.

Soil gasses, originating in the bedrock and travelling through the top soil horizons, accumulate into the bottom layer of snow. There are two ways to study geochemical signal of snow: hydrocarbons and metal-ions. The first ones can be determined using the Soil Gas Hydrogen (SGH) method, which is based on classification of large number of hydrocarbons into indicative groups for certain mineralization types. The second way is directly to measure the element concentrations in snow. Certain gasses transport elements with them and these elements give a signature of the underlying buried mineralizations. There are indications that some of

these elements accumulate in the bottom layer of the snow pack which has been under the influence of the gas transport for the longest time. The amounts of the ions can be detected with the increased detection limits of the modern assay methods to the ppt levels of concentration.

These and other low-impact geochemical exploration methods are studied in the project 'Ultra low-impact exploration methods in the subarctic' funded by the Tekes.

ORAL

### Current trends in geophysical exploration for minerals

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Exploration for minerals is in general based on utilization of data and information from a broad range of geoscientific methods and techniques. Furthermore, exploration often builds on input and contributions from several stakeholders such as geological surveys, exploration companies, companies specialised in data acquisition and instrument development, consulting companies, universities etc. This presentation focuses on current trends in utilization of geophysical methods in mineral exploration.

In addition to providing an overview of new developments and emerging techniques, the presentation will include comments and views on how to improve efficiency in utilization and integration of various geophysical data sets. Efficiency in utilization of geophysical methods is to a large extent linked to the methodologies used for combining geophysical data with other observations such as geochemical, lithological and structural data and with auxiliary techniques such as data and model visualization systems. An important but very difficult task in exploration is the ability to provide a proper analysis of model uncertainties and prediction capabilities. Although theoretical foundations are available for the analyses, this task is often severely limited due to sparse data and insufficient information content of the data. Views on how to improve exploration efficiency are provided in the presentation.

ORAL

### The origin of internal reflectivity within the Kevitsa intrusion

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The Kevitsa mafic-ultramafic intrusion hosts large Ni-Cu-PGE disseminated sulfide deposit and is located within the Central Lapland Greenstone Belt in northern Finland. A vast number of geophysical and geological datasets, in particular extensive borehole data and 3D reflection seismic data used in this study, is available from Kevitsa.

Data mining approaches, such as Self-Organizing Map (SOM; Kohonen 2001) analysis, can be used for joint interpretation and objective analysis of the complex geophysical and geological datasets typical for mining camps. In this work, we are presenting initial results from SOM analysis of Kevitsa borehole data with the aim of understanding the origin of spatially constrained internal reflectivity within the Kevitsa intrusion, and its relationship to the Kevitsa Ni-Cu-PGE deposit. Earlier (e.g. Koivisto et al. 2015) it has been suggested that the internal reflectivity originates from contacts between the tops and bottoms of smaller-scale, laterally discontinuous and internally differentiated olivine pyroxenite pulses within the intrusion, which have also been suggested to control the extent of the economic mineralization accumulated towards the bases of the pulses (Gregory et al. 2011). However, our initial results show that the origin of the internal reflectivity is more complicated. While the smaller-scale magmatic layers could potentially explain some of it, more detailed analyses are required to fully understand the origin of the reflectivity and its relationship to the Kevitsa Ni-Cu-PGE deposit.

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Koivisto, E., Malehmir, A., Hellqvist, N., Voipio, T. and Wijnns, C., 2015. Building a 3D model of lithological contacts and near-mine structures in the Kevitsa mining and exploration site, northern Finland. *Geophysical Prospecting* 63, 754–773.

## ORAL

### Time-lapse seismic tomography using the data of microseismic monitoring network in Pyhäsalmi mine (Finland)

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We present results of a seismic travel-time tomography applied to microseismic data from the Pyhäsalmi mine, Finland. The data about microseismic events in the mine is recorded since 2002 when the passive microseismic monitoring network was installed in the mine. Since that over 100000 microseismic events have been observed. One of the purposes of our study was to test how the travel-time tomography works with the passive microseismic monitoring data where the source-receiver geometry is based on non-even distribution of natural events in the mine and hence, is a non-ideal one for the travel-time tomography. The tomographic inversion procedure was tested with the synthetic data and real source-receiver geometry and with the real travel-time data of the first arrivals of P-waves from the microseismic events. The results showed that seismic tomography is capable to reveal differences in seismic velocities in the mine area corresponding to different rock types, for example, the velocity contrast between the ore body and surrounding rock. The velocity model recovered corresponds well to the known geological structures in the mine area. The second target was to apply the travel-time tomography to microseismic monitoring data recorded during different time periods in order to track temporal changes in seismic velocities within the mining area as the excavation proceeds. The result shows that such a time-lapse travel-time tomography can recover such changes. In order to obtain good ray coverage and good resolution, the time interval for a single tomography round need to be selected taking into account the number of events and their spatial distribution.

Acknowledgements: This study has been supported by ERDF SEISLAB project and Pyhäsalmi Mine Oy.

## POSTER

### The use of geophysical methods in assessment of natural stone prospects

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The scope of the study was to test ground geophysical exploration methods in the assessment of the natural stone prospects in the rapakivi granite area in southeastern Finland (Härmä et al. 2015). The measurements in the field included ground penetrating radar (GPR), electrical resistivity tomography (ERT) and induced polarization (IP) as well as ground magnetic intensity measurements (Luodes et al. 2014). Further, geophysical in situ measurements were done in ten drill holes in the target area. Also, petrophysical measurements were carried out for the drill core samples and mini drill samples at GTK's petrophysical laboratory.

The ERT method with IP revealed valuable data and information about inside the solid rock. The drill hole measurements were also good adds for the studies of natural stone quality. The petrophysical data of the drill core samples showed up a good estimate for the quality of the rock as well as reference data for the drill hole measurements. The samples taken from the surface of outcrops were not only enough for the petrophysical studies due to weathered rock on the surfaces. However, it is also important to know the thickness of the weathered zone and it can be estimated with petrophysical samples taken by mini drill. The ERT and IP measurement should be measured before the moss is taken away from the bedrock surfaces. By that way, all of the ground geophysical profiles can be executed in the same location.

Ground geophysical magnetic measurement gave valuable data from the bedrock in the study area. With high resolution ground magnetic intensity data it is possible to get hints from smaller structures or features in the bedrock.

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Härmä, P., Selonen, O. & Luodes, H. 2015. The Wiborg granite batholith - the main production area for granite in Finland. In: G. Lollino et al. (eds.), *Engineering Geology for Society and Territory* – Volume 5, 259-262.

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## POSTER

**Delineating structures hosting REE-bearing apatite iron oxide (Sweden) and apatite-rich carbonatite-alkaline deposits (Finland) through systematic geophysical and geological investigations**

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The StartGeoDelineation project, initiated in 2015, aims at studying two mining sites in Sweden and Finland. In Blötberget-Sweden our goals are to delineate and better understand structures hosting iron-apatite deposits and provide information about their depth extent that are known down to 800 m depth. Downhole geophysical logging in six deep boreholes (> 450 m and intersecting the mineralization) and laboratory measurements have been conducted. These data provide constraints and valuable information for the interpretation of surface geophysical data that were recently acquired, including an approximately 3.5 km long seismic profile complemented by high-resolution magnetic and gravity surveys. The downhole logging data suggest potential relationships between occurrences of pegmatite and hematite (low-susceptibility) found under a distinct magnetite-rich zone (high-susceptibility); they also show major weak zones in the hanging-wall in the full-waveform sonic data.

In Siilinjärvi-Finland, one of our goals is to understand the relationships between the carbonatite-apatite mineralization and shear zones as well as different generations of basic dykes. This will benefit the mine planning and reduce the risk of unexpected failure in the open pit. Defining the contact between the alkaline intrusion and country rocks is another goal of the study. Three boreholes have been logged and four short seismic profiles (2 km in total) acquired to constrain the geophysical interpretations. Preliminary results are encouraging

and illustrate the significance of a systematic approach combining physical properties, field geological mapping and surface geophysical surveys for deep exploration and multi-target tasks (e.g., exploration and mine planning).

*Acknowledgments:* Vinnova, SGU, Tekes, NIO and Yara.

## POSTER

**Geochemistry of the hydrothermally altered rocks in Orijärvi, SW Finland**

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The Orijärvi area in SW Finland is known for its unusual mineral assemblages such as the cordierite-anthophyllite rocks associated with the Cu-Zn-Pb deposits (Eskola 1914). These are now regarded as metamorphic equivalents of volcanic rocks altered prior regional metamorphism. The hydrothermal processes have almost completely destroyed the primary structures, textures and minerals, which makes the identification of primary volcanic rock types difficult.

In this study we use chemical compositions in order to interpret the alteration processes and to identify the alteration protoliths. Immobile element concentrations and ratios of the altered rocks are compared to those in the unaltered rocks outside the alteration domain (Väisänen & Mänttari 2002).

Preliminary results of our work show that the altered rocks mainly are calc-alkaline volcanic rocks in a volcanic arc setting. The cordierite-anthophyllite rocks plot in the basalt field in the Co-Th diagram and in the andesites/basaltic andesites fields in the Nb/Y-Zr/TiO<sub>2</sub> diagram. These suggest that the cordierite-anthophyllite rocks were originally mafic and intermediate volcanic rocks. Fluorine turned out to be a very mobile element during alteration and occasionally shows anomalously high concentrations in the altered rocks.

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Väisänen, M., Mänttari, I. 2002. Bulletin of the Geological Society of Finland 74, 185-214.

## S2.4 Precambrian metallogeny

### KEYNOTE

### Precambrian orogens and their hypozonal orogenic gold ores

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High-temperature (hypozonal) orogenic gold deposits formed at conditions of 500 – 700°C and 2-7 kbar in syn- to post-peak metamorphic shear zones, and appear to be restricted to the Precambrian. Their formation occurred between ca. 3030 Ma (New Consort, South Africa) and ca. 550 Ma (Navachab, Namibia), at an apparent geothermal gradient of 40–80°C/km, which is similar to mesozonal orogenic gold deposits. The PT conditions of orogenic gold formation define a linear trend resembling terrane exhumation, largely below the granite wet solidus and in the 1-phase stability field for aqueous-carbonic ore fluid compositions (Kolb et al., 2015).

Phanerozoic mesozonal orogenic gold deposits formed predominantly in external accretionary orogens with only a few and smaller examples in collisional orogens. The gold deposits in external orogens are hosted by shear zone-controlled veins in accreted oceanic and island arc terranes.

In spite other models for hotter Precambrian orogens exist, hypozonal deposits are hosted by shear zones separating greenstone belts from granite-gneiss terranes and are locally around metamorphic core complexes (in a setting similar to Phanerozoic examples in accretionary orogens). Some Archaean and most Proterozoic hypozonal deposits are hosted in collisional orogens. A possible explanation for the lack of Phanerozoic hypozonal orogenic gold deposits is a different thermal regime of the Precambrian crust, where higher metamorphic grades are reached at higher crustal levels, which however did not result in fundamentally different orogenic processes. Hypozonal orogenic gold deposits formed in the centre or foreland

of Precambrian orogens during the collision stage, when the terranes are uplifted.

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### ORAL

### Palokas Prospect: An Exciting new Gold Discovery in the Peräpohja Schist Belt, Finland

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The Palokas Prospect is an exciting new gold discovery hosted within the Peräpohja Schist Belt, approximately 35 kilometres west of Rovaniemi in southern Lapland. Recent published drilling results available on the Mawson Resources website include 19.6 metres at 7.5 g/t gold from 18.1 metres in drill hole PRAJ0107.

The gold mineralisation is hosted by a tabular package of massive to foliated pyrrhotite-bearing highly magnesian green chlorite-amphibole-tourmaline rocks cut by quartz veins, enclosed within magnesian grey pyrrhotite-bearing schistose amphibole-rich calcsilicate rocks. Extending vertically below and laterally away from the gold mineralised rocks, pyrite becomes the dominant sulphide, and the overall oxidation state of the rocks increases until pinkish albitic calcsilicate rocks predominate. The hangingwall sequence contains more reduced metasediments comprising biotite-bearing calcschists, grey calcsilicate rocks, and biotite-muscovite schists. Where the hydrothermal effects of the gold mineralisation are absent, metamorphic grade is amphibolite facies.

The gold is typically fine grained (less than 20 microns) and held at silicate-sulphide grain boundaries, but where grade increases, the grain size also increases with up to 30 % falling between 200 and 500 microns. In stark contrast to the Rompas Prospect some 10 km to the west, only two grains of visible gold have been observed in drill core. Uranium values are also low, generally less than 30 ppm. Sulphide appears to contain very little, if no gold. Accompanying the gold-pyrrhotite zone is ilmenite and scheelite.

Apparently undeformed quartz veins appear to control the chlorite distribution and are spatially related to elevated gold grades. A magnesian gold skarn is proposed as the most likely “genetic model” for this system.

At the time of writing, drilling has been restricted to a small 100 metre by 80 metre area with 25 mm diamond drill core. In winter 2015–2016 over 4000 metres of larger diameter drilling is planned to test the vertical and lateral extents of the Palokas system.

ORAL

### Tourmaline geochemistry and B-isotopes from the Palokas Au-mineralization, Peräpohja Belt, Northern Finland

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In 2012, disseminated gold mineralization was discovered in the Rajapalot area, located in the northern part of the Paleoproterozoic Peräpohja Belt. This study presents microprobe and B isotope data from tourmaline collected from three different localities: the Rajapalot gold mineralization, ca. 1.78 Ga tourmaline granite and Petäjäsoski Formation with an inferred evaporitic origin. Based on textural evidence, tourmaline in the gold mineralization is divided into two different types. Type 1 is located within the host rock and is cut by rock-forming anthophyllite crystals. Type 2 is occurs in late veins/breccia zones with the mineralogy consisting of ca. 80% of tourmaline and 20% of sulphides.

All the studied tourmalines belong to the alkali group tourmalines and can be classified as dravites and schorls.  $\delta^{11}\text{B}$  values between the three localities are identical, ranging from +1 to -4‰. Tourmalines from the Au mineralization and from the Petäjäsoski Formation show similar compositional trends and dominant substitutions. No indications of substitution of Al by Fe<sup>3+</sup> were observed, hence implying low Fe<sup>3+</sup>/Fe<sup>2+</sup> values. Compositional data indicate that the tourmaline grains in the Rajapalot Au mineralization were precipitated from reducing low-salinity fluids. Similar chemical compositions

and  $\delta^{11}\text{B}$  values imply a common boron source for all the analyzed tourmalines. The late appearance of the tourmalines and preliminary Re-Os dating of molybdenite (Vanhanen et al., 2015) indicate at least the temporal association of tourmaline in the Rajapalot Au mineralization and ca. 1.78 Ga granites.

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ORAL

### Re-Os and U-Pb geochronology of the Au-U mineralization at Rompas, Peräpohja Schist Belt, northern Finland

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The sedimentary and volcanic rocks in the Peräpohja Schist Belt were deposited from 2.44 Ga to 1.92 Ga during the protracted rifting of the Archaean basement. Greenschist to amphibolite facies metamorphism and multiple folding took place during the Svecofennian orogeny (1.9–1.8 Ga), with local intrusions of post-orogenic granitoids (1.81–1.76 Ga; Ranta et al., 2014).

The Rompas Au-U mineralisation is hosted by folded dolomite-quartz veins in mafic metavolcanic rocks, and contains uranium-bearing zones without gold and pockets of high grade gold with uraninite. Deposition and metamorphic re-crystallization of uraninite was followed by formation of pyrobitumen crusts around uraninite in some zones. Precipitation of native gold together with some telluride, arsenide and sulphide minerals was confined to fractures in uraninite and to cracks and surfaces of pyrobitumen, suggesting that gold enrichment occurred during a late hydrothermal event. Molybdenite is associated with uraninite and pyrobitumen and it is also present in quartz veins of skarn rocks around granitoid intrusions next to Rompas. Re-Os dating of molybdenite suggest 2128–2168 Ma for the primary uraninite mineralization. The 1780 Ma age obtained

from molybdenite of quartz veins in skarn confirms the role of post-orogenic granite intrusions in the late hydrothermal processes of the area. Results of the *in situ* LA-ICPMS U-Pb dating of uraninite grains indicate that some small domains in uraninite preserve the original pre-metamorphic crystallisation age, whereas other grains were formed during the Svecofennian orogeny (~1.8-1.9 Ga). Results of the chemical age dating and variation in composition of uraninite are also in agreement with these observations.

This work was supported by the Academy of Finland project No. 281670 to F. Molnár.

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ORAL

### U–Pb of hydrothermal phosphates by LA–ICP–MS: Dating episodic mineralisation along the Kiistala Shear Zone, Central Lapland Greenstone Belt

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The Central Lapland Greenstone Belt (CLGB) hosts orogenic gold deposits along the Sirkka and Kiistala Shear Zones, including the world class Suurikuusikko deposit dated at ~1.91 Ga (Re-Os isochron; Wyche et al., 2015). The timing of Svecofennian orogenic deformation events (1.92–1.77 Ga; Korja et al., 2006) and associated mineralisation remains enigmatic as evidence rests on limited hydrothermal age data. Monazite and xenotime are ideal candidates for U–Pb dating due to high U and Th as well as minimal common Pb content. By undertaking *in-situ* U–Pb of hydrothermal phosphates, with strict control on textural setting, this study provides better temporal constraints on mineralisation of orogenic gold in the CLGB.

The Iso-Kuotko deposit is located on a bifurcating fault intersection along the Kiistala Shear Zone (KSZ), 14 km north of the Suurikuusikko deposit. It has three consecutive mineralisation stages dominated by arsenopyrite, pyrite and pyrrhotite + native Bi with quartz–ankerite veinlets/breccias. Gold is refractory in arsenopyrite and pyrite but occurs

as free grains with pyrrhotite mineralisation. Vein-hosted monazite, co-genetic with pyrite, gives a U–Pb concordia age of  $1862 \pm 14$  Ma ( $2\sigma$ ;  $n = 6$ ). Pyrrhotite breccia-hosted xenotime forms two populations with upper intercept ages of  $1853 \pm 12$  Ma ( $n = 14$ ) and  $1763 \pm 7$  Ma ( $n = 45$ ).

*In-situ* U–Pb dating of hydrothermal monazite and xenotime provides evidence for two distinct mineralising events. In tandem with previous data, this study highlights episodic orogenic gold mineralisation along the KSZ over 150 Ma. This work was supported by the Academy of Finland, project No. 281670 to F. Molnár.

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ORAL

### Poly-phase structural controls on ore deposits in northern Sweden

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The Norrbotten region in northern Sweden is one of the most active mining areas in Europe and hosts several of Europe's most important ore deposits. Important examples include the Aitik Cu-Au-Ag-(Mo) deposit and the Kiruna and Malmberget Fe deposits.

Recent studies currently reconstruct the origin and evolution of ore-bearing structures in northern Sweden with special focus on the Gällivare area. It is tentatively suggested that the majority of structures in the region originated as syn-extensional structures ( $D_1$ ) forming synchronously with the deposition of ca. 1.9 – 1.89 Ga volcanic and volcano-sedimentary, the emplacement of related intrusive rocks and the formation of apatite iron ore deposits. This extensional phase is comparable to the  $D_1$ -extensional phase as reported for the Skellefte District further south (Skyttä et al. 2012). Subsequently the area was overprinted by at least to separate compressional deformation events. The first



compressional deformation event (D<sub>2</sub>) resulted in the formation of a strong and penetrative cleavage (S<sub>2</sub>) and related isoclinal folding under amphibolite facies metamorphic conditions. Likely, the porphyry copper style mineralizations (e.g. early phase in Aitik in Wanhainen et al. 2012) formed during this stage. Furthermore, distinct biotite-rich D<sub>2</sub> shear zones are spatially related to the majority of the apatite iron ores in the region. A second compressional event (D<sub>3</sub>) resulted in a strong strain partitioning. Within low strain blocks the S<sub>2</sub> fabric, the D<sub>2</sub> biotite zones and the related ore bodies are folded openly to closely. Most of the D<sub>3</sub>-strain was localized in dominantly NNE-SSW-trending, likely reactivated high strain zones that control the location of potassic-epidote-garnet alteration and relating sulfide mineralizations (e.g. second stage in Aitik in Wanhainen et al. 2012).

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ORAL

### Base Metal Zoning in the Pyhäsalmi Volcanogenic Massive Sulfide Deposit

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VMS deposits commonly show internal metal zonation where Cu is usually most abundant in the stringer zone and in the base of the deposit, while Zn and Pb are most common at the margins of the deposits (Large 1977). This Cu-Zn zoning is so common that it has been used as an indicator of stratigraphic facing direction (Sangster 1972).

Cu-Zn zonation is also present in the Pyhäsalmi deposit, being very clear in the deep parts of the ore body. There massive pyritic core is surrounded by the pyrite-chalcopyrite-calcite ore which in turn is capped by the sphalerite-pyrite-barite-calcite ore (Imaña 2003).

At the ongoing study the spatial distribution and relationships between Cu and Zn concentrations are studied by using all available assay data from the whole ore body. Leapfrog Geo 3D modelling software is used to model zones with distinct Cu/(Cu+Zn)\*100 ratios. Also the 3D model of the Pyhäsalmi ore body is being refined by using historical and modern data sets.

This study hopefully gives better insight from the Cu-Zn zoning, internal structure and structural evolution of the whole Pyhäsalmi deposit. Majority of the observed Cu-Zn zonation is probably primary in origin. However, 1.93-1.90 Ga old Pyhäsalmi deposit has experienced amphibolite facies metamorphism and multiple stages deformation. As a result, sulphide remobilization has occurred and to some extent that can obscure the primary Cu-Zn zoning.

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ORAL

### Regional scale prospectivity analysis of Outokumpu mineral district

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Prospectivity of the well-known Outokumpu mineral district endowing several Early Proterozoic massive to semimassive Cu-Co-Zn-Ni-Ag±Au sulphide deposits is being analyzed spatially as part of developing Deep Exploration (DEX) methods and Common Earth Modeling (CEM) concept for Outokumpu type ore deposits.

The study is being carried out in 2013-2016 as a sub-task of the project Developing Mine Camp Exploration Concepts and Technologies (Brownfield exploration) funded by Tekes, GTK and companies operating in the Northern Karelia Region. The project is carried out by GTK and the Institute of Seismology, University of Helsinki. International collaboration is taking place with similar research projects in Canada, Sweden, and Greece.

ORAL

### Can polymetallic mineralizations in Hiekkapohja, Central Finland be part of a one porphyritic system?

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We have re-evaluated ore showings in the SE-part of the Paleoproterozoic Central Finland granitoid complex. Several small high grade mineralizations and glacially transported boulders are known from Hiekkapohja, in the vicinity of Jyväskylä city, concentrating on an aeromagnetic low (8 \* 4 km). The mineralized samples, variably enriched in Pb, Cu, Zn, Mo, Ag and Au, display a zoned pattern. Samples richest in Au are on the outer edge of the aeromagnetic low of the negative anomaly and Cu-Mo-rich samples in the centre.

Most of the mineralized samples are variably tectonized and show variable signs of sericitization and saussuritization. Typical sulphur minerals in the area are arsenopyrite, chalcopyrite, sphalerite, pyrrhotite, galena and pyrite. Accessory phases include eg. acanthite, other Ag-sulphides and native Bi.

Most of the mineralizations could be connected to fluid activity during tectonic activity, but as they are concentrated in the area of the aeromagnetic low, they are likely generated by a spatially more restricted reason, for example a late magmatic fluid phase. This pulse would also be responsible for reducing the areal susceptibility by altering the magnetite. At the moment the best candidate for the fluid source are the small intrusions and dykes of a youngest even-grained granite phase, which could be significantly larger in depth. We interpret preliminary that: the mineralizations are co-genetic and associated to late magmatic hydrothermal activity and that the large scale zoning can be proposed as roughly similar to typical porphyritic mineralizations.

ORAL

### The Circum-Arctic Mineral Resource Project

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This presentation is based on results from a co-operative project in which the partners are:

- The geological surveys of Canada, Denmark and Greenland, Finland, Norway, Sweden and the USA.
- The A.P. Karpinsky Russian Geological Research Institute (VSEGEI)
- The National Energy Authority of Iceland, Iceland GeoSurvey

These organisations have earlier cooperated on compilation of the bedrock geology, tectonics and aeromagnetic and gravimetric fields in the Arctic. The existing Fennoscandian Ore Deposit Database is of vital importance as a template for the project database.

Products from the project will include a database of major metal and diamond deposits N of 60°N, a printed map (1: 5,000,000) showing their distribution and two publications, one for the geoscientific public and a multilingual description for other interested groups. Information from the project will be provided on a dedicated web site to be hosted at NGU. The project will be completed in July 2016.

Major ore deposits of many kinds are found in the Arctic and production of certain commodities from the operating mines is of critical importance to global needs. The Fennoscandian region has particular importance as a dominant supplier of metals to the European Market. New deposits, some of "world class" are still being discovered in the Arctic region, even in areas which have been investigated for many decades: further potential is being recognized in new areas. This presentation will provide an overview of the most important metal mining operations in the Arctic with additional focus on projects in development and on new discoveries.

The support of the Ministry of Foreign Affairs of Norway for coordination of the project and the positive approach of all the partners are gratefully acknowledged.

## ORAL

**The Barents project**I. ANTAL LUNDIN<sup>1</sup><sup>1</sup>*Geological Survey of Sweden; Ildiko.antal@sgu.se*

The Geological Survey of Sweden (SGU) was granted extra funds from the Ministry of Enterprise and Innovation to gather new geological, geophysical and till geochemical data and enhance the geological knowledge in Norrbotten County. The county located in northern Sweden is among the most economically important metallogenic regions in Europe. The area has a high potential for new Cu, Fe, Au, Ni and PGE deposits. The Barents project started 2012 and is still ongoing.

The main goals of the project have been:

- Gaining a better understanding about the regional geological framework and development, hydrothermal alterations, mineralizations, structures and stratigraphy
- Mapping the physical properties of the bedrocks using different geophysical methods
- Mapping of till geochemistry including major, and trace elements analyses

New data acquisition such as litho-geochemical and petrophysical sampling, geological observations on outcrops including structural measurements and age determinations were conducted in Norrbotten. Airborne gravity gradient (AGG) and airborne transient electromagnetic (VTEM), reflection seismic and magnetotelluric (MT) profiles were collected within the frame of the project as well as till geochemistry sampling.

In this presentation some of the new findings from integrated multidisciplinary studies carried out in the Barents projects are summarized. There are 33 reports published and can be publicly accessed and downloaded at <http://www.sgu.se/en/mineral-resources/barents-project/>.

## POSTER

**Magnetic properties for characterization and quantification of magnetite and hematite in apatite iron-oxide deposits at Blötberget, central Sweden**

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Laboratory magnetic measurements can complement ore geological and exploration geophysical studies. Analysis of statistical relationships between magnetic properties and thin section analysis can prove useful for this purpose. A methodology is developed in the current study, with the aim to characterize the Kiruna-type REE-bearing apatite iron-oxide deposits at Blötberget in central Sweden. Twenty drill core samples, received from Nordic Iron Ore, were used for this study containing up to 81 weight percent (wt%) magnetite and up to 83 wt% hematite. Magnetic susceptibility measurements were carried out as a function of temperature, using an MFK1-FA susceptibility bridge. The measurements show that magnetite with strong susceptibility contribution overshadows the hematite contribution in the samples. Susceptibility drops are noticeable when crossing the Curie temperatures; 580°C and 680°C for magnetite and hematite, respectively. Although the bulk susceptibility of magnetite is several orders of magnitudes larger than that of hematite, the signals from the two phases are readily distinguishable from the drop in susceptibility across their respective Curie temperatures. The wt% magnetite, identified in thin sections, was compared with drop in susceptibility across the 580°C. A linear relationship is identified between the magnitude drop in susceptibility and magnetite content with  $R^2 = 0.73$ . The same procedure was performed for hematite in 6, out of the 20, measurements. Thus another linear relationship with  $R^2 = 0.81$  for hematite. A lower detection limit of 17 wt% hematite was identified when characterizing susceptibilities associated with hematite using this method, and the chosen sample size. This investigation illustrates that magnetic laboratory methods are

useful to accurately quantify and characterize magnetite and hematite proportions in high grade iron mineralized bodies.

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**POSTER**
**Assessment of orogenic gold resources in Finland**

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The potential metal resources in undiscovered orogenic gold deposits in the Finnish bedrock were estimated down to 1 km depth using the USGS 3-part quantitative assessment method. A grade-tonnage model was constructed based on data from known Fennoscandian and North Australian orogenic gold deposits.

Eight permissive tracts were delineated for Archaean orogenic gold deposits, 13 for Palaeoproterozoic Karelian deposits, and 11 for Palaeoproterozoic Svecofennian deposits in Finland. The mean estimate of the number of undiscovered orogenic gold deposits is 18 for the Archaean, 45 for the Karelian, and 27 for the Svecofennian tracts.

The undiscovered resources estimated at 50 % probability in Archaean, Karelian and Svecofennian orogenic gold deposits in Finland are 140 t, 400 t and 210 t of gold, respectively. This is 55 % of the undiscovered gold resources in Finland. Based on comparison between the Finnish bedrock and areas with a longer exploration history for gold (e.g., parts of Australia and Canada), we consider these tonnages as conservative estimates for the metal content in undiscovered orogenic gold deposits in Finland.

The assessment work supports the findings of earlier and other current work, which suggest that all orogenic gold mineralisation in Finland is related to the Neoarchaean (2.7–2.6 Ga) and Svecofennian (1.9–1.77 Ga) accretional and collisional orogenic events.

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**POSTER**
**Towards a structural framework for apatite-iron oxide deposits in the Grängesberg-Blötberget area, Bergslagen, Sweden**

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The REE-bearing Kiruna-type apatite-iron oxide (AIO) deposits at Grängesberg and Blötberget represent the largest iron ore concentration in southern and central Sweden. Both regarding immediate host rocks and actual mineralisation type, this group of deposits stand out as a marked anomaly in the Bergslagen ore province. The AIO deposits are situated in the western part of this intensely mineralised Palaeo-proterozoic province along a 40 km long NNE trending winding line. This stretches from Grängesberg in the south, via Blötberget to Idkerberget in the north and further east to the small Kopslahyttan deposits. The Grängesberg deposit consists of moderately to steeply dipping magnetite-dominated lenses, which coincide with an inferred F<sub>1</sub> fold limb, suggesting a synmetamorphic structural control on the ore. Around the lenses, prolate strain is focused at the lens crests and oblate strain at the tapering edges, as a result of competence contrast between competent bodies, including the ore, and the phyllosilicate altered host-rocks during D<sub>2</sub> shortening (Persson Nilsson et al. 2013). Preliminary results from the Blötberget area suggest a similar location of prolate and oblate strain around competent lenses. Two ductile planar fabrics have been observed both in the host-rock and in the ore. Platy hematite ore is in places crenulated, with a small angle to S<sub>2</sub>, implying that this hematite type was formed prior to D<sub>1</sub>. A similar fabric has

been encountered in the phyllosilicate altered rocks in Grängesberg. To better understand the structures hosting the Bergslagen AIO deposits, provide information about their extent at depth, and their evolution and relations to other iron oxide mineralisation types, a detailed structural study is currently being carried out within the framework of the 'Start-GeoDelineation' project (ERA-MIN) supported by Vinnova, SGU, NIO, Tekes and Yara.

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#### POSTER

### Mineral chemistry, spectroscopy and parageneses of oxyborates in metamorphosed Fe-Mn oxide deposits, Bergslagen, Sweden

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Oxyborate minerals represent an important sink for boron in some mineralised systems with low silica-activity; hence their occurrence, paragenesis and character may yield insights into the hydrothermal processes transporting and distributing boron, as well as later metamorphic overprinting of such deposits.

In this study we have sampled a representative suite of Mg-(Fe-Mn) oxyborate assemblages from the western part of the Bergslagen ore province in south central Sweden, to characterise them utilising optical microscopy, field emission electron probe microanalysis (FE-EPMA) with wavelength dispersive spectroscopy (WDS), and Raman spectroscopy.

Minerals studied comprise blatterite [(Mn<sup>2+</sup>,Mg)<sub>35</sub>(Mn<sup>3+</sup>, Fe<sup>3+</sup>)<sub>9</sub>Sb<sub>3</sub><sup>5+</sup>(BO<sub>3</sub>)<sub>16</sub>O<sub>32</sub>], fredrikssonite [Mg<sub>2</sub>(Mn<sup>3+</sup>,Fe<sup>3+</sup>)BO<sub>5</sub>], orthopinakiolite [(Mg,Mn<sup>2+</sup>)<sub>2</sub>Mn<sup>3+</sup>BO<sub>5</sub>], as well as pinakiolite [(Mg,Mn<sup>2+</sup>)<sub>2</sub>(Mn<sup>3+</sup>,Sb<sup>5+</sup>)BO<sub>5</sub>], and ludwigites of variable compositions [c. (Mg,Fe<sup>2+</sup>)<sub>2</sub>Fe<sup>3+</sup>BO<sub>5</sub>]. Textural evidence suggests that the presently studied oxyborate minerals primarily formed during metamorphism of pre-existing, carbonate-hosted, variably metal-rich assemblages.

Among others, the results also suggest a correlation between the cation distribution in the examined oxyborates and their associated metal oxides, comprising spinel group minerals, hausmannite and iwakiite. The broad chemistry of the host rock phases associated with ludwigite and fredrikssonite, reveals why the two latter are more frequently found, compared to pinakiolite and orthopinakiolite. Furthermore, Raman spectroscopy verifies the structural character of boron in the examined oxyborates and shows a possible connection between the distribution of manganese and whether the BO<sub>3</sub><sup>3-</sup> ion is allowed to be positioned in less than three-fold symmetry sites within the crystal structure.

Our observations and results add to the current knowledge of silica-undersaturated deposits such as those of the Långban-type, and also provide a dataset combining highly resolved mineral chemistry and Raman spectra, to better understand structural features of the oxyborate minerals, both e.g. applicable to future boron isotope studies.

#### POSTER

### Phyllic alteration-related Cu-Au mineralisation at Raitevarri, Norway

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The historic Raitevarri Cu-Au occurrence is situated 40 km SW of the Karasjok village in Finnmark, Norway. The Cu-Au occurrence is hosted by a quartz-hornblende-plagioclase gneiss unit enclosed within the Paleoproterozoic Karasjok Greenstone Belt. The sporadically mineralised zone in the gneiss has a length of more than 7 km.

Store Norske Gull A/S conducted soil sampling in the NW part of the gneisses in 2009, which revealed an oval-shaped multi-element soil anomaly of 300 m wide and 700 m long. A drilling campaign was conducted in the area and a previously unknown Cu-Au-mineralised body was discovered.

Two alteration styles are recognized from the drill cores: (1) a phyllic alteration, associated with quartz-muscovite-sulphide or quartz-tourmaline-sulphide±muscovite±chlorite veins and (2) a plagioclase-epidote-chlorite alteration assemblage, associated with quartz-epidote veins with

amphibole selvages. The phyllic alteration is extensive in the studied bedrock and easy to detect from the hand-samples because of the bleached appearance. The phyllic alteration is associated with a significant gain in Cu, Au, Mo, Ag, As, Bi, Se, and Te as well as loss in Zn, Pb, Cd, and Mn.

The metal zonation in drill profile RAI-500 shows two central zones where Cu, Au, and Mo anomalies coincide. The Cu-Au-Mo enriched zones are surrounded by zones with elevated Zn, Mn, Pb, and Cd concentrations.

Current interpretation is that Raitevarri area encloses a metamorphosed porphyry-style mineralisation.

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**POSTER**

### Te-Se-Au-Ag-Bi-rich polymetallic vein mineralisation south of Glava, SW Sweden

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Vein-hosted, often Au and/or Ag-enriched polymetallic deposits formed in conjunction with the c. 1 Ga Sveconorwegian orogeny comprise a comparatively widespread mineralisation type in SW Sweden and SE Norway (cf. Alm & Sundblad 1994; Alm 2000).

The presently studied mineralisation occurs *in situ* c. 0.7 kilometers south to southwest of the Glava (Yttre Rud) mine field in Värmland. Minor exploration work here in the 1980s yielded high Au and Ag contents (Lundegårdh 1995). Recent sampling and study of the vein ore assemblages revealed its significantly Au-Ag-Te-Se-Bi-enriched nature. Bornite and chalcocite are the dominating sulphides. Native gold (“electrum”) is relatively common in the studied sections. Wittichenite (Cu<sub>3</sub>BiS<sub>3</sub>) is the major Bi host, whereas Bi-Te minerals, particularly tellurobismuthite (Bi<sub>2</sub>Te<sub>3</sub>), are also widespread. Hessite (Ag<sub>2</sub>Te), consisting of twinned, sub-hedral crystals, is quite abundant. Rarely, petzite (Ag<sub>3</sub>AuTe<sub>2</sub>) is observed, occurring as a reaction rim between native gold and hessite. Selenides are dominated by a Cu-bearing clauthalite [(Pb,Cu)Se]; Se is also hosted by abundant, Se-Cu-bearing galena [(Pb,Cu)(S,Se)], as

small inclusions in Cu sulphides. The occurrence of the Bi-Te-Se-rich minerals is interpreted to mainly represent formation through unmixing during cooling of a high-T Cu sulphide phase. The vein is overprinted by late oxidation, attested by both secondary Cu minerals and oxidized Te phases [close to xocomecatlite, Cu<sub>3</sub>TeO<sub>4</sub>(OH)<sub>4</sub>], replacing primary tellurides.

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**POSTER**

### Major and trace element analysis of sphalerites from W Bergslagen, Sweden

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Sphalerite is common in many of the polymetallic mineralisations in the Paleoproterozoic Bergslagen ore province in south central Sweden. Besides being the major source of Zn, sphalerite is also an important sink for “critical” metals such as In, Ga and Ge, and elevated In concentrations have been found in a few deposits in western Bergslagen (e.g. Jonsson et al. 2013, and references therein). Recently, we have analysed the major and trace element composition, including “critical” elements, of sphalerites from 19 different mineralisations in western Bergslagen, to test both a combination of methods, and the potentially more widespread occurrence of such elements in this region. The sphalerites were analysed by electron microprobe analyser (EMPA) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Utilisation of the two methods also provided the opportunity for a direct spot-to-spot comparison of their performance in trace-element analysis of sphalerite.

The analytical results verified some of the already known substitutions occurring in the sphalerite structure (i.e. In<sup>3+</sup>+(Cu<sup>+</sup>,Ag<sup>+</sup>) ↔ 2Zn<sup>2+</sup> and Fe<sup>2+</sup>+Cd<sup>2+</sup>+Mn<sup>2+</sup> ↔ 3Zn<sup>2+</sup>), however, several trace elements known to occur in sphalerite (e.g. As, Sn, Se, Sb, Ga, Ge) yielded concentrations below the detection limits of the LA-ICP-MS inhibiting examination of other possible substitutions.

Most of the studied sphalerites have In concentrations >20 ppm and the highest concentrations were found in samples from Hällefors and Gåsborn (400 and 330 ppm, respectively). Interestingly, these sphalerites also exhibit notable concentrations of either Cu or Mn.

As was expected, the direct comparison of EMPA results to those of LA-ICP-MS, showed the significantly better performance of the latter in detecting trace-level concentrations, provided an accurate calibration procedure had been followed. Importantly, it also highlighted the poor precision in analysis and subsequent problems in the application of EMPA data on trace elements in sphalerite.

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#### POSTER

### Petrophysics revealing alteration zones of ore deposits

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Circulation of hydrothermal fluids and consequent fluid–rock interaction can significantly modify the physical properties of ore-bearing deposits. These processes typically also produce changes in ferromagnetic minerals. Detailed petrophysical investigations (density, magnetic susceptibility, remanence and AMS) at outcrop scale can identify and characterize differences between the barren host rock and ore-bearing alteration zone. Rock magnetic tests give information about magnetic minerals and their grain sizes which have relevance in investigating the relation of induced and remanent magnetization, an important factor for interpretation of magnetic anomalies and for 3D modelling.

We have studied orogenic gold or porphyry copper type Cu–Au deposits in Satulinmäki, Kedonjankulma and Uunimäki of the Häme Belt, in Jokisivu of the Pirkanmaa Belt, in Saattopora, Siermäjärvi and Pahtavaara in the Central Lapland Greenstone Belt (Airo and Mertanen 2008, Mertanen and Karell, 2011, 2012, 2015) and in Pampalo in the Hattu greenstone belt (Mertanen and Karell, 2014). In all studied formations the magnetic properties have altered due to fluid infiltration. In Häme

and Pirkanmaa deposits the auriferous shear zones show higher magnetizations than the host rocks due to formation of pyrrhotite. In Pampalo the auriferous rocks have partly lost their magnetization when pyrrhotite was formed at the expense of magnetite.

Remanence directions coupled with AMS directions suggest that in most cases tectonic movements post-date the mineralization event. However, in the deposits of the Central Lapland Greenstone Belt and in part of the Uunimäki deposit, preservation of a late Svecofennian (ca. 1.8 Ga) remanence direction implies that the mineralization occurred after the last ductile tectonic movements.

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#### POSTER

### The Palaeoproterozoic Vannareid VMS occurrence in the northern Fennoscandian Shield

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The Vannareid Cu–Zn occurrence is within the West Troms Basement Complex (WTBC) in Troms, northern Norway. WTBC is a collage of Archaean to Palaeoproterozoic crustal blocks made up of a wide range of plutonic and metamorphic. In the Vanna island, the complex includes various tonalitic to anorthositic and migmatitic gabbroic gneisses older than 2.8 Ga overlain by Archaean and Palaeoproterozoic metasupracrustal rocks. A mafic dyke swarm dated at 2403±3 Ma cut the tonalites and dioritic sill dated at 2221±3 Ma cut the supracrustal rock gives the evidence for a Paleoproterozoic depositional age.

The Vannareid Cu-Zn occurrence was located by Store Norske Gull AS, and a reconnaissance drilling campaign was conducted in summer 2012 to test a Zn showing along a E-W trending fault zone. The zinc showing in a road cut was originally detected at Vannareid by Kåre Kullerud in 2008. The exploration campaign revealed almost one km long Cu-Zn mineralisation along a fault zone between tonalite gneisses and supracrustal rocks. The Cu-Zn mineralisation is hosted by quartz-carbonate-chlorite veins in tonalite gneisses, mafic sills and sericite schists. All rocks are deformed and metamorphosed at upper-greenschist to lower-amphibolite facies conditions.

Surface expression of the mineralisation is almost one km long Cu-Zn soil anomaly. In addition, quartz-chlorite breccia and vein system with sulphide dissemination is sub-cropping in the centre of the soil geochemical anomaly. IP survey detects the disseminated sulphides north of the fault and marine clays south of the fault. Reconnaissance drilling included six drill holes to test the soil geochemical anomaly. Drilling intersected a zone of quartz-carbonate-chlorite-sulphide alteration and veins in a package of sericite schists, mafic sills and tonalite. Under the strongest soil Cu anomaly, a stringer zone with the highest Cu/Zn ratio and silica-chlorite alteration was intersected.

The Cu-Zn occurrence discovered at Vannareid is new style of mineralisation in the area. The geological setting and current exploration results suggest that the mapped part of the Cu-Zn mineralization may be a stringer zone of a volcanic hosted massive sulphide (VMS) mineralization. The stringer zone shows higher Cu grades in the core with silica-chlorite alteration and higher Zn grades related to carbonate alteration at the flanks. Extensive mafic sills in and north of the stringer zone represent magmatic stage of the rifting. Consequently, the geological framework then represents favourable geological setting for a VMS system.

## POSTER

### Metallogeny of the Precambrian West Troms Basement Complex, northern Norway

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The Neoproterozoic to Palaeoproterozoic West Troms Basement Complex (WTBC), west of the Caledonian Nappes in northern Norway, is composed of TTG gneisses (2.9-2.6 Ga) intruded by mafic dyke swarms (2.4 Ga) and plutonic complexes (c. 1.8 Ga), and overlain by variously aged (2.8-1.9 Ga) greenstone belts (Bergh et al. 2010). The WTBC is thought to be a western continuation of the Fennoscandian shield (Bergh et al. 2012).

Whereas the Fennoscandian shield in Finland, Sweden and Russia is well endowed in both base and precious metal deposits, few economic deposits have been found in the WTBC. Limited historic mining (1860's) and exploration have mainly focused on base metals, but in the past 20 years interest has turned to gold exploration.

The WTBC has a complex architecture of metamorphic, igneous and supracrustal rocks subdivided into a series of segmented blocks, which were brought together during the Svecofennian and/or younger tectono-thermal events (c. 1.8-1.6 Ga). This has resulted in a complex metallogeny with known metal occurrences ranging from stratiform massive Fe-Cu sulphide deposits (assumed VMS and/or SEDEX) and several different precious metal type occurrences found within the 2.8(?) Ga Ringvassøya Greenstone Belt (RGB) (Zwaan 1989) and along the contact to the Neoproterozoic TTG gneisses, to Ni, Co, Cu ± PGE occurrences in layered mafic intrusions in the Hamm gabbro.

Despite recent advances in the geological knowledge of the region, both the syngenetic mineralisation processes and the hydrothermal alteration and remobilisation caused by the later Svecofennian deformation is still poorly understood.

The ongoing study of ore-bearing mineralisation in the WTBC includes further dating of the RGB, detailed mapping of mineralised zones, determination of relationships between the mineralisation, host rock assemblage and orogenic structures, and a wide spectrum of geochemical analyses, fluid



inclusion data, etc. that should give an insight into ore-forming processes and P-T-X conditions responsible for mobilization and deposition of ore-bearing mineralisation.

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## POSTER

### Trace element composition of Fe-oxides from Cu-Fe mineralization in the Paleoproterozoic Lätäseno Schist Belt, Finnish Lapland

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IOCG-style Cu-Fe mineralization has been discovered in the Paleoproterozoic Lätäseno Schist Belt, Finnish Lapland, as part of the Mineral Potential project of Geological Survey of Finland, during the 2011-2013 diamond drilling campaign (Hulkki and Taivalkoski, 2014; Karinen et al., 2015; Torppa et al., 2015). Fe oxides (magnetite and hematite) are associated with disseminated chalcopyrite, bornite and pyrite in mafic tuffs, skarns and carbonate-rich breccias (up to 2 % Cu and 19 % Fe). Trace element composition (Mg, Al, Si, K, Ti, Mn, Ni, Cu, Zn, Ca, V, Cr) of Fe-oxides was determined by EPMA at the GeoRessources lab. (Université de Lorraine, Vandoeuvre-lès-Nancy, France) in analytical conditions comparable to those of Dupuis and Beaudoin (2011). A total of 564 analyses on 26 magnetite and 7 hematite grains from 8 samples were carried out. Concentrations of individual trace elements together with Ni/Cr vs Ti discriminant diagram indicate that Fe-oxides are hydrothermal rather than magmatic in origin. The discriminant diagrams Ca+Al+Mn vs Ti+V and Ni/(Cr+Mn) vs Ti+V show that the composition of breccia-hosted magnetite is compatible with IOCG deposits and that the composition of magnetite and hematite in mafic tuffs and skarns is more compatible with Kiruna-type deposits. Altogether, trace element concentrations of Fe-oxides point to two different styles of Cu-Fe mineralization (IOCG and Kiruna) which have been widely recognized regionally, especially on the Swedish side of the border.

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## POSTER

### Mineralogy and geochemistry of indium-bearing polymetallic veins in the Sarvlaxviken area, Lovisa, Finland

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Polymetallic veins, in the southwestern part of the Wiborg Batholith, Finland, are hosted by both wiborgite and even-grained granites. The wiborgite-hosted veins consist of at least two generations and can be grouped by the dominant metal association: Li-As-W-Zn-Mn; Cu-As-In and Pb-Zn; locally with high contents of base, alloy and noble metals (e.g., Cu, Sn, Zn, W and Ag), as well as critical metals (e.g., In and Li). The Cu-As-In association is characterized by high In contents (up to 1,490 ppm) and very high In/Zn ratios, enabling formation of a proper indium mineral; roquesite. The Li-As-W-Zn-Mn association is characterized by high Li contents (up to 2,390 ppm) most probably hosted in mica. Structural control of the veins shows that the Li-As-W-Zn-Mn association formed before the Cu-As-In and Pb-Zn associations. The wiborgite-hosted polymetallic veins display spatial zoning with respect to different metals (e.g., In, Li, Ag, Pb, Bi) but the main metals (e.g., Sn, Fe, Zn) display either no zoning or an unclear pattern. Vein deposition was, most probably, a multi-stage event, involving evolution of the ore-forming fluids in time and space. Greisenization in the wiborgite-hosted veins was accompanied by silicification and followed by sericitization and chloritization. The veins in the even-grained granites are only observed in locally derived boulders and include the As-Sn-Cu and Mo-Bi-Be metal associations, accompanied by intense greisenization and berylification respectively.

The high concentrations of critical metals, and a potential for as-yet undiscovered mineralization, makes the area attractive for further exploration.

The diverse geochemical character of the veins provides evidence of a considerable, but often overlooked, potential for mineralization within A-type rapakivi granites.

## S3.1 Geoscience outreach

### KEYNOTE

#### Geodiversity - A strategic concept in geological outreach

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Going back some 100-150 years, geology was a popular new science with a prominent place in society. It found itself in the scientific, cultural and religious debates and caught a huge amount of interest among the general public. Today geology is of central importance for society related to all kinds of industrial and agricultural resources etc, but its position in the public is not on the level this importance indicates. Perception of geology seems quite often to be related to environmental issues of the industrial society such as destruction of nature, production of non-renewable energy.

Geology should take its rightful place in a wider context than we often see today and especially increase its relevance in important fields such as land use planning, nature conservation and landscape strategies. All these fields are of high importance in the modern society, they engage people and have political attention. It is important for geology to be visible in all fields of society and it is vital to be so also within management and policies related to land use planning and nature management.

Main recent developments within geoconservation include the breakthrough of the term geodiversity and the acceptance of terms like geoheritage and geocnservation alongside biodiversity. This is a trend that has been accepted by the world leader in nature conservation - IUCN. It forms the basis for geology to make significant contributions within nature management and broadens the perspective of how we deal with and understands nature. Geodiversity have the potential as a concept to bridge the gap between traditional use of natural recources and management of immatrial nature values. It put geology in position to cooperate along side biology for the best of nature as a central part of ecosystem services and is a valuable element in our understanding of landscape strategies.

In this way it opens up for increased geological outreach in a field were geology has been almost marginalised.

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### ORAL

#### ProGEO — Conservation of geoheritage in Europe

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PrpGEO (The European Association for the Conservation of the Geological Heritage) is an association which promotes the conservation of Europe's rich heritage of landscape, rock, fossil and mineral sites. ProGEO is open to all who are interested in geology and geoconservation. It has activity and members in more than 30 European countries.

The Objectives of the Association are to improve the status of geological heritage conservation throughout Europe. ProGEO works through national groups, regional working groups and international conferences and symposia, and through collaboration with other international bodies

ProGEO had its beginning in 1988 in Leersum, the Netherlands, when "The European Working Group on Earth-Science Conservation", was founded. The formal start for ProGEO as an association took place in 1993 and it was officially registered in 2000. ProGEO is today an affiliated organization of the IUGS and a member of the IUCN.

The protection of valuable geosites is a responsibility of all countries and their governments and each country should promote a list of geosites with conservation value. This requires a systematic inventory and evaluation of sites in every country.

Finland has participated in ProGEO activity almost from the beginning. However geoconservation has still been fairly insignificant in Finland. Although there has been a lot of geological inventories in Finland, the decisions to protect geologically valuable sites have rarely been based on systematic inventories or classifications until the early eighties. From the late 1980's there have been several national inventories concerning geological sites in which the sites have been classified into different categories according to their value.

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ORAL

### The Making of a county - geoheritage mapping in Nordland, Northern Norway

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In 2015, the Geological Survey of Norway (NGU), launched a new geoheritage mapping project in Nordland county, Northern Norway. The project is financed by NGU and Nordland County Council, with the County Governor of Nordland and Museum Nord as partners. The project runs over three years and aims to map and present geosites of interest to science, tourism and education. In terms of area, Nordland is the second largest of Norway's 19 counties. The county has about 240 000 citizens, with the town Bodø as the regional Capital city. Nordland is, geologically speaking, a rich county. Several industrial mineral and ore deposits are being exploited, and there are several deposits for potential future mining. The county display a rich geodiversity, ranging from Precambrian basement rocks, through Caledonian nappe sheets to a spectacular landscape formed during the glacial periods. The terrestrial and marine landscape also provides the base for fisheries, a significant industry in Nordland. In the summer 2015, NGU undertook the first fieldwork for the project, in the areas of Vesterålen and Lofoten, the northernmost parts of the county. As a way to systematize how information about geoheritage is valorized and assessed, NGU used a new proposed framework for assessment of geoheritage in Norway. The framework describes the geological scientific interest, the typology, the geological importance, and the condition of each site. The aim of the framework is to develop a methodology that could be used as standard for mapping geoheritage in Norway.

The project is also part of a long-term wish to update the information in NGU's Database for Geoheritage. The database is based on old registrations from the 1970's, digitalized in early 1990's as a

database on NGU. Today, there is a need to update the data, to secure the quality of the information, and to develop a new way to systematize the information.

In this presentation, we aim to present the project, the framework used for mapping, and tell about lessons learned from the first fieldwork, as well as our hopes for how information collected can be used in the future.

ORAL

### Geoheritage — the future potential of Geological Surveys

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As all other geological disciplines, geoheritage and geodiversity work requires competence, information, backing data and established networks of contacts. Today there is a lack of relevant foundation in societal planning.

To realise that geological heritage is a geological expert discipline, is to realise that it has its rightful place in the work of Geological Surveys. However, the classical activities of Geological Surveys, like mapping, writing of reports and managing databases, have traditionally not included any valuing of the geological resource. For all stake holders the needs we see as crucial to address are:

- To develop and agree on strategies, nationally and between countries
- To include the geological perspective in other strategies
- To find ways forward on a national level to address geological issues in international directives.
- To build up inventory and documentation base information
- To be a part of cross-border cooperation, to develop a shared view
- To have expert backup in a central body, like ProGEO and the IUCN Geoheritage Specialist Group, to harmonize with others' initiatives
- To develop and build upon the established MoU between ProGEO and EGS

The Geological Survey shall promote the use of geological information in societal planning, and could also have an important role in producing customized information for different purposes regarding geoheritage.

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ORAL

**The Geological Narrative**A. BROZINSKI<sup>1\*</sup>

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Geologists understand how our Earth works and functions. We are able to theorize about the ever relevant question how and thus, describe the geological processes that created the landscape we see around us. Simply put, geologists are skilled in the story of Earth, also known as the geological narrative.

A key element in the geological narrative is the experience. Experiences give meaning to life and influence the decisions we make (Boswijk, Thijssen and Peelen 2007). They are also contributed by adventures, encounters as well as learning and are affected by the physical setting (Mossberg 2007). Thus, forming a meaningful experience leads to a deeper understanding. A deeper understanding provides immaterial value to objects (Mosberg and Johansen 2006). In plain, the geological narrative helps turning a rock into the remnants of a mountain chain that formed in an orogeny.

A practical example is provided by Eerola and Brozinski (2015); non-geologist participants in a geological city walk were instructed to become part of Earth's geological processes and simulate them in various physical performances. The talk after the tour revealed a geological “awakening” among many participants.

With the growing interest towards popularized geology and geological tourism around the world, it is paramount that the research on the geological narrative, both practical and theoretical, is set forth.

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ORAL

**Geoparks promotes geological heritage**J. NENONEN<sup>1\*</sup>

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At present tourism is considered to be the fastest growing industry worldwide. In Finland, the use of geoheritage and geological sites as a promoter of tourism and as a producer of further information is rather new.

The Geological Survey of Finland (GTK) has already worked for several years with the clear aim of spreading knowledge about geological heritage to the public, to the tourism sector, and to places of education. The key task has also been the increase of geological knowledge in basic school education.

With the aims of marketing geological heritage and of increasing geological knowledge, the GTK makes an evaluation of regional nature values, mapping and popularisation of nature targets, the design of nature parks, trails and visitor centres, the production of educational and tuition materials. The work has been done in many places in different parts of Finland in co-operation with local government areas, towns, companies from the tourism sector, and with other organizations.

Today the most interesting issue in geotourism in Finland are Geoparks and the Global and European Geoparks network. Rokua Geopark is the first Geopark in Finland and still the northernmost Geopark in the world. Today there are four areas which have plans or projects aiming to European Geoparks Network; North- Karelia in eastern Finland, Saimaa lake area in south-eastern Finland, Kauhaneva – Lauhavuori area in Ostrobothnia and Salpausselkä ice marginal formation area near Lahti city.

GTK gives professional help to the local projects in their work to create new Geoparks in Finland. From GTK's point of view there are four main geological themes in Finnish Geoparks; bedrock, quarternary deposits and formations, peatlands and lake-/seascape. Geoparks based on similar geological themes should be avoided.

## ORAL

### Georhythmic and geoaesthetics: A geological city walk at the New Performance Turku Festival, Finland 2014

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During the the 2014 New Performance Turku Festival, Finland, a Walkapolis geological city walk was arranged. The walk was guided by 12 urban geological sites selected from a published geological city walk guide ([www.kivikierros.com](http://www.kivikierros.com)).

The aim of the geological city walk was to disseminate geology through the geo-aesthetics of dimension stones in a constructed milieu. During the walk, rocks were investigated and their role in building, architecture and art was analyzed. Geology provided the content for the walk and thus an interaction between humans, nature and the city was formed.

Observing rocks in public spaces can be considered as a performance. A collective study of rocks in a bank's columns, stairs and walls, and "cleaning" of granite's structures on a mall's floor caused disturbance which attracted by-passers to become spectators of a geological performances. Some spectators asked what was happening, producing encounters in which they were informed on surrounding geology.

The walk also included geo-rhythmic exercises where Earth's processes were simulated by participants' groups, bodies and their movements. These exercises were considered funny and informative by the participants.

The geological city walk managed to reach out to the participants by making them aware of the surrounding geology and its applying in urban environment. During the walk, the experience of singular geological processes lead to a deeper understanding on how our Earth works, thus giving a positive mental image of geology, dimension stones as a natural resource, their application in construction and the learned topics.

After the walk, a discussion was arranged, where positive feedback was received. Applying this cross-disciplinary and artistic approach, the image of the city and its environment can be seen from a new perspective.

## POSTER

### Aspiring Trollfjell geopark – geology and landscape at Sør-Helgeland and Leka, central Norway

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A geopark is an area with an exceptional geological heritage of international significance, where geotourism, sustainable development and education are at the forefront. The aspiring Trollfjell Geopark, central Norway, is established upon the knowledge and impression of a rich and unique geological heritage. In the autumn 2015, the geopark submitted an application to become members in the Global Geoparks Network (GGN).

The geological attractions in the geopark area are unique and diverse. The ophiolite complex at the island Leka is designated as the Geological Monument of Norway, and here you can walk on MOHO, the boundary between the Earth's crust and the mantle. The famous hole through the mountain Torghatten is one of Norway's most visited tourist attractions. In Trollfjell Geopark you can experience the outstanding landscape feature called the strandflat as a wide archipelago with a myriad of more than 13 000 islands, 6500 of which comprise a UNESCO World Heritage Area, the Vega Archipelago. The geology is the foundation for a landscape rich in resources, where the early humans settled around the rising mountains and gathered food in the shallow sea. The apparent link between geology, landscape, biodiversity and cultural history is quite distinctive – the area has been inhabited for more than 11 000 years.

The aim in Trollfjell Geopark is to raise our sights beyond the national sphere and view geological heritage and natural and cultural assets as a single entity in a region that has much in common.. Trollfjell Geopark is intended to contribute to make the area more attractive and to create values by facilitating geotourism and world-class activities and experiences based on the exceptional geological history and features.

In this presentation, we aim to present the concept and principles of the aspiring geopark as well as the geological attractions in the area.

## POSTER

### Coming to terms with geodiversity in Norwegian nature management

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The Norwegian Nature Diversity Act of 2009 defines nature diversity as the sum of biodiversity, landscape diversity and geodiversity. Within the framework of the Nature Diversity Act, there is a need to define the concept of geodiversity further. There is also a need to separate between the pure description of geodiversity and the value assessments connected to geoheritage. Both concepts should be fundamental and instrumental in the future management of environment and land use in Norway.

In 2005, a new way to classify nature types in Norway, NiN (Nature types in Norway), was published. In 2015, a new version of the classification system (NiN 2.0) was launched. NiN is the first complete classification system of nature in Norway, and was designed with the fundamental understanding that most of the variation in nature is gradual (continuous). NiN aims to give a value-neutral description of nature. NiN follows the Norwegian Nature Diversity act's definition of nature, and assigns geology to important roles in the classification system. Examples included as an environmental factor underpinning the landscape and biological diversity, or as a specific landscape element. The nature diversity act also identifies geology as a value in itself as the basis for nature protection and as special nature type relevant for management.

In this presentation, we aim to present how we define the terms geodiversity, geoheritage, geotope and geosite (in norwegian geologisk mangfold, geologisk arv, geotop and geosted), describe the importance of geology in the NiN classification system, and give some examples on why knowledge of geology is necessary to succeed with nature management in Norway.

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## S3.2 Higher education in geosciences: Experiences, practices and development

ORAL

### The role of misconceptions in the development of a reliable geological knowledge. A project on alternative ideas of Earth Science Bachelor students

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The pre-existing knowledge that Earth Science Bachelor students have when they are starting their University studies, is influential on the scientific knowledge they have achieved when they graduate. This project examines the alternative ideas that first, second and third year Earth Science Bachelor students have on basic geological topics, and if it influences the knowledge that they develop. These topics include; the definition of density, Earth's magnetic and gravity field, heat sources inside the Earth, location and movement of tectonic plates, volcanic and earthquake's distribution on surface, isostasy, weathering and erosion, earth's past and future, rock formation and the relevant age of continental and oceanic rocks. In order to process this, students' alternative ideas were assessed with a 20-item multiple choice questionnaire, which was formed online and delivered to all the Earth Science bachelor students at Uppsala University (2015). The questions were selected from the Geoscience Concept Inventory (GCI) developed by Libarkin & Anderson, 2006. The questionnaire was with SPSS software and students' scores were calculated. One way ANOVA was performed in order to determine statistically significant difference between students' scores and year of studies. The expected outcome was that third year students would have higher GCI scores/level of conceptual understanding, compared to the first and second year students, and that first year students would have the lowest. The results revealed the presence of alternative ideas to all of the students, and even that the year of studies is a factor that affects the GCI scores, even though the students' final scores are relatively low for both second

and third year students. The Earth science knowledge is not acquired by the accumulation of relevant information through the years of studies, but the existence of alternative ideas imply an resistance of or obstacle in learning science.

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Libarkin, J. C. & Anderson, S.W. 2006. Development of the geoscience concept inventory. *Proceedings of the National STEM Assessment Conference, Washington DC*, pp.148-158.

ORAL

### GTK Academy for the maintenance of high-grade professional geological survey

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GTK Academy is an in-house, geo-expertise Continuing Education programme for researchers and experts in the Geological Survey of Finland. Its objectives are to:

- broadening, deepening and updating of geo-expertise
- get the best and common practices, as well as the latest know-how for the entire organization

Within the framework of the GTK Academy training has been organized since 2011. The training is focused on the themes addressed the GTK's core areas. Determining the GTK academy's themes, development needs of skills are mapped in GTK widely. The selections have been made on the basis of their priority and extent of need. Training modules have different scopes and working methods such as lectures, workshops, exercises and excursions. Each module has a responsible person from substance and training program was co-ordinated by the Human Resources Unit. The trainers are mainly GTK's own researchers, if necessary, with external experts are used. Training is organized by the employer, and named delegates are obliged to participate in training. The training is held during working hours and participants will receive a certificate of satisfactory completion of the training.

One of the GTK academy's training programmes was focusing on geochemistry. Geochemistry is an essential part of all geological research but insufficiently considered in the syllabuses of

universities. Particularly, the applied geochemistry and good practises are not brought up in teaching. Furthermore, recent development in geochemical methods has been huge and highlights the importance of training. The programme was carried out in 2015 including basic and advanced sections, of which the first part was directed to large audience (about 65 people) and the latter for a specific group of advanced researchers (18). During a six-days-section in the spring, the whole gamut of geochemical survey from planning, sampling, analysis, data processing and interpretation to databases and sample storage with applications and practices was covered in the basic section. In the advanced part, the focus was in the basic and advanced methods for the statistical analysis of geochemical data using a free software R.

ORAL

### Educating towards expertise – self-regulated learning methods in geology

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In the future working life, in addition to substantial knowledge in geology, students are required to have extensive skills in project management, information management, co-operation, software-and hardware, oral and written communications and presentation. Moreover, they need metacognitive skills in order to understand the construction of the knowledge during their studies.

To achieve these objectives, education towards expertise, and self-regulated learning methods have been implemented. Here we describe three MSc-level courses; representing problem based learning, project based learning, and portfolio based learning. Problem-based learning course “Aeolian sediments” composed of four sessions of contact teaching and self-regulated weeks between the sessions. In project-based environmental geological course the research topic and limits of the laboratory analyses was introduced by teachers. The students made a research plan, schedule, budget, field work and laboratory analyses as well as wrote the report. Portfolio-based course “Management

of groundwater resources” composed of weekly introduction lectures and a written portfolio including supervised assignments, personal evaluations of learning experiences and a supervised summary of the course. According to feedback these activating teaching methods increased study motivation and supported the students towards deep-oriented learning. The students had managed to take responsibility of their learning process and experienced profound development in their studies.

ORAL

### Experiences of teaching in the Turkana Basin Fieldschool, northern Kenya

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The Turkana Basin Field School is run by Stony Brook University and the Turkana Basin Institute. It offers two Field Schools, each of them twice a year. One is the relatively new Sustainability Field School, the other is the long-running Origins Field School, which features five two-week modules in Geology, Ecology Vertebrate Palaeontology, Human Evolution and Archaeology. I have participated in the Origins as instructor in vertebrate palaeontology three times and will share my experiences and thoughts from this interesting experience. Collaboration with the Turkana Basin Institute is an under-used possibility for geoscience and related education in the Nordic countries.

#### References:

Origins FS <http://www.kenyastudyabroad.org/origins/>

ORAL

### **New Master's program in Solid Earth Geophysics at the University of Helsinki: Lessons from one year of operation**

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In fall 2014, the Department of Physics and the Department of Geosciences and Geography at the University of Helsinki opened a new, joint Master's program in Solid Earth Geophysics. The program is designed for students with a BSc degree in Physics, Theoretical Physics, or Geology; those entering the program with a Geology BSc degree must have a minor in Physics, and those with BSc degree in Physics or Theoretical Physics must have a minor in Geology. The teaching language of the program is English. Within the MSc program, the students have an option of focusing their studies either in Global Solid Earth Geophysics or Applied Geophysics. Hands-on exercises in the class, laboratory and in the field are a central part of our courses, in order to present the theory and practice hand-in-hand. The aim is to provide the students with relevant skills for working life both in academia and industry. An overview of the Solid Earth Geophysics specialization line can be found at our website at <https://wiki.helsinki.fi/display/SEGGeophys/>.

In this presentation, we will give a review of experiences gained during the first year of operation, and identify targets for future development. For example, bringing together a mixture of students with BSc degrees in Physics and Geology requires careful consideration with regards to their assumed background knowledge. The exercises need to be balanced in their physics and geology content in such a way that all the students are challenged yet able to solve the problems at their varying skill levels. In order to ensure successful cumulative learning throughout the program, the contents of consecutive courses need to be coordinated jointly. In the coming years, increasing emphasis will be given to the development of teaching methods. So far, we have experimented for example with the flipped classroom model that enables the teacher to pay more attention to the individual needs of the students.

ORAL

### **Applied Geophysics at Oulu Mining School: Challenges and Solutions**

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In order to enhance economically viable and sustainable Raw Materials supply and decrease dependence of EU on imports of raw materials, development of innovative methods of mineral resources exploration and their sustainable use is necessary. This, in turn, requires educating of a new generation of specialists in geosciences capable to develop and use new exploration technologies and to work in cooperation with academy and industry partners at all stages of the mine life circle. As the need for exploration of deep targets grows up, the role of applied geophysical methods in exploration and mining is constantly increasing. Traditionally, education in applied geophysics in Europe was strongly influenced by requirements of petroleum and gas industry. On the contrary, educating applied geophysics specialists for exploration of metal and other non-energy mineral resources did not receive as much attention during two last decades, when universities not directly involved into oil and gas exploration had even to cancel education programs in applied geophysics. In order to satisfy the needs of developing mining industry in Finland and respond to the challenges of new mining activities, the University of Oulu established a new faculty, Oulu Mining School (OMS). The main target for the MSc program in applied geophysics at OMS is to educate a new generation of specialists capable to plan and run multidisciplinary mineral exploration projects. In planning the program we aim to avoid early specialization in one particular applied geophysics technique and to produce well-rounded professionals able to operate in a wide variety of exploration environments and circumstances.

## POSTER

### Helping geology students to learn without teachers present

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Surveys of students' and teachers' experiences at the Department of Geology, Lund University, have shown a need and wish among students to get, for example, more practice in using and understanding geological terminology and to understand the context of different features. Among teachers a common problem is (too) limited time per student to always give meaningful feedback and support. Learning materials that students can use by themselves, without teachers present, can help address these problems. Such materials can be used as a general aid to learning and also for formative assessment. It may also take some load off teachers during a course and allow them to focus joint teacher-student time on selected issues or higher levels of knowledge (explain, apply, generalise), while more basic levels (identification, description) can at least to some extent be covered and trained by the student on her/his own.

Three examples of learning materials that students use in two different courses within the bachelor program at the Department of Geology will be presented: a GoogleEarth-based virtual tour of Sweden with questions with automated response, an image-based self-correcting quiz and a board game (Hiatus; Höglund 2014). Pros and cons from a pedagogical point of view as well as students' and teachers' experiences of these materials will be given.

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## POSTER

### International Earth Science Olympiads: inspiring a new generation of geoscientists

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Since 2007, International Earth Science Olympiads (IESO) have been held with participants from more than 30 countries. The olympiad is aimed at stimulating the interest of upper secondary school students to discover the possibilities for further studies and professions in the natural sciences in general, and geoscience in particular. Each country is represented by four students and two mentors; during three days of competition, the students increase their knowledge in a range of geoscientific disciplines, such as geology, hydrology and meteorology, as well as other science subjects such as mathematics, physics and chemistry as integral parts of geoscience. Also environmental sciences, georesources and geohazards are subjects that are vital both for the national and international communities. Working and interacting with international students with a range of backgrounds, the participants broaden their horizons and develop an appreciation for the international aspects of the geosciences.

IESO is arranged by the International Geoscience Education Organisation (IGEO), and has previously been held in South Korea (2007), Taiwan (2008), the Philippines (2009), Indonesia (2010), Italy (2011), Argentina (2012), India (2013) and Spain (2014). In September 2015, the olympiad took place in Brazil, where 26 countries were represented. Next year's olympiad will take place in Japan, whereas Thailand will host the 2018 olympiad. The host country of the 2017 olympiad is yet to be determined, but Norway has been approached by IGEO to host the event.

IESO are considered very prestigious in many countries, and the level is somewhat more advanced than what Norwegian students are taught in their upper secondary school curriculum. Norway participated for the first time in IESO in Santander, Spain, in 2014, and again in 2015 in Pocos de Caldes,

Brazil. The participants were selected based on competitive tests during local qualification rounds as well as a four-day national training and qualification session at the Department of Earth Science at the University of Bergen (UiB). Our students demonstrated that they meet the required standards as bronze medals were won during the Olympiads in Spain (1 medal) and Brazil (2 medals). In Norway, the interest for IESO has increased from 100 participating schools in 2014 to 120 schools in 2015, when 730 students participated in the qualification rounds.

In Norway the recruitment for natural science education has been low for several years. As an incentive to meet this deficit, geoscience was introduced as a subject matter in upper secondary school in 2007. Through the participation in IESO, the intention is to further incentivate and stimulate the interest in the natural sciences. Even more important than reaching the four students that qualify for the olympiad, are the big number of students that participate in the qualification and especially the c. 100 highly motivated students that go to the second round, and the 16 that go on to the national final and training session in Bergen. At the training camp at UiB, the secondary school students meet university students and young researchers studying and working with geoscience subject matters like geology, meteorology and terrestrial astronomy, and they get an introduction to field and laboratory methodology. Through national and international publicity on the achievements at the olympics, it is our hope that more students will be inspired to pursue a career in natural sciences, and geoscience in particular.

In this research the effects of the change in the entrance exam type in student-material in section of geology, University of Turku, were studied. The “traditional” entrance exam type with applied and broad question types was altered into multiple choice exam in 2011. The students’ positions for the exam-type were targetted as well.

The study was made as Webropol-inquiry for students selected before (control group 2008-2010) and after (test-group 2011-2013) the change in the entrance exam type. The inquiry included both structured and open question-types. The Student Register –material was used as well.

The answering procent was 41, and divided into 56 % old and 44 % new exam type students.

The results of this research show that the students, who succeed in multiple choice entrance exam possess higher success in previous studies, but lower success in university studies. These students have more perfunctory approaches to learning as well. In addition, this student material is clearly more predominantly male compared to before 2011.

There is a high criticism for the multiple choice exam among students as well. This exam-type is experienced to test ability to read and remembering small details instead of understanding and application.

#### References:

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#### POSTER

### Does University Entrance Exam Type Predict Student-material ?

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The units of universities may independently decide the methods how to pick the most potential student material. All the units prefer high quality, talented and motivated students with high capacity for scientific thinking. The role of university entrance exam for this selection has been under several research.

## S4.1 Drilling projects

### KEYNOTE

#### The Collisional Orogeny in the Scandinavian Caledonides (COSC) project: investigating mountain building through drilling of a Paleozoic orogen.

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The remnants of the Scandinavian Caledonides are comparable in several ways to the present day Himalayan mountain belt. In that frame, the COSC project aims to provide a deeper understanding of orogen dynamics through deep drilling and extensive geophysical data acquisition. The first part of this project, COSC-1, targeted the middle allochthon in the lower Seve Nappe Complex and its associated basal thrust zone near Åre, Sweden. Drilling operations conducted during the summer of 2014 resulted in a 2496 m borehole with an almost fully recovered core sample. Borehole and on-core logging provide an extensive and unique dataset through a continuous 2.5 km section into a high grade thrust sheet. On-going scientific investigations are summarized and include a broad range of topics, from the core microstructure analysis to active fluid flows in-situ. The borehole dataset is also used to constrain high quality geophysics in the area. The second part of the project, COSC-2, is planned to drill through the lower allochthon and the underlying Proterozoic basement in 2017. A site has been selected based on geological and geophysical investigations. Taken together, these drilling campaigns will provide a detailed record through a 5 km composite section in the Scandinavian Caledonides. This section spans from the allochthons to the basement, cutting through major tectonic contacts that are out of reach in present-day mountain belts as the Himalayas.

### ORAL

#### Hydrogeologic testing and sampling at the COSC-1 borehole

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The talk presents a summary of hydrogeologic testing and sampling activities to date at the COSC-1 borehole. During the drilling period in 2014, we were able to take advantage of one-day breaks in the regular drilling schedule to conduct Flowing Fluid Electric Conductivity (FFEC) logging in the borehole. This was a new approach which turned out to be very successful. Eight inflow zones were identified representing eight hydraulically active fractures or features between the depths of 300 and 2500 m. Initial estimates of their transmissivities and fracture water salinity were also obtained. Post-drilling hydrologic testing and sampling were done in September and October, 2015. They included three main activities. First, water sampling was done using the tube sampling method. Twenty five samples were collected, each with about 100 meters of tubing, so that the whole length of the borehole was covered. Secondly, FFEC logging over the depth range of 100–2000 m was conducted. About 10 fluid electric conductivity profiles over an extended time were obtained at two different pressure drawdowns (two different pumping rates) of about 50 m and 10 m. Third, water samples were collected with a downhole sampler, after pumping (which was part of FFEC logging), at 6 depth levels corresponding to the 6 inflows into the borehole as identified by FFEC logging. Chemical and microbiological analyses are currently underway on these samples.

ORAL

### Orientation of in-situ horizontal stress in Outokumpu, Finland

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The main aim of the Outokumpu deep drilling project was to determine the geological nature of strong seismic reflectors at 2-2.5 km depth (e.g. Kukkonen 2011). It was conducted within the International continental drilling program (ICDP).

The objectives of this study are to (1) constrain the orientation of maximum horizontal stress by mapping the occurrence of stress-induced deformation features using two sets of borehole televiewer data, which were collected six years apart, in 2006 and 2011; and (2) investigate whether any time dependent deformation of the borehole wall has occurred (creep).

Stress concentrations are formed at the borehole wall when rock is removed by drilling. Two types of stress-induced features exist (e.g. Tingay et al. 2008): (1) Borehole breakouts that form parallel to the orientation of minimum horizontal stress if the stress concentration exceeds the compressional rock strength; and (2) Drilling-induced fractures (DIF) that form parallel to the orientation of maximum horizontal stress if the stress concentration exceeds the tensile rock strength. Few opportunities exist for studying time-dependent borehole deformation.

BHTV data were collected from 260 m to 1900 m in 2006. In 2011 logging was repeated at 160-235 m and 950-1900 m. Preliminary results of the first data set indicate that stress-induced features (and core diskings) start to form 1800 m depth, with roughly N-S orientation of maximum horizontal stress to the magnetic north.

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- Kukkonen, I. T. (ed.) 2011. Outokumpu Deep Drilling Project 2003–2010. Geol. Surv. Fin., *Spec. Publ.* 51: 252 pp.
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ORAL

### Helsinki University Kumpula Campus Drill Hole Project

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The Kumpula Campus Drill Hole Project aims at drilling a fully cored diamond drill hole in the Kumpula campus of the University of Helsinki. At the moment of writing the abstract, the drilling is scheduled for November-December 2015. In addition to the core, a number of downhole logs will be acquired as a contracted service for a full characterization of the geology and geophysics of the hole. The main use of the drill hole will be in undergraduate education in borehole geophysics, wireline logging, petrophysics and geological logging of the core as well as 3D modeling of downhole and surface structures. The Precambrian bedrock in the Kumpula campus is steeply dipping hornblende gneiss, amphibolite, tonalite and granite. The drilling site is on a hilltop on an extensive 1 ha size outcrop. The hole diameter will be 76 mm and the hole is oriented to NE with a dip of 70°.

The campus drill hole will be an important component in the university infrastructure for the education and research of geosciences. The presentation reviews the drilling and logging operations on a densely built campus area and the planned post-drilling use of the hole and the core.

## ORAL

**Project DAFNE: Deep drilling in the Pärvie postglacial fault system**

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We are currently developing an ICDP project 'Drilling Active Faults in Northern Europe' (DAFNE) which aims at investigating, via scientific drilling, the tectonic and structural characteristics of the Pärvie postglacial fault system (PFS) in northern Sweden, including the hydrogeology and associated deep biosphere in the fault system.

During the last stages of the Weichselian glaciation (ca. 9,000 - 15,000 years B.P.) reduced ice load and a glacially affected stress field resulted in active faulting in Fennoscandia with fault scarps up to 160 km long and 30 m high. These postglacial (PG) faults are usually SE dipping, SW-NE oriented thrusts, and represent reactivated, pre-existing crustal discontinuities. Postglacial faulting indicates that the glacio-isostatic compensation is not only a gradual viscoelastic phenomenon, but includes also unexpected violent earthquakes, suggestively larger than other known earthquakes in stable continental regions.

We aim at drilling three deep holes in two phases in the Pärvie fault system which is the longest of the known PG faults. The first drilling phase comprises two 1 km deep core holes, and second phase one 2.5 – 5 km deep hole targeted to reach the seismogenic zone.

## POSTER

**Deep drilling for geothermal energy in Finland**

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There is a societal request to find renewable CO<sub>2</sub>-free energy resources. One of the biggest such resources is provided by geothermal energy. In addition to shallow ground heat already extensively used in Finland, deep geothermal energy provides an alternative so far not exploited. Temperatures are high at depth, but the challenge is, how to mine the heat? In this presentation, the geological and geophysical conditions for deep geothermal energy production in Finland and Sweden are discussed as well as challenges for drilling and conditions at depth for geothermal energy production. Finland is located on ancient bedrock with much lower temperatures than geologically younger volcanically and tectonically active areas. In order to reach sufficiently high temperatures drilling to depths of several kilometres are needed. Further, mining of the heat with, e.g., the principle of Enhanced Geothermal System (EGS) requires high hydraulic conductivity for efficient circulation of fluid in natural or artificial fractures of the rock. There are many issues that must be solved and/or improved: Drilling technology, the EGS concept, rock stress and hydraulic fracturing, scale formation, induced seismicity and ground movements, possible microbial activity, etc. An industry-funded pilot project currently in progress in southern Finland is shortly introduced.



## S5.1 Archean of the Fennoscandian shield: From bits and pieces towards a bigger picture

### KEYNOTE

#### New insights into the geological evolution of the Archean Norrbotten province, Fennoscandian shield

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The Archean Norrbotten province is exposed in northern Sweden and northwestern Finland (Råstojaure–Rommaeno and Muonio complexes) and isotopically traced subsurface south to the Luleå–Jokkmokk area (Mellqvist 1999). New age determination data suggest that ca. 3.2 Ga orthogneisses are found in the NW corner of the province, forming its oldest part. The major part of the Råstojaure–Rommaeno complex is composed of ca. 2.8–2.72 Ga orthogneisses and granitoids, with the ages generally being younger in the E part of the block near the contact of the Proterozoic greenstones. Leucogranites and pegmatite dikes with ages in the range of 2.7–2.6 Ga cross-cut the orthogneisses. Some 2.9–2.8 Ga greenstone belt and paragneiss fragments are found within the gneiss complex but contacts are commonly not observed due to limited outcrop. Proterozoic granitoids intrude the southern part of the Råstojaure–Rommaeno complex. On the eastern side of the Karesuando–Arjeplog shear zone and the Proterozoic greenstone belt that delimit the Råstojaure–Rommaeno complex the exposed Archean fragments of the Muonio complex show ages between 3.0 Ga and 2.7 Ga. Detrital zircon population in the lowermost Proterozoic quartzites (Palovaara fm/Tjälro quartzite) is solely Archean whereas the younger quartzites have large amounts of Proterozoic zircons. Nd isotope data may be used to delineate the extent of Archean crust outside the exposed blocks. Some ca. 1.78 Ga granitic pegmatites in the Karesuando area were derived from purely Archean source whereas the older,

ca. 1.88 Ga granitoids show a more juvenile Nd isotope composition with mixed Archean–Proterozoic source similar to the Luleå area.

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Mellqvist, C. 1999. Proterozoic crustal growth along the Archean continental margin in the Luleå and Jokkmokk areas, northern Sweden. Doctoral Thesis, Luleå University of Technology, 1999:24.

### ORAL

#### Archean evolution of Volgo-Uralia – isotopic constraints

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Volgo-Uralia, which forms the eastern part of Baltica, is buried beneath a thick sedimentary cover, and the knowledge about its basement is based on geophysical data and drill core materials alone. Neoproterozoic granulite- and high amphibolite facies rocks of supracrustal and plutonic origins apparently dominate this complex high-grade crustal terrain. They compose separate domains and belts that were more or less reworked in the Paleoproterozoic.

Combining U-Pb, Hf and O isotope investigations of zircon from metasedimentary rocks and the textures of individual zircon crystals, we found several groups of detrital zircon with ages from 3.8 to 2.7 Ga; the latter indicating the maximum age of sediment deposition. Major metamorphic reworking is constrained to 2.6–2.5 Ga, which age is similar to that of a period of extensive bimodal magmatism in the region. The Hf crustal provenance ages of the zircons are dominantly Mesoproterozoic, while a minority has an older, up to Eoproterozoic crustal provenance. Much of the zircon has mantle-like  $\delta^{18}\text{O}$  compositions, demonstrating a dominantly juvenile nature of their host rocks.

Further work will shed more light on the architecture and evolution of Volgo-Uralia, and its relation to Fennoscandia and other crustal segments.

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ORAL

### Chronostratigraphic aspects of the Archean Suomussalmi-Kuhmo-Tipasjärvi greenstone complex

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The Archean greenstone belts in Finland have been under elaborate research during past decades. However, the research has been concentrated mainly on the mafic and ultramafic volcanic rocks. Suggested stratigraphic interpretations have mainly been based on spatial relationships of the volcanic rocks, on their chemical compositions and sporadic age determinations.

The purpose of this study was to construct a detailed chronostratigraphy for the Suomussalmi-Kuhmo-Tipasjärvi greenstone complex, which is the largest Archean greenstone complex in Finland. Systematic sampling from felsic and intermediate metavolcanic rocks was done across individual belts, and zircon grains were dated from each sample with single grain analysis methods. The aim was to distinguish volcanic and sedimentary events within individual belts and between the different belts.

The main conclusions are:

1) The felsic and intermediate volcanic rocks in the Suomussalmi-Kuhmo-Tipasjärvi greenstone complex have formed in several stages (ca. 2.94 Ga, 2.84 Ga, 2.82 Ga, and 2.80 Ga);

2) Age variation can be seen between the different greenstone belts and in inside individual belts. For example the Tipasjärvi greenstone belt contains three felsic-intermediate volcanic successions: ca. 2.84 Ga, 2.82 Ga, 2.80 Ga;

3) The granitoid plutons in the immediate vicinity of the greenstone complex are contemporaneous with the volcanic episodes;

4) The belts contain metasedimentary rocks with detritus deposited tens of millions of years after the cessation of the youngest volcanism. Metasedimentary rocks contain also significantly older material than the volcanic rocks within the belts.

ORAL

### Archean Belomorian collisional orogen: new data and implication for supercontinent reconstruction

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An assembly of Meso-Neoproterozoic igneous (TTG-granitoids and S-type leucogranites and calc-alkaline-, tholeiite-, komatiite-, boninite- and adakite-series metavolcanics) and metamorphic (2.88-2.82, 2.72 Ga eclogite- (Li et al, 2015), moderate-pressure (MP) granulite- and MP amphibolite-facies rocks) complexes is preserved in the Belomorian province (BP) of the Fennoscandian Shield.

There are four subduction-accretion events in BP: 2.88-2.82, 2.81–2.78 2.75 and 2.73-2.72 Ga (Slabunov, 2008)

From ca 2.71 Ga collision tectonics manifested itself in BP as nappe-folded, MP metamorphism (kyanite-orthoclase subfacies) and S-type granite formation. A new isotope study of zircons from leucosomes of kyanite-orthoclase gneisses and granites, whose formation is attributed to collisional processes, yielded an age of 2687 ± 31 and 2706 ± 14 Ma, respectively (Slabunov et al., 2016), which is interpreted as the exact time of collision.

Archean Belomorian collisional events are correlated with 2.68 Ga Minnesotan orogeny (Suprior Province) and Neoproterozoic (2.7-2.67 Ga) processes in the Limpopo complex, South Africa. Reconstructions, based on paleomagnetic data (Lubnina & Slabunov, 2011), suggest that the above Neoproterozoic complexes are part of one orogenic belt which marks the formation of Kenorland Supercontinent.

This is a contribution to RFBR Project 15-05-09288.

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## ORAL

### Deeper meaning of the compositionally diverse Neoproterozoic magmatism in the Karelia Province?

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Over the last decade significant amounts of new geological data and interpretations concerning the various Neoproterozoic plutonic suites of the Lentua complex of the Karelia Province has accumulated. Lentua and adjacent parts of the Karelia province display archetypical evolution from uniform “TTG-only” granitoid magmatism (aged mainly 2.84–2.78 Ga, some 2.75–2.72 Ga) towards a compositionally significantly more diverse system of plutonic suites (aged 2.75–2.65 Ga). TTG suite rocks of the Lentua complex do not display any subduction signature and have been interpreted as partial melts of amphibolites bearing variable amounts of garnet.

During Neoproterozoic the Lentua complex was intruded by several magmatic suites derived from variable mantle sources: sanukitoids (mainly 2.72 Ga, some 2.695 Ga), quartz diorites (mainly 2.70 Ga, but up to 2.74 Ga), alkaline enriched gabbros (2.75–2.70 Ga) and syenitic rocks (2.74–2.65 Ga). These suites have been interpreted as a result of partial melting of unevenly metasomatized lithospheric mantle, with variable input also from the asthenospheric mantle as well as possible crustal contamination. These suites were followed, and partially overlapped by anatectic leucogranites (mainly 2.71–2.69 Ga) following a continental collision. The different suites display certain differences in areal distribution and composition (LILE, HFSE enrichment), but also show overlap in both aspects. This is likely linked to heterogeneous sources due to differences in degree of metasomatism due to varying distance from the active Neoproterozoic arc system(s) further east and/or differences in amount of input from asthenospheric mantle and/or differences in amount of input from alkaline upwellings. In large scale the partial melting of the mantle continued for 80 Ma and progressed from east to west below the Lentua and adjacent complexes, at the same time evolving from sanukitoids to quartz diorites.

Modern analogue of the Neoproterozoic evolution of the Lentua and adjacent complexes could be the Tibetan plateau, area which also shows sifs in the

place and composition of the alkaline magmatism, interpreted as result of slab roll back, slab breakoff and crustal delamination, following change from subduction to collisional setting. These processes in variable combinations affecting a heterogeneous source provide the most plausible solution for the observed complexity of compositions in both cases.

## POSTER

### Magnetotellurics in Northern Finland

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Magnetotellurics (MT) is an electromagnetic geophysical method where temporal variations of the natural electromagnetic field of the Earth are measured on its surface. The measurements contain information about the electrical conductivity structure of the subsurface. We analyse MT data collected within the Magnetotellurics in Scandes (MaSca) -project. In 2014 we measured total of 79 MT sites in Northern Finland. The site array covers parts from the Peräpohja Belt, the Central Lapland Granitoid Complex and the Central Lapland Area. This is the first time extensive MT studies are being conducted in the area. With an average site spacing of 15–30 km and a period range of 0.001–10000 s, the data set contains information about the large scale conductivity structure of the crust and upper mantle below the site array. The complex geological setting requires three-dimensional (3-D) inversion to infer the conductivity variations in the most realistic manner. With some success so far, the 3-D inversion of the data set is an ongoing challenge. Preliminary results will be presented.

## S5.2 Archean-Proterozoic transition

ORAL

### Longevity of Archean oceanic environments – insights from the Ilomantsi greenstone belt

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There is continuing, vigorous and convective debate over the viability and nature of plate tectonic processes in the Archean time. Theoretical considerations of thermal and physical boundary conditions for the early earth have promoted the concepts of thick, buoyant oceanic lithosphere that is inherently difficult to subduct, combined with rapid recycling of abundant, small plates. The Kaapvaal and Pilbara cratons reveal that some stable cratonic environments existed from at least 3.0 Ga but is there evidence to constrain the longevity of oceanic crust prior to recycling?

Recent dating of volcanic and sedimentary sequences and intruding orogenic pluton rocks in the Ilomantsi greenstone belt have confirmed a clustering of eruptive ages at about 2.89 Ga and 2.75-2.73 Ga. There is as yet no evidence to suggest deformation and metamorphism of the older, 2.89 Ga Kovero greenstones prior to eruption and deposition of the younger, 2.75 Ga Hattu assemblages, nor is there evidence to support the tectonic juxtaposition of two totally different terrains. The simplest scenario is one where Archean oceanic crust – or at least mafic to ultramafic volcanism on a submarine substrate at 2.89 Ga, remained submerged and undisturbed for about 150 Ma, until it was juxtaposed with a rapidly evolving volcanic and plutonic terrain heralding the onset of orogenic consolidation between 2.75-2.70 Ga. How does this differ from areas in the modern Pacific Ocean where ocean floor of Jurassic age is approaching active convergent margins?

ORAL

### High-grade metamorphism of the Archean to Palaeoproterozoic gneiss complex in Vesterålen, North Norway

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The Archean to Palaeoproterozoic Gneiss Complex of Vesterålen, North Norway, is dominated by orthopyroxene-bearing migmatitic gneisses. The gneiss complex includes horizons of quartzites, calcsilicates and amphibolites, and is intruded by a Palaeoproterozoic AMCG-suite and gabbros. Evolution of high-grade metamorphism is constrained from garnet-orthopyroxene-bearing parts of the migmatitic gneiss complex: The gneisses occur as banded rocks with migmatitic layers and are typically characterized by a brownish colour. Locally preserved relationships illustrate the migmatitisation process where leucosome intrusive melts breaks up finer grained and foliated restites preserved in lenses. The gneisses consist of perthitic feldspar, quartz, orthopyroxene, minor plagioclase and a variable content of biotite. Garnet is present in extensive parts of the complex. The perthite is normally mesoperthite, but patch perthite and antiperthite is present. Plagioclase is An<sub>27-33</sub>, orthopyroxene En<sub>49-60</sub> and garnet Alm<sub>59-72</sub>Prp<sub>14-31</sub>Grs<sub>4-13</sub>Sps<sub>2-4</sub> with Mg# = 0.17-0.37. Biotite has Mg# = 0.54-0.65. P-T condition of the metamorphic event is modelled by conventional thermobarometry using Thermocalc software and calculations of P-T pseudosection by Theriak-Domino. P-T calculation yields estimates of P up to 0.86 ± 0.23 GPa and T up to 903 ± 113 °C. For the calculated P-T-range, pseudosection modeling shows liquid-in above 830-860 °C, biotite-out above 840-870 °C and garnet-in above 0.60-0.85 GPa. Calculation of garnet isopleths for grossular and Mg# restricts the conditions for P to 0.8-0.9 GPa and T=860-880 °C, in accordance with the upper stability field of biotite and presence of melt. Local corona-growth of garnet and amphibole on orthopyroxene reflect a retrograde or secondary high-grade

influence. Our geological mapping in combination with petrographic and petrological studies and modeled P-T conditions of the gneisses document a regionally extensive medium-pressure granulite-facies metamorphism of the Archean to Palaeoproterozoic Gneiss Complex in Vesterålen.

ORAL

### Age and Sm-Nd isotopes of Palaeoproterozoic mafic rocks in Finland – evidence for rifting stages and magma sources

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Isotopic studies on mafic dykes, intrusions and volcanic rocks from the Karelian domain in Finland indicate rifting of the Archaean lithosphere at several distinct stages including ca. 2.44 Ga, 2.3 Ga, 2.22 Ga, 2.15 - 2.11 Ga, 2.05 Ga, 2.0 Ga, 1.95 Ga and 1.8 Ga (Huhma et al 2011 and references therein). This view is based on a database comprising U-Pb zircon (or baddeleyite) ages for ca. 150 mafic samples, supported by Sm-Nd mineral ages for ca. 50 samples. Many of these results date regionally important dyke swarms and large gabbroic intrusions, and can also be used to reliably constrain ages of the main Karelian volcanic events, which have produced the mafic formations that are a major component of bedrock especially in Central Lapland.

Samarium-neodymium mineral and whole-rock analyses have been made at GTK since the early 1980's. The database currently includes more than 800 analyses on Palaeoproterozoic mafic rock units in the Karelian domain. As many of the initial  $\epsilon$ Nd values are based on the Sm-Nd mineral isochrons, they should give reliable estimates for the initial isotopic composition of the investigated, in most cases ultimately mantle-derived rocks. These data together with U-Pb ages and geochemical and other geological information provide tools for constraining the age and origin of the magmas of the major

mafic episodes and thereby the evolution of lithosphere and mantle components. The observed initial  $\epsilon$ Nd values range from very positive to strongly negative. High initial values suggest derivation from depleted mantle sources, whereas low values point to a large contribution from old enriched continental lithosphere.

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ORAL

### Spherule layers in the Paleoproterozoic Zaonega Formation, Karelia: new data from drill-core OnZap1

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Organic-rich sedimentary rocks of the Zaonega Fm, Onega basin, Karelia, Russia with depositional age between  $1975.3 \pm 2.8$  and  $1967.6 \pm 3.5$  Ma (Martin et al., 2015) contain spherules (spherical aggregates) typically associating with dolostone breccias. The spherules were first discovered in three intervals in drill-core 13A and some in 12A of the FAR-DEEP Project and it was proposed that they are of meteorite impact origin (Huber et al. 2014). In 2012 three additional cores were drilled in the Zaonega Fm and similar spherules were discovered in core OnZap1. In this contribution we present the new results on the distribution, morphology, mineralogy and geochemistry of spherules in OnZap1. We interpret the brecciated sedimentary beds containing the spherules in 13A, 12A and OnZap1 drill-cores as representing one event rather than several and suggest new correlations. Different from other Precambrian spherules, the ones found in Zaonega Fm consist mainly of secondary mica/clay (phlogopite) and calcite with minor apatite, pyrite and quartz reflecting variable diagenetic and/or hydrothermal replacement and recrystallization paths. It is important to note that the new age constraints on the deposition of the Zaonega sediments suggest an undiscovered large impact happened in this time period.

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## ORAL

### Petrography and the composition of apatite in the Paleoproterozoic Pilgijärvi Sedimentary Formation

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The first significant P-rich deposits appear in the global rock record during the Paleoproterozoic around 2 Ga but their origin remains under debate. In this contribution we study phosphorus-rich rocks (up to 8 wt% P<sub>2</sub>O<sub>5</sub>) in ca 1.9 Ga old Pilgijärvi Sedimentary Formation, Pechenga Greenstone Belt, NW Russia. Phosphate minerals (primarily apatite) in these rocks occur in allochthonous sand-to-gravel sized clasts that have been transported and redeposited. They often exhibit soft-deformation features suggesting the semi-lithified nature of clasts during deposition.

Phosphate clasts can be subdivided into four petrographic types (A-D), each being represented by a distinct REE signature reflecting different early-to-late diagenetic conditions and/or metamorphic overprint. Type A represents angular to subangular clasts of massive, impurity-free submicrometer size apatite crystal aggregates; Type B clasts are elongated and subrounded and consist of quartz-feldspar-mica/chlorite siltstone-shale or chert with pore-filling of submicrometer crystal-size apatite cement; Type C clasts are subangular to rounded and comprise apatite aggregates with abundant quartz and feldspar, possibly representing a transitional type between A and B types; Type D clasts contain apatite crystal aggregates with abundant pyrite. Petrographic and trace element characteristics suggest that the Type D clasts are the best preserved amongst the four types, hence carry the best

record of the environmental conditions during apatite precipitation. The negative Ce anomaly and positive Eu anomaly in PAAS normalized REE patterns of Type D particles suggests precipitation under (sub)oxic basinal conditions with significant hydrothermal influence.

## KEYNOTE

### Paleoproterozoic carbon isotope excursion: updating the evidence from the Fennoscandian Shield

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A positive carbon isotope excursion in marine dissolved inorganic carbon is one of the major global events affecting the surface environments of the Paleoproterozoic Earth. This excursion, known as the Lomagundi-Jatuli isotope event, is clearly global in character. It started before 2200 Ma and ended after 2100 Ma. Through the operation of the global carbon cycle, the Lomagundi-Jatuli isotope event is considered to have been connected to the oxygenation of the atmosphere.

Possibly the most complete stratigraphic successions of sedimentary carbonate rocks from that time period have been preserved in the Fennoscandian Shield. During the past few years, a wealth of new carbon isotope data from these sequences has been published, and especially the termination of the excursion is well covered. Important new data represent successions in the Onega Basin (e.g. Črne et al., 2014) and the Pechenga Belt (e.g. Salminen et al., 2013). The carbon isotope records from these sections are here compared to unpublished data from the Peräpohja Belt in northern Finland. Characteristic to all these successions is a generally decreasing trend in their carbon isotope ratios. Available isotopic age constraints provide strong support for a conclusion that the termination occurred at the same time in separate basins surrounding the Archean core of the Fennoscandian Shield at about 2100 Ma. Furthermore, the carbon isotope records from the Pechenga Belt and the Onega Basin indicate that the positive excursion was followed by a minimum, possibly related to erosion of earlier organic-rich sediments accumulated during the Lomagundi-Jatuli isotope event.

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Salminen, P.E., Karhu, J.A. and Melezhik, V.A., 2013. Kolosjoki Sedimentary Formation: A record in the aftermath of the Paleoproterozoic global positive  $\delta^{13}\text{C}$  excursion in sedimentary carbonates, *Chem. Geology* 362, 165-180.

ORAL

### Global to continental-scale glaciations and their sedimentary record during the Archean-Proterozoic transition

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Earth's climate during the Archean-Proterozoic transition was marked by the first major glacial events with evidence for large continental ice sheets on many cratons, and with sedimentological data indicating that glaciers had extended to sea-level. This study emphasizes the sedimentological and sequence stratigraphic responses to glaciations to evaluate the major driving forces of glaciations during the Archean-Proterozoic transition. First- and second-order sequences are recognized related to continental-scale fragmentation and formation of marine rift basins wherein sedimentary rocks indicate glacial influences and pronounced tectonic-climatic linkages. These glacial deposits seem always to be associated with extensional tectonic setting, although not necessarily always having very intimate relationships to the Earth's supercontinent cycles. It is suggested, however that some long-lived marine terminated glaciers were also situated at low paleolatitudes.

There is a need to continue detailed sedimentological studies of pre-glacial and post-glacial deposits as well as to interpret syn-glacial lithofacies for their inferred transportation and depositional processes. Pre-glacial deposits, especially, should provide a new target to help us understand the processes that initiated the Paleoproterozoic glaciations.

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ORAL

### Palaeoproterozoic Earth history: a proposed revision

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A long-standing concept of Palaeoproterozoic Earth history is the presumed time-equivalence of organic-rich rocks (averaging 2–5% total organic carbon) that are found on several cratons, e.g. the Shunga Event. Similarly, major positive carbonate-carbon isotope excursions ( $\delta^{13}\text{C} > +5\text{‰}$  and locally much higher) are viewed as marking coeval, worldwide perturbations of the global C cycle, e.g. the Lomagundi-Jatuli Event. Here we combine new and published geochronology that shows that the main Palaeoproterozoic carbon burial episodes (PCBEs) preserved in Russia, Gabon and Australia were temporally discrete depositional events between c. 2.10 Ga and 1.85 Ga. In northwest Russia we also show that the termination of the Lomagundi-Jatuli Event may have differed by up to 50 Ma between localities.

Intriguingly, PCBEs and Mesozoic Oceanic Anoxic Events (OAEs) share features that hint at a commonality of cause(s) and feedbacks: both are exceptionally organic-rich relative to encasing strata, associated with contemporaneous igneous activity and marked by organic carbon isotope profiles that exhibit a stepped decrease followed by a stabilisation period and recovery. What is different is that PCBE strata are thicker and of greater duration than OAEs (100 s of metres versus a few metres,  $\sim 10^6$  versus  $\sim 10^5$  years durations). This suggests that PCBEs represent processes that can be basin-specific and formed by conditions that are not singularly unique to the Palaeoproterozoic.

ORAL

### Resolving history of the early Paleoproterozoic time

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Transition from anoxic to oxygenated Earth's surface environments in the early Paleoproterozoic (2.5-2.0 Ga) was accompanied by a number of equally dramatic changes. Geochronologic and stratigraphic data helps constrain cause and effect relationships among these events. The low-latitude positioned supercontinent Kenorland was impacted by a number of magmatic events resulting in emplacement of LIPs between ~2.50 and 2.42 Ga in association with the protracted supercontinent rifting. Intense chemical weathering of juvenile magmatic rocks under low-latitude conditions and enhanced biological productivity related to a large terrestrial P flux likely led to CO<sub>2</sub> drawdown and, ultimately, to glaciations. Rises and falls in atmospheric and ocean oxygenation were closely coupled to the Huronian glaciations, with oxygenation events leading to and reducing conditions restricted to the Snowball Earth glaciations and their immediate aftermaths. This period marked by dramatic surface redox fluctuations and three glaciations ended up with the ~2.36-2.32 Ga magmatic activity at high latitudes and irreversible surface oxygenation. Extensive magmatic activity at ~2.22 Ga at low latitudes affected all continents and initiated the breakup of the supercontinent; in South Africa, it is associated with a glaciation, which is not yet recognized on other continents. Carbon isotope values in sedimentary carbonates, reflecting global organic carbon burial, began to fluctuate before the first Huronian glaciation with the progressively increasing magnitude with the decreasing age. Large, positive carbon isotope excursions occurred between the second and third Huronian glaciations, at ~2.32 Ga, and, finally, between ~2.22 and 2.1 Ga (as the long-lasting, large-magnitude Lomagundi Excursion). The Lomagundi Excursion was followed by a deoxygenation event inferred to be due to either decreased terrestrial nutrient (P) flux or chemical weathering of organic-rich shales deposited during

the Lomagundi Excursion. Short-lived carbon isotope excursions might have continued after the end of the Lomagundi Excursion. Tantalizingly, similar events and temporal trends are also observed in the Tonian leading to the Neoproterozoic oxygenation event. It seems likely that tectonic and magmatic activity rather than evolution of life and surface conditions determined long-term changes in climate and composition of the atmosphere and ocean at both ends of the Proterozoic.

ORAL

### Mo and Os as indicators of atmospheric oxygenation: evidence from Paleoproterozoic black shales at Talvivaara, eastern Finland

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Compared to average continental crust or average shale, black shales are generally enriched in several redox-sensitive elements, such as U, V, and Mo, making them useful indicators of redox conditions in marine settings and indirect indicators of atmospheric evolution. We have studied the geochemistry of black shale samples from the Kuikkalampi Formation, which lies above the Talvivaara Ni-Zn-Cu-rich black shale unit in eastern Finland (Kontinen & Hanski 2015; In: Mineral Deposits of Finland, Elsevier, p. 557-612.). These black shales were deposited ca. 1.90–1.93 Ga ago and thus post-date the beginning of the Great Oxygenation Event by several hundreds of millions of years.

The Mo contents of the analyzed Kuikkalampi Fm samples are very high, averaging 167 ppm and reaching values up to 326 ppm, thus clearly exceeding the world black shale median of 20 ppm. Similar levels are normally only found in some Phanerozoic black shales. Mo correlates well with U and C<sub>org</sub> and occurs as tiny molybdenite flakes in close association with carbonaceous nodules 0.01–0.2 mm in size. We analysed several molybdenite-bearing light mineral fractions for Re-Os isotopes, yielding an isochron with an age of 1848 ± 18 Ma,



which likely represents a time of meta-morphic re-equilibration. After correcting for isotopic evolution between 1.92 and 1.85 Ga, a radiogenic initial  $\gamma\text{Os}$ (1.92 Ga) value of ca. +220 is obtained.

Exceptionally high Mo contents and elevated initial  $\gamma\text{Os}$  of the Kuikkalampi Formation black shales suggest an elevated Mo content and radiogenic Os isotopic composition of sea water at 1.92 Ga, due to oxidative weathering of sulfides in exposed Archean and Paleoproterozoic crust. Modern analogues suggest operation of a particulate Mn–Fe-oxyhydroxide shuttle in a weakly restricted anoxic depositional basin during the black shale deposition.

## POSTER

### Neoarchaean(?) and Palaeoproterozoic tectonometamorphic events affecting the basement-cover sequence on Ringvassøy, West Troms Basement Complex

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The West Troms Basement Complex is composed of blocks of 2.9–2.6 Ga TTG gneisses divided by 2.8–1.9 Ga supracrustal inliers, and is intruded by a 2.4 Ga mafic dyke swarm and c. 1.8 Ga plutonic complexes. The WTBC is considered a western continuation of the Fennoscandian Shield, supported by regional aeromagnetic data.

On Ringvassøy, basement tonalite gneiss has U–Pb zircon crystallisation ages of 2.84–2.82 Ga, similar to U–Pb zircon ages of 2.85–2.83 Ga for metavolcanics in the overlying Ringvassøy Greenstone Belt (RGB). Massive mafic dykes cutting the basement have U–Pb zircon and baddelyite ages of 2.40 Ga, with a titanite age of 1.77 Ga interpreted as a metamorphic overprint. In one newly mapped location, the same dykes are observed to occur in the RGB but are displaced along the contact to the basement.

The main ductile foliation ( $S_1$ ) in the basement and RGB is cut by the assumed 2.4 Ga dykes. This would place the  $D_1$  event in the period 2.8–2.4 Ga. The presence of a small 2.7 Ga alkaline stock in another part of Ringvassøy may further constrain the upper age of  $D_1$ .

The assumed 2.4 Ga dykes are cut by  $S_1$ -parallel dextral shears ( $S_2$ ).  $S_2$  is in turn cut at a high angle by a set of steeply dipping sinistral shears ( $S_3$ ) occupied by ultramafic dykes 2–3 m wide.  $S_3$  shears seem to refract where they cross  $S_2$ . The relationship of the ultramafic dykes to  $S_3$  is uncertain: they could be pre- $D_3$  dykes exploited by  $D_3$  shearing; or syn- $D_3$  intrusions from an ultramafic source at depth.

Age determinations of samples from the map area have been unsuccessful. However,  $D_1$  evidently predates the assumed 2.4 Ga dykes and occurred within the Neoarchaean to earliest Palaeoproterozoic.  $D_2$  and  $D_3$  clearly postdate the assumed 2.4 Ga dykes and are separate events. At least one of them may be Svecofennian, given the interpreted metamorphic overprint at 1.77 Ga in mafic dykes in the basement further south on Ringvassøy.

## POSTER

### Mantle source of the 2.44-2.50 Ga mantle plume-related magmatism in the Fennoscandian Shield: evidence from Os, Nd and Sr isotope compositions of the Monchepluton and Kemi intrusions

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Wide-spread mafic-ultramafic magmatism occurring in the Fennoscandian Shield at 2.44-2.50 Ga is believed to be related to a mantle plume activity. Earlier work has revealed that most of the intrusions have negative  $\varepsilon_{\text{Nd}}$  values of about -1 to -2. One potential explanation is crustal contamination of magma derived from sublithospheric mantle, but another possibility is a metasomatized subcontinental lithospheric mantle. Because the two mantle sources show contrasting Os isotope signatures, we determined Os isotopic compositions of chromite separates from the Monchepluton and Kemi intrusions to constrain the mantle source of the magmatism.

Chromite separates in the Monchepluton show near chondritic  $\gamma_{Os}$ , similar to the Kemi main ore. The constant near chondritic  $\gamma_{Os}$  values, suggest that the magma was derived from a mantle plume source and that the Os isotope composition of the magma was not significantly changed by crustal contamination. On the other hand, some samples from the upper chromite seams of the Kemi intrusion, and most samples from the Koitelainen and Akanvaara intrusions have slightly elevated  $\gamma_{Os}$  values. Modelling of Os and Nd isotope suggests a plume mantle source followed by variable degrees of crustal contamination, also consistent with the slightly elevated Sr isotope composition.

## S5.3 Proterozoic orogens

### KEYNOTE

#### Paleoproterozoic collisional history of northern Fennoscandia

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Northern Fennoscandia is a collage of at least three Archean continental blocks: Kola/Murmansk, Karelia and Norrbotten. The Kola-Karelia collision produced the Lapland-Kola orogen where the most conspicuous component is the Lapland granulite belt, formed during the SW thrusting (D1a) at  $\geq 1.91$  Ga. Nearly simultaneously a collision between the Norrbotten and Karelia continental blocks is seen as an east vergent thrusting (D1b) where both the Kittilä allochthon and the Martimo belt show thin-skin style thrusting whereas the Central Lapland aulacogen probably evidenced more thick-skin style deformation. The collision vectors rotated anticlockwise towards the NE in central Fennoscandia and caused orogen parallel shortening towards N (D2) and a partial basin inversion in the Central Lapland aulacogen at 1.89-1.88 Ga.

Major accretion and collision stage between 1.88-1.87 Ga in the southern and central part of Fennoscandia is seen in the SW-NE shortening (D3) phase in northern Fennoscandia. The effects of this shortening are strongly partitioned and localized, and are often seen as composite structures (D2/D3). The effects of proposed buckling around 1.87-1.86 Ga, forming the Bothnian oroclines in central Fennoscandia and an orocline in the NW part of Fennoscandia, are not clear but the 1.87-1.85 Ga extension associated with migmatization and magmatism in northern Fennoscandia are tentatively linked to the buckling.

The extension-related subhorizontal structures in the Central Lapland aulacogen were folded (D4) due to NW-SE shortening at 1.85-1.81 Ga. This folding and associated NW and SE doubly vergent reverse faults are also seen in other parts of northern Fennoscandia. This event can be linked either to strong shortening occurred in southern Finland at ca. 1.83-1.82 Ga and/or to an unknown collision event (e.g., Nagssugtoqidian orogeny in Greenland).

A continued NE-SW near-orthogonal shortening (D5) with increasing transpressive component

at 1.80-1.76 Ga is a dominant feature in the NW part of northern Fennoscandia, along the Norrbotten-Karelia boundary and in the Central Lapland aulacogen. The D5 deformation as a whole is seen as a strong 1.79-.77 Ga tectono-metamorphic event in northern Fennoscandia. We attribute D5 either to a major continent-continent collision or an advancing accretionary orogen (Andean-type) with retro-arc fold and thrust belts.

### ORAL

#### Gravitational Spreading of the Central Part of the Svecofennian Orogen

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The central part of the Paleoproterozoic Svecofennian orogen formed in arc-collision at 1.91 Ga. The collision led to crustal thickening and partial melting of the crust. The partial melting formed a large batholith (Central Finland granitoid complex; CFGC) at the upper-middle crustal transition zone and a weak middle crust, which enabled crustal scale gravitational spreading in the central part of the orogen.

It is used analog modeling, geophysical data, geochronology, geochemistry and field observations to study 1) existence, and duration, timing and amount of gravitational in the central part of the Svecofennian orogen, 2) formation and deformation of crustal scale structures, and the CFGC during gravitational spreading, 3) explanations for the stabilized, but thick crust in the area.

1) The analog models are proposing that crustal scale structures, which earlier are connected to shortening, may also be explained by westward gravitational spreading. The duration of gravitational spreading of 45-50 % may be varying between 16 and 23 my depending on the amount of the reactivated weakness zones. The age results are proposing the start of the gravitational spreading at ca.1884 Ma and duration between 9 and 24 my in the CFGC, and the analog models are proposing up to 50 % of spreading. 2) The exhumation is explained by the gravitational spreading, which has reactivated and rotated the large scale weakness zones such as terrane and arc boundaries in the area, and have uplifted, rotated and subsided crustal scale

blocks. The deformation can be detected as changes in the metamorphic grade, in the texture or in the structure at the exposure level, or as changes at the Moho depth. The resulted deformation pattern is dependent on the mechanical properties of the crust. The deformation degree is not following the emplacement ages and all rock types is having both deformed and undeformed varieties in the CFGC. Hence the deformation degree cannot be used as a criterion for rock classification, but are reflecting the exhumation of the rocks. 3) The analog models suggest that the Paleoproterozoic and the Archean side have thinned up to 20 % and 10 %, respectively. This can explain the remained thick crust in the central Svecofennian orogen.

ORAL

**The Central Russian fold belt:  
Paleoproterozoic boundary of  
Fennoscandia and Volgo-Sarmatia, the  
East European Craton**

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The Central Russian Fold Belt (CRFB) is a large Paleoproterozoic mobile belt in the central part of the East European Craton [1]. The belt is covered by a thick sequence of platform sediments. We report the results of interpretation of geophysical data, and of petrographic, geochemical, isotopic and geochronological studies of core samples from 25 deep boreholes.

The southern part of CRFB consists of Paleoproterozoic (~2.0 Ga) juvenile volcano-sedimentary rocks and various granitoids with island arcs affinities. These rocks are similar in age and composition with the adjacent Osnitsk-Mikashovich belt, and as the latter, it were probably formed in an active margin setting on the edge of the Volgo-Sarmatia megablock.

The northern part of CRFB consists of the Archean (3.2 to 2.7 Ga) gneisses and granitoids and numerous ca. 2.5 Ga intrusions of high-Ti monzodiorites and metagabbro. These intrusions have geochemical and isotope features typical of Phanerozoic LIPs, particularly of the Parana province [2],

and it could be considered as an indicative for a passive margin of the Fennoscandian megablock.

The boundary of these two domains is marked by a wide mylonite zone of granulite facies rocks that could be a result of collision of the Fennoscandia and Volgo-Sarmatia megablocks at 1.8- 1.7 Ga.

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ORAL

**The Precambrian crust in the Baltic Sea region**

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The Precambrian crust under the Baltic Sea represents the southeastern extension of the Fennoscandian Shield, covered by Phanerozoic sedimentary rocks up to 1.5 km thick. Sundblad et al. (2003) recognized a shift from 1.89-1.90 Ga Svecofennian crust in north and central Gotland to 1.77-1.81 Ga Transscandinavian Igneous Belt (TIB) granitoids at Kvarne on southernmost Gotland, as well as 1.49 Ga igneous activity at Grötlingbo, southern Gotland.

In this study, K-feldspar Pb-Pb isotopic results from a number of Precambrian units at 15 drill sites (mostly percussion drilling) on Gotland and adjacent offshore regions are reported, along with a U-Pb zircon age from a granitoid in an offshore drill core from Latvia. We acknowledge the Geological Surveys of Sweden and Latvia for providing access to the study material.

The least radiogenic Pb isotope signature of each sample revealed four distinct populations. Deformed granitoids east of Gotland have <sup>206</sup>Pb/<sup>204</sup>Pb ratios as low as 15.77, comparable with the Svecofennian ore lead signature of Bergslagen, Sweden. This implies the presence of Svecofennian crust beneath the Baltic Sea 100 km west of the Latvian coast. The <sup>206</sup>Pb/<sup>204</sup>Pb ratios from the Kvarne granite are as low as 15.81, nearly identical to the

ore lead composition of TIB in the adjacent Vimmerby Batholith. This confirms the presence of TIB granitoids on the southernmost tip of Gotland.  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios of  $\sim 16.45$  were recognized at several sites on southern Gotland and adjacent offshore regions, among them the 1.49 Ga Grötlingbo granite. Very high  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios ( $> 25$ ) were recognized in a granitoid immediately adjacent to a fracture zone in offshore Latvia. This likely reflects Caledonian reactivation of the U-Pb system in a TIB granite.

The granitoid from offshore Latvia yielded a U-Pb zircon age of  $1764 \pm 7$  Ma, which is only marginally younger than the TIB granitoids in the Växjö region, Sweden. This age, along with drill core observations from Öland and offshore Poland, may imply that TIB granitoids occur in vast areas in the southern part of the Baltic Sea.

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ORAL

### The Danopolonian orogeny: rotation of Baltica between 1.55 and 1.40 Ga

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Major deformation, intracontinental magmatism and sedimentation, together named the Danopolonian orogeny (Bogdanova, 2001) affected the central part of Baltica/the East European Craton between ca. 1.55 and 1.40 Ga. These processes were accommodated within EW-trending belts superimposed on the Paleoproterozoic tectonic grain and along pre-existing NW zones of deformation. The Danopolonian events were semi-simultaneous with the Telemarkian (1.52-1.48 Ga) and Hallandian (1.47-1.38 Ga) events of accretionary orogeny along the western margin of Baltica. In the east, however, sedimentation and magmatism occurred during rifting of the crust and formation of aulacogens (Bogdanova et al. 2008). Such differences convincingly suggest that rotation of the craton during plate reorganization controlled its overall tectonic settings, which is also confirmed by paleomagnetic reconstructions for the concerned period (Pisarevsky et al. 2014).

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ORAL

### Tracing Proterozoic mantle Hf-isotope depletion through coupled zircon U–Pb and Lu–Hf isotopes

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In calculating mantle extraction ages, and when constructing crustal growth models, a linear evolution of incompatible trace elements in a depleted mantle since  $>4$  Ga is routinely used. Mantle depletion may however vary regionally and over time, and  $>100$  Myr residence times for crustal precursors are common in the literature. Subduction of sediments and crust leads to a mantle-wedge that is enriched relative to normally depleted mantle.

Here we propose that use of coupled zircon U–Pb and Lu–Hf isotopes from primitive syn-orogenic intrusions can provide better constraints of the temporal shifts in mantle depletion in a convergent orogen. Interpolation of Paleoproterozoic gabbro suites from Fennoscandia enables the construction of a regional mantle evolution curve, providing improved constraints on model ages, crustal residence times and the fraction of juvenile versus reworked continental crust. Convergent margins are assumed to be one of the main sites of continental crust growth, and using an overly depleted mantle source yield model ages that are too old and hence cumulative crustal growth models show too much crust generation early in the Earth's history.

ORAL

### 1.90-1.88 Ga magmatism in central Fennoscandia: geochemical and Sm-Nd isotopic data from southern Finland

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The earliest Svecofennian magmatism in southern Finland has been dated at 1.90-1.88 Ga. In this study we present whole rock geochemical data and Sm-Nd isotope data from two magmatic centres in southwestern Finland; the Orijärvi (c. 1.90 Ga) and Enklinge (c. 1.88 Ga) areas. They comprise plutonic centres surrounded by volcanic rocks of comparable ages and chemical compositions. Both of them show very well-preserved primary structures in lower metamorphic grade, compared to other volcanic areas in southern Finland, which helps us to understand the nature of the oldest magmatism in southern Finland.

Compositionally the studied rocks range from gabbros to granites and they show clear volcanic arc affinities. The cogenetic relationship between the intrusive and extrusive rocks is emphasised by overlapping U-Pb zircon ages and Sm-Nd isotope compositions. The initial  $\epsilon_{\text{Nd}}$  values from the mafic rocks from both locations, with one exception, fall in the range +1 to +3. The felsic rocks have initial  $\epsilon_{\text{Nd}}$  values around 0 to +1. This suggests a larger inherited crustal component in the felsic rocks compared to the mafic ones. The mafic magmas may derive from a mildly depleted mantle and the felsic magmas, at least partly, from older Palaeoproterozoic crust.

ORAL

### Is mafic magmatism a heat source for the high temperature metamorphism in southern Finland?

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The bedrock in southern Finland was affected by high temperature/low pressure metamorphism (c. 600-800 °C/4-6 bars) late in the orogeny causing wide-spread crustal melting. Heat source for this is controversial. Previously, mafic intraplate or underplating was suggested as heat sources. Lately, Kukkonen and Lauri (2009) suggested that crustal thickening and radioactive decay of the earlier formed rocks led to crustal melting during the lateorogenic stage. Väisänen et al. (2012) emphasised the role of mafic magmatism in transferring external heat from the mantle to the crust. Stephens and Andersson (2015) proposed that mafic underplating was responsible for the two-stage metamorphism in SE Sweden.

There are quite new evidences, published and unpublished, which show that the crust was intruded by mafic magmas before and during the high-grade metamorphism at 1.85-1.81 Ga. Although the number of the so far discovered mafic intrusions and their areal extent are quite low, they nevertheless inevitably show that mantle-crust interaction took place at the time. It is probable that more of these intrusions will be found in the future. A hypothesis is that mantle-derived mafic magmatism, combined with ubiquitous radioactive decay, incrementally increased the crustal temperatures high enough to cause wide-spread melting and formation of migmatites and granites during the lateorogenic stage. In summary, according to the present model, all the here cited models are in part responsible for the high metamorphic temperatures.

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## ORAL

## News of the Mauri sandstones

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The amphibolite facies Mauri succession, subdivided in ascending order to sandstones (ca. 2 km), felsic volcanic rocks (ca. 5 m) and mudstones (< 500 m), was deposited earliest at ca. 1.88 Ga. It belongs to the youngest supracrustal part of the ca. 1.9 Ga Tampere Schist Belt, in which most of the volcanogenic rocks show arc affinities.

Field observations and reprocessed GSF aeromagnetic map support an interpretation that the Mauri succession is folded in a pair of asymmetric F<sub>1</sub> synclines-anticlines with an E-W trending sub-horizontal fold axis and subvertical axial surface; these structures were deformed by a prominent F<sub>2</sub> dextral folding with a ca. SW-NE subvertical axial surface.

The rocks of the sandstone unit contain ca. 20 % polycrystalline pseudomorphs after euhedral phenocrysts/-clasts of quartz but are dominated by felsic fine- and even-grained as well as porphyritic clasts of evident volcanic origin. A minor component is granitic.

The lower part of the sandstone unit is fine grained and characterized by parallel lamination and low-angle cross-bedding. The grain size increases successively upwards and trough cross-bedding, commonly bipolar, as well as hummocky cross-bedding become prominent. A few thin, pebbly, bedding parallel lags are observed in the uppermost 100 m of the sandstone unit. The ca. 5 m thick felsic volcanic unit resting on the sandstone unit is composed of volcanoclastic sandstones and mudstones, which in part show cross-bedding and erosional bases. The mudstone unit overlying the former is characterized by parallel lamination, normal grading and occasional hummocky cross-bedding. The sandstone unit was deposited in a wave-dominated, tidal shallow sea, whereas the mudstone unit was deposited below the contemporaneous fair-weather wave base.

Geochemical analogs suggest that the main sources of the sandstone unit were formed during

temporary rifting of a volcanic arc. It is probable that the Mauri succession sedimentation was partly driven by tectonic faulting combined with erosional dissection of volcanoes.

## POSTER

## Sveconorwegian albitites, Bamble Sector, S-Norway – new U/Pb geochronological and stable O-isotopic data

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Na-metasomatism causing albitisation was regionally extensive in the Precambrian crust of southern Norway, particularly in the Bamble Sector. The albitites have been studied in detail in the region around the city of Kragerø. The occurrences have been described as megascale Cpx-Ttn-bearing albitite, albitisation along veins, breccias, albitic felsites and albite-carbonate deposits.

U-Pb geochronology of Cpx-Ttn-bearing albitite shows zircon data partly reset but pointing to upper intercept ages reflecting an origin of the rocks in the period 1250-1300 Ma. The minerals titanite, monazite and rutile reflect transformation stages: Titanite ages are in the range 1102 ±2 to 1093 ±2 Ma. The oldest monazite age is 1101 ±3, while a younger age shows 1079 ±4 Ma. Rutile is moderately discordant and reflects ages in the range 1094-1085 Ma. The whole alteration mineralogy seems to have developed in pulses over a period of about 20 m.y.

Stable O-isotopic analyses, on a variety of albititic rocks, give  $\delta^{18}\text{O}_{\text{SMOW}} = 5.1\text{-}8.4$  for albite originating from mafic protoliths, and  $\delta^{18}\text{O}_{\text{SMOW}} = 8.5\text{-}11.1$  for albite in albitite of tonalitic origin. The results exclude a meteoric fluid, and overlap with primary values indicated by the protoliths. A large amount of fluids is necessary to change O-isotopic values, the spread in reported values could be explained by influx of seawater.

The spread in both the U-Pb geochronological data and the O-isotopic data supports earlier interpretation of fluid control on the formation of albitite in the Kragerø area. The mineral replacement reactions illustrate fluid transport by a H<sub>2</sub>O-CO<sub>2</sub> fluid

rich in Na. We document that the albitisation as reflected in the Cpx-Ttn-bearing albitite occurred in the final stages of the tectonometamorphic Arendal phase of the Sveconorwegian event in the Bamble Sector, although overprints by younger lower-grade replacement processes are not excluded.

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**POSTER**
**U-Pb SIMS dating of granitoids from eastern Blekinge, southern Sweden**

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Zircons from seven granitoids in eastern Blekinge, previously dated by conventional multi-grain thermal ionization mass spectrometry (TIMS) to in most cases rather imprecise ages between 1.78 and 1.65 Ga (Kornfält 1993, 1996), have been redated using secondary ion mass spectrometry (SIMS) spot analysis. The analyzed rocks include one Småland granitoid from north of the Småland-Blekinge Deformation Zone (SBDZ), and six "Småland-type" granitoids from within the Tving granitoid area south of that zone: two samples of megacrystic "Filipstad-type" granite, one sample of the medium-grained Rödeby granite, and one sample each of the fine- to medium-grained, leucocratic and in part strongly foliated Almö, Tjurkö and Jämjö granites. The results yield a crystallization age of  $1776 \pm 6$  Ma for the Småland granitoid north of the SBDZ, in agreement with the previously obtained TIMS age, and magmatic crystallization ages between  $1770 \pm 4$  and  $1758 \pm 6$  Ma for the other granitoids, in most cases substantially older than previous TIMS ages. These data show that the "Småland-type" granitoids in eastern Blekinge are similar in age to the surrounding Tving granitoids (Johansson & Larsen 1989; Johansson et al. 2006), and the more felsic of them may represent late-stage differentiates belonging to the same magmatic suite. As the Tving granitoids show differences, not only in degree of deformation, but also in geochemistry (Lindh et al. 2001; Kornfält & Bruun 2002) and possibly in age, when compared with the Småland granitoids north of the SBDZ, it is suggested that these represent two separate but closely related igneous suites, which could both be included within a TIB-1 supersuite.

The investigated zircons showed very limited signs of metamorphic overgrowths, and no metamorphic ages could be determined. However, the combined evidence from field observations combined with earlier U-Pb geochronology (Johansson et al. 2006) would suggest the presence of two separate metamorphic episodes in Blekinge, one in close connection with the formation of these rocks at 1.76 – 1.75 Ga, and one connected to the intrusion of the Karlshamn granitoid suite at around 1.45 Ga.

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**POSTER**
**Titanite and zircon U-Pb ages from West Uusimaa complex, Finland, and implications to titanite geochronology**

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Five pyroxene granulites from extensional shear zones within West Uusimaa Complex (WUC), and a mylonite sample from the lower-grade, mostly strike-slip Karkkila-Somero shear zone (KSSZ) were dated with titanite and zircon. The peak metamorphic conditions in the WUC are c. 700-825°C and 3-5 kbar. The PT conditions of the mylonitic phase of the KSSZ are undetermined but are approximately in the lower amphibolite facies. All of the samples with zircon in them show a large spread of inherited ages, mainly Paleoproterozoic (ca. 2.0-1.9 Ga) but also a prominent Archean component. Generally, this corresponds to the age distribution in Svecofennian detrital zircon suggesting that all samples are of predominantly sedimentary origin.

The zircon ages tend to have two maxima, one at an older, early Svecofennian (~1.9 Ga) range (zircon cores) and a younger one at 1825-1805 Ma (zircon rims). The younger ages are interpreted to rep-



resent metamorphic growth at the time of deformation along the shear zones. Titanite yields slightly older ages than the younger zircon rims in the three samples that are from extensional shear zones. This is somewhat surprising as titanite is usually considered to be a more reactive mineral compared to zircon, and in our samples displays euhedral, metamorphic crystal habit. However, a SEM examination reveals that the titanites are often somewhat heterogeneous, probably due to deformation and/or prograde metamorphism: the titanites seem to have retained older material and, although heterogeneous parts were avoided in the age determinations, the ages of these titanites are probably mixed ages. The implication is that titanites may not re-equilibrate as completely and fast during deformation and metamorphism as often assumed. It is uncertain whether this is a common phenomenon, but the high Ca-content of the host rock may be important. A routine SEM or similar microanalytical investigation of titanites should perhaps be undertaken in all geochronological studies using titanite, in order to recognise inherited material.

## POSTER

### New bedrock geological map and database of Finland 1:1 000 000

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The new geological map of Finland in the scale 1:1 million is a printed map that is delivered together with a new 1:1 million bedrock database.

The printed map shows rock associations and their tectonic environments as well as structures and dyke swarms. The legend is based on a tectonic interpretation. It is designed to show large lithospheric units – tectonic provinces – and amalgamation of these provinces to form a continental crust at 1.9 Ga. A Guide book includes description of the tectonic provinces and their boundaries, as well as a plate tectonic model that spans from Neoproterozoic to Quaternary. The model focuses on Paleoproterozoic events: rifting of the Archean crust, opening of oceanic basins, and closing of the oceans during collisions.

The database includes information of each rock association like age, stratigraphy and tectonic setting. Thus the database serves as a tool for several different map interpretations.

## POSTER

### 1.86 Ga granites in the Salo area, SW Finland

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The Svecofennian bedrock in the Salo area in SW Finland comprises granitoids and migmatized metasedimentary and metavolcanic rocks, metamorphosed in higher amphibolite and granulite facies conditions. The area is characterised by sub-horizontal structures in large areas. We performed U-Pb zircon and monazite age determinations on two granites using the single-grain LA-MC-ICP-MS method.

One of the homogenous leucogranites, intruded into the subhorizontal structures, yielded a zircon age of c. 1.86 Ga. A younger c. 1.83 Ga age is interpreted as a metamorphic overprint. The sample also contained inherited zircons of various Palaeoproterozoic and Archaean ages. The monazites of the same sample showed two populations: c. 1.85 Ga and 1.81 Ga. At least the latter is interpreted as a metamorphic age. The other sample, a porphyritic granite, yielded an age of approximately 1.86-1.85 Ga. Monazite was not detected in this sample.

The 1.86-1.85 Ga granitoids are younger than those regarded as typical synorogenic Svecofennian ones but older than the voluminous late-orogenic granites related to high metamorphic temperatures. Although so far rarely described in Finland, they are common in the Ljusdal area in Central Sweden (Högdahl et al. 2008). Coeval mafic enclaves in the granites indicate a contemporaneous mantle activity and a possible heat source for the melting for which a middle crust source has been suggested (Väisänen et al. 2012). The inherited zircons imply that the magmas to some extent have a sedimentary origin. Future work will further examine this topic through in-situ Lu-Hf analyses on zircon.

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## POSTER

### Remnants of pre 1650 Ma sediments in the Western Gneiss Complex, Norway

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The Western Gneiss Complex in south-western Norway are dominated by Proterozoic orthogneisses, which formed during three main episodes of magmatic activity: two "Gothian" episodes at 1600-1650 Ma and 1490-1520 Ma and a Sveconorwegian episode at 950-990 Ma (Skår, 2014). Sedimentary rocks, on the other hand, are scarce. The western parts of the WGC was later heavily deformed and metamorphosed during the Caledonian Orogeny, whereas in the east the Proterozoic rocks are more preserved.

This study, still in its early stages, focus detrital zircon age data from three sedimentary units in the WGC. These units occur in two different settings: a) as slivers embedded within the Proterozoic basement, and b) within the late Caledonian Nordfjord Sogn Detachment Zone (NSDZ). A quartzite sampled from the lower parts of the NSDZ yield a detrital zircon age distribution very similar to the age distribution of the WGC itself. We interpret these sediments as either a part of the Middle Allochthon or the Neoproterozoic sedimentary cover of the WGC that was brought down along the NSDZ. The sediments placed within the autochthonous part of the WGC yield very different age distributions. One, from the inner part of the Sognefjord area yield a distribution which is grossly similar to what is found elsewhere in southern Norway, south of the Caledonian nappes. Another sample is from further west within the area affected by Caledonian HP-metamorphism. This rock is either folded into- or form a xenolith in a 1650 Ma granite. The age of detrital zircon ages in this rock is exclusively between 1730 and 2900 Ma. This age range is more typical of the Svecofennian domain in the eastern-north eastern part of Scandinavia, and we suggest these rocks are slivers of svecofennia-derived sediment into which the surrounding 1650 Ma granites

intruded. The detrital zircon age distribution display similarities with the presumably oldest sediments in the Telemark sector of southern Norway, suggesting a link.

## References:

Skår, Ø. 2014. 31<sup>st</sup> Nordic Geological Winter Meeting, Abstract volume, p. 96

## POSTER

### The 1.83-1.80 Ga volcano sedimentary sequence in southern Lithuania: origin, evolution and correlation with south-central Sweden

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The concealed crystalline crust in the SW East European Craton consists of several domains younging towards present south. Remnants of the c.1.83 Ga volcano-sedimentary sequence are preserved among the 1.86-1.84 Ga magmatic rocks in south-central and southern Lithuania.

The sequence is mainly composed of metamorphosed peraluminous tholeiitic rhyolites and calc-alkaline andesitic volcanics, interlayered with silica-clastic and carbonate sediments, crosscut by pegmatitic granite and quartz veins. The U-Pb zircon ages of c. 1.83 Ga and c. 1.79 Ga from a felsic metavolcanic rock are interpreted to indicate a major volcanic event and a later volcanic contribution respectively. Sm-Nd isotopic data from the same rock yielded TDM = 2.08 Ga age and  $\epsilon_{\text{Nd}}$  (1.83) +1.02. The rocks have experienced amphibolite facies thermal metamorphism of 650°-570° C and 4.5 kbar at 1.53-1.50 Ga as was implied from the EPMA chemical dating of monazites. Redox conditions were estimated using the magnetite-ilmenite geothermobarometry (Lindsley and Spencer, 1982), which yielded 405° C temperature and -35 log( $f_{\text{O}_2}$ ) oxygen fugacity.

The available geochemical data, positive  $\epsilon_{\text{Nd}}$  values and a narrow range of zircon population are in a favour of the depleted mantle source for a considerable part of the magma. We assume that the metamorphism was caused by an intrusion of nearby 1.53-1.50 Ga AMCG Mazury complex which was

also a major source of metasomatising fluids. During the subsequent cooling, rocks have been exposed to hydrothermal alteration, causing a nucleation of Fe-Cu sulfides. The available data suggests that some small isolated back-arc basins might have existed in southern Lithuania likely contemporaneous with the Oskarshamn-Jonköping belt and Vetlanda supergroup in south-central Sweden (Mansfeld et al., 2005 etc).

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Mansfeld J., Beunk F. F., Barling J., 2005. 1.83 – 1.82 Ga formation of a juvenile volcanic arc – implications from U-Pb and Sm-Nd analyses of the Oskarshamn – Jönköping Belt, Southeastern Sweden. *GFF* 127, 149 – 157.

#### POSTER

### Trans-Baltic Palaeoproterozoic correlations as a key to the Svecofennian orogeny

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The Palaeoproterozoic Svecofennides in the Baltic Shield correlates well with their unexposed counterparts across the Southern Baltic Sea. Apart from the effects of some microcontinents and oroclinal, they feature 100 to 300 km wide tectonic domains and belts younging SSW. Major disturbance was caused by the collision of Fennoscandia with Volgo-Sarmatia at 1.82-1.80 Ga followed by the formation of the Andean-type Transscandinavian Igneous belt (1.81-1.76 Ga). We also find that the Svecofennian orogen was not a part of the westward Laurentia-Baltica margin of supercontinent Columbia/Nuna but older than that 1.7-1.2 Ga accretionary margin.

## S5.4 Challenges in isotope dating of Precambrian terrains

### KEYNOTE

#### Isotope dating from a Nordic perspective – past, present and some thoughts about the future

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The first absolute ages of rocks and minerals from the Nordic countries, based on isotope analysis of radiogenic isotopes and their daughter products, were published more than 50 years ago. Since then, we have seen a dramatic development in the use of natural isotope variations not only as geological clocks, for determination of the ages of rocks and metamorphic events, but also as e.g. petrogenetic tracers in the study of various aspects of crustal evolution. Today isotope analysis is an integral and indispensable tool within many fields of geoscience, and advances in analytical techniques combined with developments in our understanding of the systematics of an increasing number of isotope systems continue to open up for new applications.

In this contribution I will present my personal view on this remarkable development and its impact on geoscience in the Nordic countries. Main focus will be on the study of the complex crustal history of the Fennoscandian Shield, based primarily on long-lived radiogenic isotopes and illustrated by a number of case studies. Contributions by both early pioneers and some more modern followers will be presented, and the crucial importance of micro-analytical techniques for scientific progress will be highlighted.

### ORAL

#### Re-Os and U-Pb geochronology –complementary systems

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Re-Os geochronology offers an alternative to U-Pb dating in Precambrian terrains, not as a replacement, not better or worse, but as a complement. U-Pb geochronology has the advantage of the dual decay schemes of <sup>235</sup>U and <sup>238</sup>U, providing an internal check on concordance. Geologic significance of Re-Os ages can be assessed by analysing multiple samples from the same geologic occurrence. Both U-Pb and Re-Os systems offer single-mineral chronometers: zircon, titanite, and others for U-Pb, and molybdenite for Re-Os. Molybdenite has proven highly robust in the absence of extreme oxidation producing ferrimolybdenite, and surviving metamorphic conditions up to osumilite grade.

Spot analyses of zircon reveal temporal zoning, exposing multiple events in a single grain. In some cases, however, unusual age distributions suggest internal redistribution of daughter and/or parent. Spot analyses are not feasible for molybdenite chronology because the daughter Os isotope is readily mobilized within the crystal and thereby spatially decoupled from its parent Re. Still, because neither Re nor Os are soluble in reducing fluids and neither has a home in non-sulphide phases, the molybdenite crystal is a resilient time capsule. Zoning has been observed in a rare case, but is generally recognizable in polished thin section.

Re-Os depositional ages can also be determined from syn-sedimentary sulphides or organic matter in organic-rich sedimentary rocks. This offers another geochronological method in those Precambrian systems for which U-Pb dating opportunities are sparse. The Re-Os isochron ages will inevitably appear less precise than related U-Pb ages. To the non-expert, lower precision is taken as a measure of quality, with more precise ages assumed to be 'better' and (most likely) more accurate. In part, this is because the <sup>187</sup>Re decay constant, derived from U-Pb chronology, carries an uncertainty of 0.31% that must be propagated with other errors. More importantly, the reported precisions for Re-Os and U-Pb

ages are mathematically different statistics, are generated from markedly different numbers of analyses, may reflect very different culling of data, and may neglect decay constant uncertainties. These differences, and potential inaccuracies that may exceed reported uncertainties, should be communicated fully in any comparison of age results.

ORAL

### Dating the hidden Archaean bedrock of Kimberley South Africa

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We mapped and sampled Archaean granitoids and mafic greenschists exposed in the 750-850m deep bedrock of Kimberley mines. The granitoids are mainly trondhjemites and tonalites (TTG). We dated zircon and monazite by laser ablation ICP quadrupole mass spectrometry.

The mafic sample we investigated is a greenschist facies metamorphic basaltic komatiite. It contains scarce zircons which proved to be a single near-concordant population with weighted mean Pb-Pb age of  $2916 \pm 22$  Ma, supported by a Th-Pb age of  $2917 \pm 73$  Ma. Considering the whole rock concentrations of only 10 ppm Zr and 52% silica, these scarce zircons are most likely xenocrysts. The age either represents that of the country rock through which the magma extruded, or more likely reflects resetting of older xenocrysts within the hot komatiitic basalt magma.

We zircon-dated this  $2956 \pm 24$  Ma tonalite cut by  $1993 \pm 24$  Ma pale granitic veins. They both also contained monazite, yielding  $2856 \pm 21$  Ma and  $1043 \pm 42$  Ma respectively. The 1993 Ma age reflects previously unknown granite generation due to the massive 2 Ga Bushveld (or Vredefort?) thermal event which affected the Kaapvaal Craton. The monazite ages each reflect the first metamorphic event to which their host rocks were exposed. The 1200-1000 Ma Namaqua-Natal Orogeny clearly caused the 1043 Ma metamorphism in the Kaapvaal Craton, also evidenced by an imprecise  $1180 \pm 440$  Ma granitic zircon lead-loss event

We have identified the oldest crust-forming event in the Kimberley Block at 3280 Ma, represented by one trondhjemite magmatic age and a group of xenocrysts. Development of a substantial granite-greenstone terrane is reflected by seven dates covering 150 Ma of magmatic activity between 3019 and 2856 Ma, probably due to subduction with TTG generation, terminated by terrane collision between the Kimberley and Witwatersrand blocks of the Kaapvaal Craton.



Figure 1

ORAL

### A new U-Pb baddeleyite age for the Ottfjället dolerite dyke swarm in the Scandinavian Caledonides – a minimum age for late Neoproterozoic glaciation in Baltica

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Emplacement of the Ottfjället mafic dyke swarm in the Swedish Caledonides has been related to the break-up of Rodinia and opening of the Iapetus ocean. The swarm represents part of the Baltoscandian Large Igneous Province, which has provided radiometric ages in the range of 605 to 665 Ma, including an Ar-Ar age on the Ottfjället dykes themselves. In Härjedalen and Jämtland, the Ottfjället dykes intrude the Tossåsfjället Group of the Särvi Nappes, which host glacial deposits of Neoproterozoic age. No fossils are found from the under- and overlying clastic units for a reliable age estimate for these glacial deposits. In order to constrain a minimum age for Neoproterozoic glaciation

in Baltica, a coarse-grained dyke of the Ottfjället swarm was sampled from Häckelåsen in Härjedalen for U-Pb dating. Fine-grained baddeleyite from this sample is mostly near-concordant and define an emplacement and igneous crystallization age at 596 Ma.

This age determination, together with U-Pb ages for the Egersund dykes ( $616 \pm 3$  Ma; Bingen et al. 2005), and Sarek dykes of the Svea Nappes ( $608 \pm 1$  Ma; Svenningsen, 1994) may reflect a protracted 15-25 m.y. interval of extension and Laurentia-Baltica breakup. The Ottfjället mafic dyke age directly overlaps that of the dominantly basaltic Tayvallich volcanic complex of Scotland ( $595 \pm 4$  Ma, U-Pb zircon; Halliday et al., 1989), which likely erupted at the adjacent, conjugate Laurentian margin. All events likely record evolving early stages of an opening Iapetus ocean. The Ottfjället dyke age represents the first robust isotopic minimum age for late Neoproterozoic glaciation in Baltica.

## ORAL

### The Varangerian/Marinoan glaciation in Scandinavia – new age constraints

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Neoproterozoic glacial units in Scandinavia have been referred to the Varangerian glaciation. The Smalfjord and Mortensnes formations in E. Finnmark have recently been correlated with the worldwide Marinoan glaciation (635-650 Ma) and the local Gaskiers glaciation (580-590 Ma), respectively. Neoproterozoic glacial formations in the Caledonian nappe region have been correlated with the Mortensnes Fm in Finnmark and should be of Gaskiers age. However, the Lillfjället Fm in Härjedalen contains two glacial diamictite units separated by a >500 m thick sandstone and mudstone

unit; a stratigraphy similar to that in Varanger where the Nyborg Fm siltstone separates the Smalfjord and Mortensnes formations. Neoproterozoic glacial units in Scandinavia are floored with carbonate platform formations, lack cap dolomites, and are overlain by several hundred meters thick late Cryogenian (?) – Ediacaran fluvial to shallow-marine sandstones. In Härjedalen, this tripartite compound unit is cut by the Ottfjället dolerite dyke swarm. A U/Pb baddeleyite age of 596 Ma from an Ottfjället dyke (Kumpulainen et al. this volume) shows that the Lillfjället Fm was buried and cemented well before the dolerite dykes were emplaced; a Gaskiers age of glaciation is excluded. The Neoproterozoic glacial units of Scandinavia thus appear to correlate with the Marinoan glaciation, a supposed “Snowball Earth” event. The term Varangerian is still valid, covering the whole time interval from the first to the second glacial Neoproterozoic stratigraphic unit in Scandinavia, including interglacial sediments, as the Nyborg Fm in Finnmark and the unnamed sandstone-mudstone unit between the two major glacial diamictites of the Lillfjället Fm. The new age constraint and revised correlation is of crucial importance for the global Neoproterozoic glacial history.

## POSTER

### Precise U-Pb (ID-TIMS) and SHRIMP-II ages on single zircon and Nd-Sr signatures from Achaean TTG and high aluminum gneisses on the Fennoscandian Shield

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Ingosersky TTG complex are in the Central-Kola domain. New U-Pb data on single zircon from Bt-gneisses is  $3149 \pm 49$  Ma, metamorphic alterations were in  $2725.2 \pm 2.5$  Ma and reflect the origin of Amf-Bt gneisses with  $2733.6 \pm 6.6$  Ma. The very coeval isotope-geochemistry data have been obtained for rocks from greenstone belts from Finland (Huhma et al., 2012).

New U-Pb (ID-TIMS) data on single zircon from paragneisses near Murmansk in the Central-Kola domain gave 3.17 Ga. Core from these zircon population has the age  $3695 \pm 5$  Ma by SHRIMP-II and older about 100 Ma compared with paragneisses of Kola block according to (Myskova et al., 2015). Time of amphibolites metamorphism was dated with  $2753 \pm 3$  Ma.

Archaean gneisses in Monchegorsk ore region were firstly dated in the Central-Kola domain. Single zircon from gneisses in Monchegorsk region which are the basement for Paleoproterozoic PGE layered intrusions with U-Pb ages on zircon and baddeleyite from 2.4- to 2.5 Ga has 3.16 Ga. Single zircon from gneisses gave  $2776 \pm 3$  Ma and is considered as amphibolites metamorphism. Voche-Lambina international polygon lies on the boundary between Belomorian mobile block and Central-Kola domain (Morozova et al., 2012). New neorhaean U-Pb data on single zircon from TTG of polygon yielded  $3158.2 \pm 8.2$ . Zircon are characterized by low concentration U and Pb, low U/Th ratio with 0.2. REE diagrams of grey gneisses reflect high fractionation  $\text{La/Yb} > 30$ , enriched by light REE and depleted by heavy  $\text{Yb} < 0.6$  ppm. Model Sm-Nd ages on the rocks have protolith from with the ages 3.4 to 3.2 Ga, positive  $\epsilon_{\text{Nd}}$  from +1.29 to +3.3, ISr equals 0.702. Precise (ID-TIMS) age of amphibolites metamorphism has been dated on single zircon with  $2704.3 \pm 5.9$  Ma.

Therefore based on the new data on single zircon from TTG and high aluminum gneisses from Central-Kola domain leads to the long history of continental crust origin in the Baltic or Fennoscandian Shield from 3.16 to 3.7 Ga.

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## S6.1 Marine geology

ORAL

### Marine base maps: Making seabed sediment mapping relevant for all

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The majority of Norway's inhabitants live at or near the coast. The coastal zone accommodates a variety of economically important activities such as fisheries, aquaculture, tourism and industrial enterprises. With more and more interests competing for space, the need for marine spatial planning grows urgent. In most areas, however, decision-makers will not have access to detailed knowledge of seabed properties and other conditions of importance for the marine environment. Spatial planning consequently has to be carried out with little consideration of marine diversity, a fact that may lead to poorer management of coastal areas.

The Geological Survey of Norway (NGU) aims to provide much-needed knowledge of the seabed's spatial variation for managers and other interested parties alike. In cooperation with local and regional administration and with the Norwegian Mapping Authority, NGU produces *marine base maps* at large scales (1:10 000 to 1:50 000) based on multi-beam echosounder data, video observations, physical sediment sampling and acoustic profiling. A set of base maps will generally include seabed topography, acoustic backscatter, interpreted seabed sediment distribution and derived thematic maps of e.g. slope, anchoring conditions, trenching properties (diggability) and sediment accumulation areas. The intention is to convey relevant geological information in a format accessible to end-users outside the geological community, and upon completion of a mapping project all results are made publicly available online. Marine base maps can be used directly for management or other purposes, or they can form basis for further research. Examples of additions to a set of base maps through multidisciplinary collaboration include pollution status, current and temperature regimes and benthic habitats.

At present, NGU carries out the production of marine base maps through a series of discontinuous local- to regional-scale projects. Completed projects have proven to be cost-effective and beneficial for local communities, and have been met with

much enthusiasm. NGU and the Norwegian Mapping Authority now propose a national programme (MAGIN) dedicated to mapping bathymetry and seabed properties along Norway's entire coast, starting in 2017.

ORAL

### Large scale seafloor classification based on sediment quality guidelines

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Thorough maritime spatial planning requires proper knowledge of the seafloor. When a sea area like the Baltic Sea is loaded with harmful substances, sometimes with rather high toxicity levels, established sediment quality guidelines (SQG: s) provide good frame for evaluation of sediment quality for the permitting authorities. In the Gulf of Finland this approach was used on two datasets of 84 sediment cores of different length and subsample separation. The data consists of altogether 1806 subsamples which were classified using North American SQG: s. The obtained results reveal that in the majority of the subsamples the metals and arsenic exceed the threshold levels of the used SQG: s, some exceed also the probable effect level. Heavy metal and arsenic deposition in surface sediment of the eastern Baltic Sea is declining, but As, Cd, Hg, and especially Zn concentrations still occur at unacceptably high levels in the Gulf of Finland sediments. This is important to remember in environmental impact assessments and maritime spatial planning of the Gulf of Finland.

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## ORAL

**Societal needs and marine geological mapping in Finland – case Pyhäjoki**

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In the past most of the marine geological mapping in Finland was done systematically map sheet by map sheet. Recently needs-oriented mapping has taken over and nowadays most of the mapping is done to fulfill specific needs of society.

A good example of needs-oriented mapping project is the Pyhäjoki case. Fennovoima Oy is planning to build a nuclear power plant in Hanhikivi, offshore Pyhäjoki, western coast of Finland. For various purposes Fennovoima needed information on the seabed within 25 km radius of the planned power plant site.

According to Fennovoima's assignment GTK launched a marine geological mapping project for years 2012-2014. During the project GTK conducted 2654 line kilometers of acoustic-seismic surveys covering an area of about 1000 km<sup>2</sup>. Seabed substrate maps were drawn for the entire survey area.

Mapping project provided a lot of new information on the seabed conditions of the study area. For example, the submarine continuation of the moraine field south of Raahe is clearly recognisable and the eroding effect of pack ice can be detected in detail.

## ORAL

**Geo-biointeractions in a fragmented seafloor area, the Eastern Gulf of Finland**

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Ecosystem based management (ESBM) requires accessible and reliable information concerning the state, species distributions and physical characteristics of coastal and marine environments. Nevertheless this type of marine environmental data is often spatially limited and collected using different methods. Here we will present an example of an interdisciplinary approach that targeted to integrate marine environmental knowledge with information about human pressures.

We have produced new spatial knowledge on marine environmental characteristics by studying geo-bio interactions in a fragmented seafloor area, the Eastern Gulf of Finland. Here we will present our key findings regarding the benthic environment and demonstrate that physical (geological) heterogeneity of the seafloor should be considered in broad scale habitat mapping and marine spatial planning. We have had a close co-operation with the Regional Council of Kymenlaakso in their regional plan for the trade- and sea area process, already in the early phase of regional planning process.

The study was made within ENPI CBC funded Finnish-Russian co-operation project, the TOPCONS (2012-2014). The aim was to develop innovative spatial tools for the regional planning of the sea areas in the Gulf of Finland, the Baltic Sea.

## ORAL

**Paleohighlights of IODP Expedition 347, Baltic Sea Paleoenvironment**T. ANDRÉN<sup>1</sup>

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During IODP Expedition 347 more than 1600 meters of sediments were recovered from 9 sites in the Little Belt, Kattegatt and Baltic Sea area.

Some of the more spectacular paleoceanographic results achieved so far can be summarised as:

An amazingly high sedimentation rate of 5 to 7 mm/yr. in the Holocene sequence at Site M0059, Little Belt.

An intriguing hiatus indicating a rapid regression separating the varved glacial clay and the onset of the Holocene sedimentation in Little Belt

At the Sites M0064, Hanö Bay, and Site M0065, Bornholm Basin, an gyttja clay with an age of c.

45 700±1970 cal yr BP is separating two different sequences of varved glacial clay

Site M0063, Landsort Deep, displays a c. 25 meters laminated Holocene sequence with a resolution of c. 5 mm/yr.

The varved glacial sequence at this site may contain as much as 2000 varves (years) older than the short brackish phase of the Yoldia Sea and have thus recorded the entire Youngre Dryas.

#### References:

Andrén, T., Jørgensen, B.B., and Cotterill, C., and the Expedition 347 Scientists, 2015. *Proc. IODP, 347*: College Station, TX (Integrated Ocean Drilling Program). doi:10.2204/iodp.proc.347.2015

ORAL

### Unconformities in the stratigraphic division of strata in a formerly glaciated semi-enclosed basin, the Baltic Sea

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Sediments filling formerly glaciated epicontinental basins are characterized by frequent unconformities for two reasons: 1) the dynamics of the retreating ice-sheet, and 2) relative sea-level changes (including post-glacial rebound).

This study examines the kinds of unconformities (regional/local) recognized in the Baltic Sea basin in seismic-acoustic profiles and sediment cores (e.g. Virtasalo et al., 2014). The potential of these unconformities in the stratigraphic classification and basin-wide correlation of sediments is explored using the combined allostratigraphic and lithostratigraphic approach (CUAL by Räsänen et al., 2009).

It is expected that defining stratigraphic units based on unconformities will facilitate mapping the lateral extent and geometry of those units by seismic-acoustic methods, which eventually will improve our capability to visualise and predict the kinds of sediments that are exposed on the seafloor for the benefit of e.g. maritime spatial planning.

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ORAL

### Holocene sedimentation processes in the Ångermanälven River estuary

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Ångermanälven River estuary, in the northern Baltic Sea, deglaciated ca. 10 ka ago. It has long been known (e.g. Cato 1987), that varve deposition is an ongoing process, which has continued for several thousand of years, at the estuary. At least AD 1901-1971 a correlation between maximum daily discharge and mean varve thickness exists in the Ångermanälven River (Sander 2002). Thus varve thickness and sediment geochemistry may yield estimations of the past changes in the precipitation and the sedimentation processes.

Up to 35 meters long sediment cores from two sites, M0061 and M0062 were studied. The cores were recovered during the IODP Expedition 347 "Baltic Sea Paleoenvironment". The sediment analyses included e.g. grain-size, LOI, xrf, total carbon and ICP-MS geochemical analysis (M0062). The preliminary age model for the cores is based on the compound specific-, paleomagnetic- and OSL-dating, and Pb-content records.

The Fe/Ca ratios show gradual increase from 17 to ca. 10.2 mcd, where the values drop sharply. From 10.2 to 5 mcd the ratios increase again, 5-0 mcd they decrease steadily. The Al/Si ratios show a relatively similar pattern. The Ti/Al ratios peak distinctively at 12.5 mcd, 4.5-5.5 mcd and 2.5-3.5 mcd.

This work is a part of the CISU project funded by the Academy of Finland and the Russian Foundation for Basic Research.

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Sander, M., Bengtsson, L., Holmquist, B., Wohlfarth, B., Cato, I. (2002). The relationship between annual varve thickness and maximum annual discharge (1909-1971). Journal of Hydrology 263, 23-35.

ORAL

### Preliminary results of seabed investigations in the Baltic Sea and the Gulf of Finland

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High-resolution sea bottom relief maps have been compiled for large areas of the Gulf of Finland and the Baltic Sea, using multibeam echosounder surveys by the Estonian Maritime Administration spanning the latest twenty years. Multibeam echosounder is a type of sonar that is used to map the bottom of a water body. The high-resolution maps provide opportunities for distinguishing a number of interesting geomorphological objects, the Neugrund impact structure in particular. Remote sensing methods (sidescan sonar and continuous seismic acoustic profiling, video recording, etc.) and direct sampling of submarine outcrops were used for further studies of the identified structures.

**Pockmarks.** A number of trench-like N-S structures, from which hydrocarbons seep, are observed in the gas-saturated mud and clays covering the westernmost part of the Neugrund impact structure. These features are obviously related to the fault zones.

**Ice scratch marks.** A set of shallow straight trenches is observed in the shallow (5 -15 m deep) seabed on top of mud- or clay-covered hillocks. These are obviously scratches made by pressure ice ridges.

**Streambeds.** Bunches of streambeds are observed in the mud- and clay-covered seabed at the foot of submarine slopes and escarpments in the central part of the Gulf of Finland. These features are up to 20 m deep, 200 m wide and some kilometers long. Streambeds are especially well observed on the top of the submarine Odensholm Peninsula where bottom current is particularly strong.

**Iron-manganese concretions.** Iron-manganese concretions were mapped in large areas of the Gulf of Finland and the Baltic Sea at the

seabed depth of over 50 m. The chemical composition of the concretions is being studied.

Together with these findings, some other interesting submarine structures were studied near the islands of Väike-Pakri, Krass, Hiiumaa and Saaremaa.

ORAL

### Radocarbon dating of Baltic Sea sediments

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Dating of Baltic Sea sediments have traditionally been done by radiocarbon (<sup>14</sup>C). They should preferably be performed on terrestrial macrofossils to avoid the marine reservoir effect and the error introduced by "old" carbon being resuspended from the shores present in the sedimentary system. In the open Baltic Sea, however, are terrestrial macrofossils rare and the only datable material is often the sediment itself. This raises a problem as it has been shown on several occasions that the sediment gives ages older than fossils and other time markers from the dated levels in the sediment sequence.

Within the presently running project UPP-BASER (Understanding Past and Present Baltic Sea Ecosystem Response) we have sampled sites in the archipelago in the western Baltic Sea between Norrköping and Stockholm on the Swedish east coast. The sediment sequences from several of the sites cored contains both marine and terrestrial macrofossils which have been dated. We have also dated the sediment itself from the same core depths and the mean difference between the two types of material is 730±50 cal yr BP. In this presentation we will demonstrate and discuss the entire material dated and the possible explanation for the difference in age between the two types of material with special emphasis on changing sedimentary environment over time.

## POSTER

### Physical properties of glacial sediments from the Landsort Deep

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Landsort Deep, located in the Baltic Sea proper, is the deepest basin in the Baltic Sea. It displays a high-resolution late-Weichselian and Holocene sediment record.

Samples between ca. 50 and 80 mbsf. from one hole, M0063C, will be studied. These cores were recovered during the IODP Expedition 347 “Baltic Sea Paleoenvironment” from the water depth of 437 m.. At this stage, sediment analyses will include grain-size and LOI. The IODP 347 physical properties dataset will be utilised too. The relative age determination for analysed cores is based on knowledge on certain geological events in the Baltic Sea Basin history.

Preliminary interpretation of sedimentary environment for units V and VI is based on the Expedition 347 report (Andr n et al. 2015) and will be complemented with ongoing grain-size analysis.

Unit V (48–53 mbsf) is laminated, partly contorted, convolute bedded clay possibly of glaciolacustrine origin. Clay unit has possibly been remobilised by a slump event.

Unit VI (53–93 mbsf) is finely laminated varved clay with a down-core increase in the content of silt and sand. These are glacial lake deposits, recording a transition from ice-distal (upper part) to ice-proximal (lower part).

This work is a part of the CISU project funded by Academy of Finland and Russian Foundation for Basic Research.

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Andr n, T., J rgensen, B.B., Cotterill, C., Green, S., and the Expedition 347 Scientists, 2015. Proc. IODP, 347: College Station, TX (Integrated Ocean Drilling Program). doi:10.2204/iodp.proc.347.102.2015

## POSTER

### Long-term trends in coastal hypoxia in the Archipelago Sea of Finland – is it a natural phenomenon?

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Human-induced spreading of coastal hypoxia is currently a growing global problem that has deleterious effects on marine ecosystems. Although long-term spatio-temporal trends in hypoxia in the off-shore areas of the Baltic Sea have been widely studied, coastal areas have received less research interest so far. In addition, the conventional environmental monitoring programmes of the Archipelago Sea were not initiated until 1970s, when human impact in the area was already significant, denoting a lack of long-term information on environmental conditions predating the recent eutrophication. Therefore, we use a multiproxy approach combining sedimentology, ichnology, microbiology, mineral magnetic measurements, and mineral-specific *in situ* microanalyses of long sediment cores to assess bottom water redox shifts in the Archipelago Sea coast over the past 2000 years, encompassing the most recent climatic fluctuations of the Medieval Warm Period (950–1250 AD) and the Little Ice Age (1350–1850 AD).

Our preliminary results suggest that the most recent shift to at least episodically hypoxic conditions occurred around 1910s at the study sites. Such multidecadal oxygen deficiency, characterized by the lack of bioturbation by macrobenthic fauna, seems to be unprecedented in the studied cores, although a complete chronology is yet to be constructed. Interestingly, we found significant magnetic enhancement in the laminated sediments deposited under hypoxic conditions during the past 50 years. Based on the acquirement of strong positive rotational remanent magnetization, relatively low coercive force of ~ 13 mT, and high interparametric ratio of SIR-M/K this enhancement could be ascribed to bio-

genic greigite (Fe<sub>3</sub>S<sub>4</sub>) produced by obligatory anaerobic magnetotactic bacteria. Identification of such enhancements, could provide a proxy for past occurrences of hypoxia.

## POSTER

### Seabed substrates and sedimentation rates of the European Seas – EMODnet Geology

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The European Union's (EU) Marine Strategy Framework Directive targets to achieve Good Environmental Status (GES) of the EU's marine waters by 2020. However, it has been acknowledged that the poor access to data on the marine environment is a handicap to government decision-making, a barrier to scientific understanding and a break on the economy. The effective management of the broad marine areas requires spatial datasets covering all European marine areas. As a consequence the European Commission adopted the European Marine Observation and Data Network (EMODnet) in 2009 to combine dispersed marine data into publicly available datasets covering broad areas.

The second phase of the EMODnet Geology project started in 2013 and it will run for 3 years. The partnership includes 36 marine organizations from 30 countries. The partners, mainly from the marine departments of the geological surveys of Europe (through the Association of European Geological Surveys – EuroGeoSurveys), aim to assemble marine geological information at a scale of 1:250,000 from all European sea areas (e.g. the Baltic Sea, the Barents Sea, the North Sea, the Iberian Coast, and the Mediterranean Sea within EU waters). In comparison to the urEMODnet project (2009-2012) the data will be more detailed and aim to cover much larger area.

The EMODnet Geology project includes collecting and harmonizing the first seabed substrate map for the European Seas, as well as data showing sedimentation rates at the seabed. The data will be essential not only for geologists but also for others interested in marine sediments like marine managers and habitat mappers. A 1:250,000 GIS layer

on seabed substrates will be delivered in the portal, in addition to an updated 1:1 million map layer from the previous phase (2009-2012). A confidence assessment will be applied to all areas to identify the information that underpins the geological interpretations.

## POSTER

### Seabed sediment grain size prediction using multibeam backscatter data and spatial regression models

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INFOMAR have been exploring the possibilities offered by the emergent field of spatial statistics to geo-acoustic modelling in marine environments. We will report on a trial study in which we tested the premise that the known complexities of the backscatter data response to the seabed can, within certain confines, be greatly simplified for the purposes of predicting seabed properties. A shallow-water embayment, Dunmanus Bay in southwest Ireland, was chosen as the study area on the basis that a large number of groundtruthing samples were available (n=175). Following exploratory data analysis, a strong linear correlation between percentage sand and mean backscatter data was identified for fine-grained sediments. In total, four linear regression models were fitted to the data: Ordinary Least Squares, where spatial dependence was not factored and three variations on Generalised Least Squares where spatial dependence was modelled using spherical, exponential and Gaussian variogram models respectively. Based on Akaike's Information Criterion, GLS using an exponential variogram model was identified as the most parsimonious. Predictions using both this model and OLS regression were subject to validation testing for prediction accuracy and uncertainty by calculating various model diagnostics from the results of a leave-one-out cross-validation. The key diagnostics indicated that the spatial model should be preferred to the non-spatial. Predictions produced for the study area

had average error bands of  $\pm 10\%$  Sand at the 90% confidence level. The implications are that acoustic data could, potentially, be used to predict percentage sand for fine-grained sediments. While the empirical model devised is specific to the datasets employed, this study outlines a successful approach to prediction and mapping of seabed characteristics.

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**POSTER**

### Iron and manganese in coastal sediments of the Gulf of Finland: relevance for methane dynamics

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Recent studies have suggested that iron (Fe) and manganese (Mn) oxides may play a role in the anaerobic oxidation of methane in Baltic Sea sediments (Egger et al., 2015). However, it remains to be established which forms of Fe and Mn oxides are involved in this process, and whether the process is also widespread in the coastal zone of the Baltic Sea, where gradients of salinity and oxygen conditions influence the mobility of these elements.

In this study, we investigated sedimentary Fe and Mn dynamics along a transect of sites in Pohjanpitäjänlahti, a silled estuary in Uusimaa, Finland. The estuary is fed by the Karjaanjoki river system and discharges into the Gulf of Finland through a narrow salinity-stratified channel. Fe and Mn contents and mineralogy of sediments were determined by sequential extraction, including a separate extraction scheme for sulfur-bound phases. The results show that sedimentary Fe contents decrease steadily offshore, implying capture of riverine dissolved Fe by flocculation, and/or direct sedimentation of riverine suspended Fe. In contrast, Mn contents are highest in the deep inner basin of Pohjanpitäjänlahti, some 12km from the river mouth, implying internal shuttling of Mn related to redox conditions in the estuary. The Fe and Mn mineralogy of inshore sites is dominated by more reactive phases such as poorly-crystalline and crystalline

oxides, while at offshore sites, less reactive phases such as sheet silicates are quantitatively more important. These results have strong implications for the distribution of anaerobic oxidation of methane by Fe and Mn oxides in Baltic Sea sediments.

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Egger, M., Rasigraf, O., Sapart, C., Jilbert, T., Jetten, M.S.M., Roeckmann, T., van der Veen, C., Banda, N., Kartal, B., Ettwig, K. and Slomp, C., 2015. Iron-mediated anaerobic oxidation of methane in brackish coastal sediments, *Environmental Science and Technology* 49 (1), 277–283.



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## S7.1 Mineralogy

ORAL

### Reconciling modal mineralogy and chemical compositions of a sample

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Knowledge of the grade of valuable elements and its variation is not sufficient for geometallurgy. Minerals define not only the value of the deposit, but also the method of extraction and concentration. However, mineralogy is quite rarely used as the key information in geometallurgy and it is even more exceptional in mineral resource estimation.

One of the reasons is the lack of fast, low-cost but still reliable modal analysis. The other is that the results from various methods of modal mineralogy such as automated mineralogy and quantitative XRD are not consistent with chemical assay. In other words, the chemical composition back calculated from modal analysis does not match with the true chemical assay.

Element-to-mineral conversion is the known method to get modal mineralogy that matches with the chemical composition of samples. However, in complicated mineralogy or the lack of enough chemical components assayed, it fails to provide accurate results.

Reconciling the results of a modal analysis with chemical assays can improve the agreement between chemical assays and back-calculated chemical composition. This is achievable by doing minor adjustments to modal mineralogy. The method used here is called combined method and it principally uses Levenberg-Marquardt algorithm to minimize differences (residuals) between chemical assays and back-calculated chemical composition of a sample. The advantage of the method over other combined methods is that it does not use weighting factors. Additionally, the adjustments are minor unlike other methods that can cause mineral grades to drift away significantly. These features make it possible to apply the method for a large number of samples unsupervised.

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Parian, M., Lamberg, P., Möckel, R., Rosenkranz, J., Analysis of mineral grades for geometallurgy: Combined element-to-mineral conversion and quantitative X-ray diffraction, *Minerals Engineering*, Volume 82, 15 October 2015, Pages 25-35.

ORAL

### The sulphide ores in the Alvdal-Tynset region, SE Norwegian Caledonides

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A number of copper-bearing sulphide ores are located in the Tynset-Alvdal region, central Norway. Most of the investigated ores are located on the southern parts of the Tron mountain, but the Baugsberget mines were also included in the study. All ores were discovered after King Christian IV initiated a national search for metals, ores and minerals in 1632. They were mined in small scale from the 17<sup>th</sup> century until the early 20<sup>th</sup> century. In many cases, the local farmers discovered and operated the mines themselves. When the mines closed in 1911, more than 1200 tons of copper ore had been mined.

The ores are hosted in supracrustal units in the lower parts of the Seve Nappe Complex in the Upper Allochthon of the Caledonides (Ramsay & Siedlecka, 2001). This tectonostratigraphic position is located *above* the Tännäs augen gneiss and the metasedimentary Hummelfjell Group of the Middle Allochthon, but *below* a zone of solitary ultramafic bodies that connect the Vågåmo ophiolite in Gudbrandsdalen and the Feragen ultramafics. The latter zone separates the Seve Nappe Complex from the VMS-bearing turbidites of the Røros district in the Köli nappes. In this way, the Tynset-Alvdal copper ores occur at a lower tectonostratigraphic level than anywhere else in the Norwegian Caledonides.

All ores are stratiform and probably syngenetic with the supracrustal sequence. The ores in the Tronsvangen and Baugsberget mines are hosted by mica schists, are small and irregular and are mainly Cu dominated (up to 8.5 % Cu), locally with Zn-Cu dominated parts. The dominating ore minerals are pyrite, chalcopyrite, pyrrhotite, sphalerite and possibly galena. In contrast, the ores in the Klettgruva, Vesle-trond and Grøtådalen mines are hosted in the overlying green-schists and share many features of proper VMS ores. The dominating ore minerals are

pyrite, chalcopyrite, pyrrhotite and possibly sphalerite.

The geological environment of the ores is correlated with similar ore-bearing environments and tectonostratigraphic positions in the Ramundberget, Grönfjället and Vargtjärns-stöten areas (Härjedalen) and Rengen (Jämtland), Sweden.

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Ramsay, D., and Siedlecka, A., 2001: Berggrunnskart ALV-DAL 1619 II, M 1:50 000, foreløpig utgave, NGU.

ORAL

### Origin of gem and ore minerals obtained in gold sluicing in Finnish Lapland

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Corundum, garnet and dense ore minerals are obtained as side product of gold panning and sluicing in the gold rush areas of Ivalojoiki and Lemmenjoiki. Several types of corundum were observed including some rubies and sapphires. The chemistry of corundum varies from pure Al<sub>2</sub>O<sub>3</sub> to Cr and Fe bearing varieties. Inclusions vary from monazite and zircon grains to irregular, epidote, zoisite, margarite, granular and fibrous hematite etc. Thermodynamic modelling of a polycrystalline ruby bearing amphibole rock sample indicates clockwise PT-evolution from ~14 kbar and 600 °C to ~7-9 kbar and 800 °C. U-Pb ages from monazite inclusion give monotonous 1.9 Ga age population regardless of the type of corundum host. This and the PT-evolution suggest that most corundum grains are derived from unknown host rocks in marginal zone of Lapland granulite belt (LGB), which suffered high grade metamorphism during tectonic juxtaposing of the granulite units.

More than 5000 heavy mineral grains were analysed by SEM-EDS from 12 black sluicing sand samples, further enriched by Spiral Gold Panning Machine. Some concentrates were enriched in PGMs or REE-, Nb- and Ta-minerals. Pure gold showed no correlation with other minerals apart from electrum. Sperrylite rich samples also contained other PGMs but the amount of individual

mineral grains was too low to demonstrate statistically significant correlation. The same applies also to columbite-tantalite group minerals and other minerals typically occurring in complex pegmatite. Monazite, zircon, rutile and garnet seem to correlate with each other suggesting their major provenance from khondalitic bedrock of the LGB. The results suggest that bedrock source for placer gold did not contain significant amounts of other weathering resistant heavy minerals thus excluding basic igneous rock provenance for gold. Occurrence of several PGM species in certain samples and several Nb-, Ta-, Th-, REE-, W-, Sn- etc. minerals in others, indicates that till samples probably have drifted material from PGE-deposits and complex pegmatite deposits, accordingly. This suggests, combined with recent knowledge on ice movement directions and composition of the bedrock in the area that the marginal zone of the LGB is potential for PGE and complex pegmatite deposits, as well as gemstone occurrences.

ORAL

### Effects of Microstructures and Mineralogical Variables to the Thermal Shock Resistance of Carbonate Soapstone

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Soapstone industry utilizes different types of soapstone mainly as a construction material for fireplaces. In this application, they have to meet the requirements of different temperature conditions. Some components on the outer surface of the fireplaces warm only up to 70 °C, whereas other parts are exposed to combustion gases with temperatures of as high as 1000 °C. Mineralogical and structural knowledge is required to be able to place an appropriate type of soapstone in an appropriate position in the fireplace construction. This will make it possible to employ higher temperatures and achieve more particulate-free combustion allowing soapstone industry to develop more efficient and more environmentally friendly fireplaces.

Of many soapstone types, which differ from each other in their chemical composition and thermal properties, carbonate soapstone and its microstructural variations were investigated in this



study. Exposing carbonate soapstone samples representing different textural types to steep temperature gradients, it was possible to determine the parameters that effect the ability of the rock to resist thermal shock.

The results indicate that the type of microtexture is an important factor in controlling the thermal shock resistance of carbonate soapstone. The soapstone samples with a high thermal shock resistance show deformation textures, such as crenulation cleavage and S/C- mylonite. A strong negative correlation was observed between the thermal shock resistance and the length of cleavage domains. Also a slight elevation in the iron concentration of talc and magnesite was discovered to improve the thermal shock resistance of carbonate soapstone. Attention should especially be paid to the length and planarity of cleavage domains of spaced foliation occurring in studied carbonate soapstones.

ORAL

### The mineralogical characteristics that influence the functionality of "The ÅA Route" –carbonation method

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Single geological and mineralogical characteristics found in different rocks directly influence a rocks suitability for mineral carbonation. Therefore, a detailed mineralogical characterization has been essential when aiming to develop "The ÅA Route" carbonation method. In "The ÅA Route" carbonation process, Mg(OH)<sub>2</sub> is produced from rock material and then reacted with CO<sub>2</sub> in an exothermic reaction that produces a magnesium carbonate, magnesite (MgCO<sub>3</sub>) (Sjöblom and Eklund 2014).

Based on the results, the characteristics that need to be regarded are the crystal water- and the Mg-content in the minerals (Sjöblom and Eklund 2014), the crystal structure (Lavikko and Eklund 2015) as well as the composition of the parental rock (Sjöblom and Eklund 2015). Thus, the raw material should be an ultramafic rock with sufficient amounts of Mg (> 17 %) as well as crystalline H<sub>2</sub>O (> 12.5 %). It should be a phyllosilicate descending from a phyllosilicate, as the remaining characteristics of the parent rock influence the functionality.

The structural complexity and the location of Mg in the lattice are significant factors to the successfulness of a rock. Unexpectedly, the grade of metamorphism was not a factor for the net productivity. However, it had a negative influence in the preparation of the raw material.

Based on their successfulness in "The ÅA Route", different rock types and minerals are stated as suitable, with reduced suitability or as unsuitable.

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ORAL

### FennoFlake: a project to find flake graphite ores in the Fennoscandian shield and utilize graphite

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The European Commission's "Report on critical raw materials for the EU (2014)" state that natural graphite is one of the 20 most critical materials for EU. In 2012, EU consumed 13% of all flake graphite in the world but produced only 3%, which stresses the demand for the material. Flake graphite is important in several applications like batteries, carbon brushes, heat sinks, etc. Flake graphite is formed in high metamorphic areas. Graphite

can also serve as raw material for the production of graphene (a single layer of graphite), which is commonly used in many nanotechnological applications, e.g. printed electronics, sensors, etc. The processing steps to obtain pure graphene from the graphite ore include fragmentation, flotation and exfoliation, which usually are cumbersome and result in damaging of the graphene structure. We have started a new project, FennoFlakes, where geologists and chemists cooperating to fill the whole value chain for graphite; 1. Exploration of graphite ores (geological and geophysical methods). 2. Petrological and geochemical research on the ores. 3. Development of fragmentation methods for graphite ores. 4. Chemical exfoliation of the enriched flake graphite to separate the pure flake graphite into single and multilayer. 5. Test the quality of the produced graphite/graphene material in several high-end applications with totally environmentally friendly green and disposable material combinations.

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**POSTER**
**Overview of lithium pegmatite exploration in the Kaustinen area**

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The lithium potential of the 500 km<sup>2</sup> Kaustinen (Emmes, Kruunupyy-Ullava) Li province in western Finland has been known and explored since the 1960s. During 2003–2012, one of the main targets of the industrial mineral mapping projects by the Geological Survey of Finland (GTK) was to evaluate the Li (Ta, Nb, Be) potential and to discover new resources in the Kaustinen area (Ahtola et al. 2015).

GTK carried out RC, percussion and diamond drilling, together with ground geophysical surveys in seven different exploration areas. Regional till samples from the 1970s were also re-analysed. All the Li pegmatites belong to the albite-spodumene subgroup of the LCT pegmatite family. As a result, four new spodumene pegmatites (Matoneva, Päiväneva, Heikinkangas and Rapasaaret) were discovered. In addition, the knowledge of the dimensions and mineral resources of the previously known Leviäkangas and Syväjärvi pegmatites were

improved. In total, Li potential mapping by GTK increased several million tonnes the known Li pegmatite resources in the province. The exploration permits of three deposits (Leviäkangas, Syväjärvi and Rapasaaret) are now owned by Keliber Oy as a result of international tender notice of the Ministry of Employment and the Economy (MEE). According to the results from the re-assaying of old till samples, there are areas with good potential for new discoveries on the northwest and southeast sides of the known deposits. The Kaustinen region is the most potential area for Li mineralisation in Finland and also a significant Li province in the EU.

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**POSTER**
**The crystal structure of blödite under extreme conditions and its implications to planetary mineralogy**

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An exceptionally large and pure crystal of blödite, Na<sub>2</sub>Mg(SO<sub>4</sub>)<sub>2</sub>(H<sub>2</sub>O)<sub>4</sub>, with a high degree of perfection from the mineral collection of the Natural History Museum in Copenhagen gave us possibility to study the crystal structure of this mineral under various pressures and temperatures. The measurements were performed on the laboratory diffractometers as well as at the ESRF synchrotron facility and ILL neutron diffraction instrument in Grenoble.

Blödite is monoclinic,  $P2_1/a$ ,  $Z = 2$ ,  $a = 11.115(9)$ ,  $b = 8.242(2)$ ,  $c = 5.538(1)$  Å,  $\beta = 100.82(4)^\circ$  (at room conditions).

At high pressure up to 11 GPa no phase transition is observed. The density increases by 20%. The compressibility is anisotropic with  $\beta_a : \beta_b : \beta_c = 0.72:0.94:1$ . Na coordination polyhedron is the most compressible, whereas the SO<sub>4</sub> coordination tetrahedron remains practically incompressible in this pressure range. The increased strength

of H-O<sub>acceptor</sub> bonding with pressure with concomitant strengthening of the Metal-O<sub>water</sub> bonding is observed.

Neutron diffraction down to 20 K shows accurate positions of the hydrogens, and the two water molecules with different strengths of hydrogen bonds.

Blödite shows an isotropic expansion with temperature with volume increase of only 1% up to the point of dehydration. It dehydrates in two steps, at 110° C and 225° C. During the first dehydration it transforms to löweite (Na<sub>12</sub>Mg<sub>7</sub>(SO<sub>4</sub>)<sub>13</sub>(H<sub>2</sub>O)<sub>15</sub>). At the second dehydration step, löweite disintegrates to  $\alpha$ -Na<sub>2</sub>Mg<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> with still unknown crystal structure and vanthoffite (Na<sub>6</sub>Mg(SO<sub>4</sub>)<sub>4</sub>).  $\alpha$ -Na<sub>2</sub>Mg<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> transforms at 590° C to  $\beta$ -Na<sub>2</sub>Mg<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> with the crystal structure of the langbeinite type.

Blödite is an important mineral phase on the surfaces of water saturated planets. On the Earth it is found in evaporites from sulphate lakes. On surfaces of Jupiter moons Ganymede and Europa it is expected to be constituent of the icy surface material, and due to its increased stability under pressure it is expected also to play an important role in the under-surface composition of these planets. Our investigation defines its relations to the other hydrous and anhydrous Na-Mg sulphates and helps understanding the genetic cycles of complex sulphates from the volcanic to the lacustrine environments.

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**POSTER**
**Flake graphite occurrences in a high-grade metamorphic region in Sortland (NW Norway)**

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The aim with this study is to determine the quality of flake graphite in high-grade metamorphic rocks in Sortland, NW Norway. Flake graphite

is present in graphite schist and samples were collected at three different locations in Sortland: Hornvatnet, Lamarkvatnet and Vikeid. The host rocks of the graphite schist are dolomite or calcite marble, pyroxene gneiss and amphibolite. Metamorphism reaching high temperatures on organic and sedimentary material in the Proterozoic led to the formation of flake graphite. According to previous studies, the graphite content in the area varies between 5 and 30%<sup>1</sup>. Sampled graphite schists were fragmented by selective fragmentation (selFrag) and analyzed using polarization microscopy, scanning electron microscopy, Raman spectroscopy and X-ray diffraction. The grain size and texture of the sampled graphite schists vary macroscopically. Some contain abundant, visible, big (up to 5 mm in size), and ordered graphite flakes with layered structure while other schists contain smaller graphite flakes and a lower graphite content. Pictures from the SEM indicate that the graphite flakes consist of several parallel layers with clean surfaces. The results from both Raman spectroscopy and XRD support the SEM analyses that the flake graphite consists of several parallel layers and also imply that the flake graphite is almost free from defects.

**References:**

<sup>1</sup>Gautneb, H. & Tveten, E. (2000) The geology, exploration and characterisation of graphite deposits in the Jennestad area, Vesterålen, northern Norway. *Norges geologiske undersøkelse Bulletin*, 436, pp. 67-74.

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**POSTER**
**Mineralogy and applications of Sokli vermiculite**

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Vermiculites ((Mg,Fe,Al)<sub>3</sub>(Al,Si)<sub>4</sub>O<sub>10</sub>(OH)<sub>2</sub>·4H<sub>2</sub>O) are naturally occurring minerals from hydromica group with a high cation exchange capacity (CEC) and large surface area.

The purpose of this study is to give a mineralogical description of vermiculite from the weathered top of the Sokli massif, northeast Finland, and show

its ability to absorb ammonium into the mineral lattice of NMV (nanomodified vermiculite).

In the present study vermiculites from Sokli massif, were investigated in detail using electron probe microanalysis (EPMA, Microprobe), X-ray diffraction (XRD) and Thermal analysis (TGA). The results showed that vermiculite was present as dominant mineral phase, but they also showed the existence of minor phases of phlogopite.

The application tests were performed using landfill leachate. Crude vermiculites have been nanomodified by heat treatment using a patented technology. Vermiculite samples are heated in an oven until the interlayer distance of them is 11.7 Å. After this, they have been exposed to the leachate. In this experiment 200 ml of leachates were treated with 4 g of solid samples. In performed test NMV from Sokli and Kovdor were compared. Tests were performed at room temperature (24°C) using small grain size (0.075-0.125 mm) and stirring of the solution.

Ammonium decrease in leachate was higher for heat treated Sokli NMV than it was for Kovdor NMV. The decrease of ammonium in leachate was from initial 280 mg/l to 89 mg/l (reduction 68%) for Sokli NMV and the reduction of ammonium in leachate was 50 % for Kovdor NMV.

15 and 20°C were performed to test the upper temperature limit for ikaite precipitation.

In Ikka Fjord, ikaite forms hundreds of columns over sodium carbonate springs issuing at the bottom of the fjord. When mixed with seawater, ikaite precipitates – not calcite. A combination of low water temperature (<6°C) and the presence of PO<sub>4</sub> ions (9-25 ppm) in the spring water has been suggested as the main reason for the formation of ikaite (Buchardt et al., 2001), as phosphate is a well known inhibitor of calcite growth.

Our results, using XRD analysis, show that ikaite precipitates readily at 5°C when mixing sodium carbonate solutions with natural seawater from Ikka Fjord, Skagerak, and Øresund, and artificial seawater. Phosphate had no effect on the ikaite precipitation. It formed equally well PO<sub>4</sub>-free as with 5-25 ppm PO<sub>4</sub>. When using a CaCl<sub>2</sub> solution in place of seawater, calcite was the main precipitate. Hence, seawater chemistry is the key factor controlling ikaite precipitation in Ikka Fjord. In our experiments, ikaite precipitates easily at 10°C over a 6h period. At 20°C an amorphous (CaCO<sub>3</sub>?) phase is formed as judged from XRD results, but no calcite.

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- Buchardt, B., Israelson, C., Seaman, P. and Stockmann, G., (2001). Ikaite Tufa Towers in Ikka Fjord, Southwest Greenland: Their formation by mixing of seawater and alkaline spring water. *J. Sed. Res.* 71, 176-189.

#### POSTER

### Synthetic ikaite precipitation simulating conditions in Ikka Fjord, SW Greenland

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Two series of experiments precipitating synthetic ikaite were carried out, one using a 5°C cooling room at the University of Copenhagen, and one using cooling baths at Stockholm University to keep the temperature low. Ikaite is a hydrated calcium carbonate mineral (CaCO<sub>3</sub>·6H<sub>2</sub>O) and is generally assumed to be unstable above 6°C. The aim of the experiments was to test if the presence of PO<sub>4</sub> (aq) is a key factor to form ikaite over calcite in a system simulating Ikka Fjord in Greenland, where ikaite forms naturally. In addition, experiments at 5, 10,

## S8.1 Palaeoclimatology: New insights from proxy data and palaeoclimate modeling

ORAL

### Effects of melting ice sheets and orbital forcing on the early Holocene warming in extratropical Northern Hemisphere

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The early Holocene is a critical period for climate change, as it marked the final transition from the last deglaciation to the relatively warm and stable Holocene. It is characterized by a warming trend that has been registered in numerous proxy records and was accompanied by major adjustments in different climate components. The climate response to the forcings together with the internal feedbacks before 9 ka remains not fully comprehended. In this study, we therefore disentangle how these forcings contributed to climate change during the earliest part of Holocene (11.5–7 ka) by employing the LOVECLIM climate model for both equilibrium and transient experiments.

The results of our equilibrium experiments for 11.5 ka reveal that the annual mean temperature at 11.5 ka was lower than the present in the Northern extratropics, except in Alaska. The magnitude of this cool anomaly varies regionally as a response to varying climate forcings and diverse mechanisms. In eastern N America and NW Europe the temperatures throughout the whole year were 2–5 °C lower than in the preindustrial control as here the climate was strongly influenced by the cooling effects of the ice sheets. This cooling of the ice-sheet surface was caused both by the enhanced surface albedo and by the orography of the ice sheets. For Siberia, a small deviation in summer temperature and 0.5–1.5 °C cooler annual climate compared to the present were caused by the counteraction of the high albedo associated with the tundra vegetation which was more southward extended at 11.5 ka than in the preindustrial period and the orbitally-induced radiation anomalies. In the eastern Arctic Ocean, the annual mean temperature was 0.5–2 °C lower than at 0 ka, because the cooling caused by a reduced northward

heat transport overwhelmed the orbitally-induced warming. In contrast, in Alaska, temperatures in all seasons were 0.5–3 °C higher than the control run primarily due to the orbitally-induced positive insolation anomaly and also to the enhanced southerly winds which advected warm air from the South as a response to the high air pressure over the Laurentide Ice Sheet.

Our transient experiments indicate that the Holocene temperature evolution and the early Holocene warming also vary between different regions. In Alaska, the climate is constantly cooling over the whole Holocene. In contrast, the overall warming during the early Holocene is faster in N Canada than in other areas (up to 1.88 °C ka<sup>-2</sup> in summer) as a consequence of the progressive decay of the LIS. In NW Europe, the Arctic and Siberia, the overall warming rates are intermediate with about 0.3–0.7 °C ka<sup>-2</sup> in most of seasons. Overall, our results demonstrate the spatial variability of the climate during the early Holocene, both in terms of the temperature distribution and warming rates, as the response to varying dominant forcings and diverse mechanisms.

ORAL

### Palaeoclimatic indicators of the Holsteinian Interglacial in Eastern Europe in the light of research in the Polish-Belarusian cross border area

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The study on regional key horizons and Middle-Late Pleistocene climate in a southern part of the Polish-Belarusian cross border area was focused on paleoclimatic reconstruction of the Holsteinian Interglacial (Mazovian in Poland and Alexandrian in Belarus), based mostly on palynological data. Paleoclimatic indicators from the Mazovian Interglacial at Ossówka in Eastern Poland were compared with the ones from the Alexandrian Interglacial at Rechitsa in Western Belarus. Both sites are located at a

distance of 80 km from each other. A large number of *Taxus* pollen acts as a significant paleoclimatic indicator in Eastern Poland. It is one of the most important criteria for assessing a biostratigraphy, indicating a beginning of a mezocratic stage and one of diagnostic features in the Mazovian pollen succession. A lack of *Taxus* in the initial phase of a mezocratic stage at Rechitsa site confirms a more continental climate than in Eastern Poland. Pollen succession at Rechitsa presents a much higher content of *Pinus* in the early climatic optimum if compared with Ossówka. Moreover, *Pinus* peak is less distinct and it is interpreted as a simultaneous cooling. The pollen succession from Rechitsa provides constant continental climatic conditions at that time. There were differences in mean temperatures of the warmest and the coldest month, with higher temperature in July and lower temperature in January in western Belarus than in eastern Poland.

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ORAL

### Past precipitation changes in Finland inferred from annually laminated lake sediments

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Three annually laminated (varved) lake sediment records were studied in Central and Eastern Finland. Each record extends more than 3 000 years back in time. Sediment in two of the lakes, Lake Kalliojärvi and Lake Kuninkaisenlampi, are of clastic organic varve type. A varve year consists of three laminae. The first, clastic minerogenic lamina, results from increased erosion caused by spring snow melt. The second and third laminae consist of organic matter. The second lamina is composed of organic matter from autochthonous biogenic production and allochthonous organic matter transported from the catchment. The third lamina is composed of fine homogenic organic matter that is accumulated under the ice cover during winter. Lake Kallio-Kourujärvi sediment is of organic varve type that consists of the alternation of the second and third lamina types.

Both minerogenic and organic matter accumulation are related to precipitation during winter and

growing season, respectively. The amount of erosion is controlled by the amount of accumulated snow during the previous winter and the length and intensity of the melting episode. In addition to spring floods, the growing season precipitation regulates transportation of nutrients and allochthonous organic matter from the catchment into lake. Thus clastic and organic laminae can be used as proxies in order to reconstruct seasonal precipitation changes. The reconstructions from the studied three lakes shed light on the mechanisms that produce changes in precipitation. The results suggest that winter precipitation is related to North Atlantic Oscillation in Central Finland while solar forcing explains the precipitation variation in Eastern Finland.

ORAL

### Mid- to late Holocene aeolian activity recorded in a coastal dunefield and lacustrine sediments on Andøya, northern Norway

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The coastal area of western Norway is frequently visited by synoptic scale low-pressure systems carrying high wind speeds and storm surges. In an effort to reconstruct past storminess, we have investigated a foredune stratigraphy and a continuous lake sediment record from the largest dunefield on Andøya in northern Norway. The dunefield extends landwards in a north-eastward direction, and consists of several parabolic dunes, foredunes and blowouts. The sediment record (169 cm) from the nearby lake Latjønna and the foredune stratigraphy (10 m) covers the last 6200 and 3800 cal. yr BP, respectively. The lake sediment record consists of several sections dominated by sand grains interspaced by organic layers. The core has been examined by use of several sediment analysis such as XRF, magnetic susceptibility and loss-on-ignition. Mineral grains were detected by wet sieving of the ignition residue, and the relative influx of sand grains to Latjønna was calculated based on the weight of sand grains >250  $\mu\text{m}$  per cm divided by accretion rate determined by the radiocarbon chronology. Phases

with high influx of sand is recorded around 4800, 4250, 3000-2000, 1850-1750, 1600-600, 450, 300 and 150 cal. yr BP. The two investigated sites show quite contrasting chronologies, where high sedimentation rates in the lake record, associated to more aeolian influx, are corresponding to erosion and hiatuses in the foredune stratigraphy.

ORAL

### Novel Bayesian models for past climate reconstruction from pollen records

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Understanding and predicting future environmental changes is partly based on what is believed to have happened in the past. We use Bayesian hierarchical multinomial regression models to reconstruct past climate from fossil pollen records since these records provide continuous and long-term information on climate variation from the times which are not covered by instrumental records.

The simplest model describes a single core reconstruction with a fixed chronology. We propose to extend such a basic approach in two important ways. First, we introduce a single core model with time uncertainty. The handling of time uncertainty in the sediment sample dates is integrated as a separate module in to the hierarchical model. Second, a multi-core model is introduced. This multi-core model takes into account correlations in the environmental variable both within each core (temporal dependence) and between the cores (spatial dependence). All three models are applied to reconstruct the Holocene annual mean temperature from pollen records from Finland, Sweden and Estonia.

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ORAL

### The preboreal retreat of the Iceland Ice Sheet (IIS) and Neoglacial landscape destabilization in the Central Highlands, West Iceland

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Terrestrial records from lake cores are essential for linking the influence of the oceanic, atmospheric, and land processes that bring abrupt climate changes observed throughout the late Holocene in Iceland<sup>2,3</sup>. Iceland's lakes provide unparalleled records of Holocene climate variability due to their high sedimentation rates and abundant tephra, which allow for high-resolution records with robust age models.

An 8 m-long core was obtained from Arnarvatn Stóra, Central Highlands, West Iceland (540 m. a.s.l.) in March of 2015. Deglacial silt in the bottom 2 cm of the core is overlain by the Saksunarvatn tephra (~10.3 kyr BP), indicating the retreat of the Iceland Ice Sheet (IIS) from this area during or shortly after the Pre-Boreal period, contrary to previously estimated ice extent maps for this time period<sup>5</sup>.

Physical and biological proxies from the cores indicate three major periods of landscape evolution during the Holocene: ca. 10-6 ka, a period of landscape stability and andesol formation<sup>1</sup> probably due to extensive vegetation cover; ca. 6-4 ka, a time of increased explosive volcanism (indicated by tephra in the core) with subsequent landscape destabilization; and ca. 4-0 ka, a time of intense and increasing soil erosion,<sup>1</sup> changing in-situ biological activity, and landscape destabilization representing Neoglacial cooling<sup>4</sup> following the decrease in Northern Hemisphere summer insolation. First order Neoglacial destabilization trends culminate for all biological proxies at the peak of the Little Ice Age (LIA), about 200 yr BP. This 3-phase pattern of landscape evolution, including LIA peak destabilization, is similarly noted in cores from

the proglacial lake Hvítarvatn (HVT), east of Lan-jökull. However, the HVT record does not extend beyond the Saksunarvatn tephra.<sup>3</sup> Future work with this core will include age-model improvement using microprobe analysis of tephra layers and synchronization with other Iceland lake and marine records.

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#### ORAL

### Phytoplankton response to the environmental and climatic variability in a temperate lake over the last 14,500 years in eastern Latvia

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Phytoplankton species are the primary producers in lakes and play important roles in food-web structures. Any shift in their diversity and productivity has an impact on other aquatic life forms. Fossil phytoplankton identified alongside pollen analysis holds great potential to improve our knowledge on environmental requirements of specific algae, their responses to stress factors and species co-occurrences. Using pollen, non-pollen palynomorphs, temperature reconstructions and lithological information as proxies of environmental factors, we statistically test their associations with

the fossil phytoplankton community composition. Results reveal that the climate warming and following decrease in landscape openness, and increase in organic matter were significant environmental variables affecting dynamics of phytoplankton communities in both Lateglacial and Holocene. Ontogeny of lake varied through terrestrial development that affected lake indirectly but increased mean summer temperature affected lake directly leading to increased aquatic productivity. Water tolerance indicating moist soils in the surroundings of the lake positively correlated with *Pediasstrum*, *Scenedesmus* and *Tetraedron* during the Early Holocene (11,650–8000 cal yr BP). Redundancy Analysis results display a positive association between cyanobacteria and mean air summer temperature and suggest that warming led to higher cyanobacterial abundances and favoured cyanobacteria over other phytoplankton taxa. Therefore, bearing in mind future possible climate warming, dominance of cyanobacteria in temperate lakes is likely.

#### POSTER

### 7500 years of pine tree-ring $\delta^{13}\text{C}$ values from northern Finland

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Long-term efforts of collecting pinewood (*Pinus sylvestris* L.) preserved as subfossils in lake sedimentary archives in northern Finland (e.g. Eronen et al. 2002), and their subsequent tree-ring analysis and dating have resulted in a tree-ring chronology and climatic analyses covering the past ~7.5 ka (e.g. Helama et al., 2002; 2008).

During the past three years, this supra-long pinewood chronology, complemented with newly sampled subfossil trunks, has been measured for its isotopic composition of carbon ( $\delta^{13}\text{C}$ ) which serves as a sensitive proxy for past photosynthesis, yielding indirect estimations of temperature, moisture and cloudiness.

Dendrochronologically cross-dated tree-ring material was dissected in either annual or decadal



segments from living trees and subfossil samples and  $\alpha$ -cellulose extracted for isotopic analysis. In addition to the recent calibration period, an annually resolved chronology was produced to cover much of the 6<sup>th</sup> century CE. The 7500-year chronology is decadal resolved, with sample replication  $\geq 5$  throughout the sequence.

The  $\delta^{13}\text{C}$  data reveal new insight into regional climatic trends of the mid- and late Holocene, systematics of large scale geographical and within-tree isotopic variability and the existence and nature of age trends in tree-ring  $\delta^{13}\text{C}$  records

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#### POSTER

### Dinoflagellate cysts as a sea-ice proxy – new insights from the Hudson Bay system

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Dinoflagellates are single-celled marine plankton organisms, whose cyst (resting cell) assemblages are one of the most widely applied proxy for late Quaternary sea-ice reconstruction. The reconstructions provide much needed quantitative estimates for comparison with modern and predicted sea-ice trends, and for climate modeling purposes. However, sea-ice reconstructions based on dinoflagellate cysts do not always corroborate with commonly observed large-scale temperature trends inferred from other proxies. This stimulates questions related to the limited explicit knowledge of underlying ecological, temporal and spatial factors that link the proxy distribution to sea ice.

This presentation introduces a viewpoint to sediment-core cyst assemblages that is based on continuous year-round series of in situ cyst production. A compilation of species-specific cyst flux data from seasonal (trap) and spatial (surface-sediment) components is used to define seasonal and environmental fingerprints of dinoflagellate cyst production within the Hudson Bay system. The results demonstrate that contrary to the hypothesis of sea-ice governed light regime being the overarching control of cyst production, in the Hudson Bay system the trophic composition and its seasonal patterns are not related to sea-ice, even though species-specific seasonal fingerprints are. In an attempt to elucidate the trends and variability evident in dinoflagellate-cyst based climate and sea-ice reconstructions, it is important that future research attempts to investigate dinoflagellate life-cycle patterns over several annual cycles and across different sea-ice covered systems.

#### POSTER

### Sokli: a hotspot for climate change research in the North Atlantic region

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Results from a decade of intensive studies at Sokli (NE Finland) have drastically changed classic ideas of glaciations, vegetation and climate in northern Europe during the Late Pleistocene. Sediments with age up to 130 kyr have been preserved in their original stratigraphic position in a deep hole formed in the strongly weathered rocks of the Sokli Carbonatite Massif. This unique preservation of Late Quaternary sediments stands in sharp contrast to earlier studies which were mostly based on the long-distance correlation of highly fragmented and poorly dated stratigraphic evidence. Furthermore, the unusual thickness of the warm stage deposits in the Sokli basin, and the fossil-richness of the sediments, allow for high-resolution, multi-proxy based paleoenvironmental reconstructions.

So far, sediments dated to MIS 5d-c (at ca. 110-90 kyr BP), early MIS 3 (around ca. 50 kyr BP),

and the Holocene (last 11 kyr) have been studied in detail, while analyses are ongoing on thick MIS 5e (ca. 130–115 kyr BP) and MIS 5a (ca. 85–75 kyr BP) deposits in the Sokli basin. In collaboration with a group of international scientists, a multitude of proxies are analysed (geobiochemical data, pollen, macrofossils, chironomids, diatoms), detailed multi-proxy comparisons are made, and climate parameters are reconstructed quantitatively using both the transfer function approach and indicator plant species.

Our data from Sokli reveals a highly dynamic Fennoscandian Ice Sheet, with ice-free conditions and present-day summer temperatures at Sokli, during early MIS 3. These conditions contrast sharply with earlier reconstructions that assumed ice-cover over major part of Fennoscandia during this time period. Additionally, Sokli records strong continental climate conditions, instead of glaciation, for MIS 5d, and boreal interglacial conditions, instead of arctic conditions, for MIS 5c.

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**POSTER**

### Drivers of regional and local boreal forest dynamics during the Holocene

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Here I present the results of my PhD work that is based on three publications (Kuosmanen et al. 2014, 2015, submitted to *Boreas*). Fossil pollen and stomata records from lake and small hollow sites were used to investigate the Holocene history of western taiga forest in northern Europe and to assess the importance of climate, forest fires, local moisture conditions and human population size on the long-term boreal forest dynamics, at both regional (lake records) and local (small hollow records) scales. Statistical methods variation partitioning and wavelet coherence analyses were employed to assess the importance of these variables on long-term boreal vegetation dynamics.

The results demonstrate the constant Holocene presence of Siberian larch (*Larix sibirica*) and Norway spruce (*Picea Abies*) since 10 000 cal yr BP. The expansion of spruce population at 8000 - 7000 cal yr BP caused notable change in forest structure towards more dense spruce dominated forests and

seems to mark the onset of the spruce migration into Fennoscandia.

Climate is the main driver of the long-term regional scale vegetation changes. However, at the stand-scale boreal forest dynamics the role of local factors increases indicating the important role of site-specific factors. Especially fires can have a significant effect on the short-term changes in individual tree taxa and have profound effect on forest structure at local scale. The importance of human population size on variation in long-term boreal vegetation was first time statistically assessed and the unexpectedly low importance is likely due to the bias caused by the differences in the spatial representativeness between the human population size data and the forest composition derived from pollen data.

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**POSTER**

### Re-coring Lake Kråkenes: a high resolution lake archive of palaeohydrological variability

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The Lateglacial stable hydrogen isotope record of varved Lake Meerfelder Maar shows the potential of using biomarker isotope measurements in high resolution lake sediments<sup>1</sup>. The excellent chronology of Lake Kråkenes allows for the direct comparison between its pollen and macrofossil proxy records<sup>2</sup> and the Greenland ice cores and other terrestrial – and marine records. The biomarker record of Lake Kråkenes remains currently uninvestigated, but analyses from other lake sediments supports the

potential of its sedimentary record<sup>3</sup>. We will re-core Lake Kråkenes in the spring of 2016 and analyse the sediment on organic geochemical biomarkers using a combination of gas - and high performance liquid chromatography and (isotope ratio) mass spectrometry methods.

During the Younger Dryas, the catchment of Lake Kråkenes hosted a small cirque glacier<sup>4</sup>. Changing moisture sources are known to imprint their signal onto the stable hydrogen isotopic composition of n-alkanes<sup>1</sup>. This means that the isotopic signal recorded in the n-alkanes can be the result of a shift in moisture source, driven by changes in the position of the westerlies<sup>5</sup>, or it can be the result of a change in the relative amount of glacier meltwater input to the lake, or a combination of the two.

This caveat can be tackled by employing the same analysis techniques on a lake nearby, which is not under the influence of a cirque glacier, and thus only records a change in precipitation moisture source. For Lake Kråkenes, two potential sites are available: Lake Movatna, just over the watershed boundary (A. Nesje and J. Mangerud, personal communication), and proximal palaeolake Dimnamyra<sup>6</sup> on Dimnøya.

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#### POSTER

### Parameter correlations in paleoclimatics – PIXE, PIGE and RBS

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Physics-based techniques have been well applied in lake sediment research, but the innovative use of new approaches has been limited. Basic measurements are commonly used, but attempting modern applications has been seen too risky and unfamiliar to experiment for most researchers.

This research focuses on physics-based approaches to be applied in paleoclimatics. By the means of modern approaches novel knowledge of climate change and lake anoxia can be attained. This

study obtains parameter correlations between basic, commonly used and modern physics-based applications.

In addition to basic magnetic measurements and techniques, such as susceptibility, remanent magnetization and varve analysis, the application studied in this research is particle induced x-ray emission (PIXE), that is a non-destructive total element analysis method that is considered to be highest on its accuracy. Measurements were made as cooperation with accelerator laboratory at University of Jyväskylä. Furthermore, proton induced gamma-ray emission (PIGE) and Rutherford backscattering spectroscopy (RBS) that have only been used in modern physics will be attempted on varved lake sediments.

The correlation in parameters may suggest different accuracies in studied applications and therefore inaccuracy in parameter values.

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#### POSTER

### Major Cooling Intersecting Peak Eemian Interglacial Warmth in Northern Europe

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Sokli in NE Finland is one of few terrestrial sites in N Europe with sediments unequivocally

dated to the Eemian Interglacial (MIS 5e). Furthermore, the steep-walled depression, formed in deeply weathered rocks of a Palaeozoic magma-intrusion, has allowed for the accumulation of unusually thick Eemian and Holocene lake sequences. Here we present a first integration of multi-proxy data obtained on 3 m of glacial lake sediment overlain by 9 m of diatom gyttja of Eemian age from the Sokli basin. Our data, at unprecedented resolution, reveals a major cooling event intersecting peak Eemian warmth. Two independent temperature reconstructions based on terrestrial plants and chironomids indicate a summer cooling of the order of 2–4 °C. The cooling event started abruptly, had a step-wise recovery, and lasted 500–1000 yr. Our results demonstrate that the common view of relatively stable interglacial climate conditions on the continent should be revised, and that perturbations in the North Atlantic oceanic circulation under warmer-than-present interglacial conditions may also lead to abrupt and dramatic changes on the adjacent continent.

## POSTER

### Climate signals in tree-rings from the Norwegian Stave Churches

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Tree-rings are a valuable climate proxy because of the high degree of dating precision offered by the annual resolution. One challenge is finding suitable material that is both climate sensitive, and that extends as far back in time as possible. In Norway, a lot of work has been put into dendrochronological dating of the Stave Churches. This material roughly covers the period AD 800–1300, and substantial sample depth is available from both the eastern and western side of the water divide in southern Norway. As the growing sites of the trees are unknown, validation of the climate signal is a challenge. However, high matches between regions, and with building timber from other medieval buildings indicate a strong common signal. Here, we present the tree-ring records from the Stave Churches, and discuss the climatic information that can be gained from it.

## POSTER

### From eutrophic towards hypertrophic – the story of southern Finnish lakes

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Eutrophication continues to be a major environmental problem worldwide. The reference state of a lake (i.e. prior to human disturbance) is a crucial piece of information in lake management as some lakes are naturally nutrient-rich and some are not. Paleolimnology is a valuable tool in determining these reference states and quantifying the change between pre-disturbance and present-day conditions. The use of a paleoecological transfer function together with a top-bottom approach is a particularly effective way of examining several lakes simultaneously.

We used the top-bottom approach and a diatom-total phosphorus (TP) transfer function to study the diatom assemblages of modern (i.e. surface sediment) and pre-disturbance samples from 19 lakes in the clayey catchments of southern Finland. The pre-disturbance samples were selected based on the magnetic susceptibility profiles of the sediment cores and their age was estimated with radiometric dating. The transfer function is targeted for naturally eutrophic lakes but its calibration set consists of eastern Finnish lakes from till-dominated catchments. Therefore, our other aim was to examine the applicability of the transfer function to the southern Finnish lakes that have similar water quality but different catchment geology.

According to the results, the lakes can be divided into two distinct groups based on their pre-disturbance samples. One group has notably higher diatom diversity and generally lower diatom-inferred TPs (DI-TP) than the other group (mean 28  $\mu\text{g l}^{-1}$  and 56  $\mu\text{g l}^{-1}$ , respectively). Till-dominated catchments are common in the former group and clayey catchments in the latter one. A majority of the lakes have suffered from further eutrophication via human-induced nutrient loading, which can be seen as a clear shift in the diatom assemblages and an increase in the DI-TP from pre-disturbance to modern samples. Furthermore, the eastern Finnish

model works rather well for the naturally eutrophic southern Finnish lakes despite the difference in the catchment geologies and land use histories of the two areas.

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**POSTER**

### Plant macrofossil evidence for an early onset of the Holocene summer thermal maximum in northernmost Europe

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Holocene summer temperature reconstructions from northern Europe based on pollen records suggest an onset of peak summer warmth around 9000 years ago. However, pollen-based temperature reconstructions are largely driven by changes in the proportions of tree taxa and thus the early-Holocene warming signal may be delayed, especially at high latitudes, due to the geographical disequilibrium between climate and tree populations. Here we show that quantitative summer-temperature estimates in northern Europe based on macrofossils of aquatic plants are in many cases ca. 2°C warmer in the early-Holocene (11 700–7500 years ago) than reconstructions based on pollen data. Towards mid-Holocene the reconstructed temperatures converge at all study sites. The modified climate scenario is important for understanding early-Holocene climate changes and for the validation of palaeoclimate model simulations, so that the processes influencing past climate can be better understood, especially during the period of rapid climate change in the early Holocene.

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## S9.1 Life-Earth Processes in Deep Time

### KEYNOTE

#### Tracing the Evolution of Oxygen on the Archean Earth

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A remarkably coherent ensemble of evidence points to a significant accumulation of atmospheric oxygen for the first time in Earth's history beginning ca. 2.45 Ga, the so-called Great Oxidation Event (GOE). Briefly, this includes the disappearance of detrital pyrite, uraninite and siderite from fluvial and deltaic deposits, an increase in the retention of iron in paleosols, an enrichment of Cr and U in iron formations, and perhaps most importantly, the disappearance of sedimentary sulphur isotope mass-independent (S-MIF) anomalies indicative of atmospheric SO<sub>2</sub> processing in the absence of appreciable ozone. However, several trace element and isotopic proxies have recently suggested oxidative weathering hundreds of millions of years earlier<sup>1-2</sup>. The superposition of pre-GOE signals for oxidative weathering at a time of global anoxia represents a conundrum for which the most accepted explanation is that pre-GOE oxidative weathering is the result of transient oxygenation events driven by 'oxygen oases' in the marine realm. Lalonde and Konhauser<sup>3</sup> recently proposed an alternative model, that being intense O<sub>2</sub> generation – and immediate consumption – at sub-meter scales by benthic oxygenic photosynthesis in the terrestrial realm. Despite the absence of a UV-protective ozone layer in the Archean, a terrestrial phototrophic biosphere may have existed in various sheltered environments, including biological soil crusts and freshwater microbial mats covering riverbed, lacustrine, and estuarine sediments. We calculate that the rate of O<sub>2</sub> production via oxygenic photosynthesis in these ecosystems provides sufficient oxidising potential to mobilise sulphate and a number of redox-sensitive trace metals from land to the oceans while the atmosphere itself remained anoxic with its attendant S-MIF signature. An intriguing question that follows from this hypothesis is if cyanobacteria were

conceivably metabolising at modern rates on land by perhaps 3.0 Ga, what happened in the hundreds of million years between the first, rare signals of oxidative weathering and the first significant accumulation of atmospheric oxygen, i.e., the GOE? While the exact confluence of factors controlling the success of Earth's earliest oxygenic phototrophs remains an open question, several factors may have depressed areal coverage or photosynthetic efficiency of cyanobacteria, and thus masked their potential presence prior to the GOE, including the lack of emergent and colonisable land for oxidative weathering.

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### ORAL

#### The Ediacaran succession and fauna of the Digermulen Peninsula, northern Norway

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First discovered in the late 1980's, the Digermulen Peninsula in Finnmark, northern Norway, is the only locality in Scandinavia with Ediacara-type fossils. The Ediacaran to Lower Ordovician sedimentary succession here consists of over 3000 m of siliciclastic-rich deposits formed in a foreland basin marginal to Baltica. Since 2011, studies by the Digermulen Early Life Research Group have recorded significant new finds, promising to establish the site as a new key Ediacaran biota locality. The Ediacaran succession is close to 1000 m thick. It starts with interglacial sediments of the Nyborg Formation (tentatively earliest Ediacaran), followed by the glaciogenic diamictites of the Mortensnes Formation (~60 m thick), probably representing the

~582 Ma Gaskiers glaciation. Ediacara-type fossils occur in the Innerelva Member of the succeeding Ståhpogiedde Formation. This is followed by the Lower Cambrian Breidvika Formation. The Ediacaran–Cambrian boundary is located within the Manndraperelva Member of the Ståhpogiedde Formation, identified by the trace fossil *Treptichnus pedum*, associated trilobed trace fossils and microfossils. The Ediacaran assemblage is dominated by discoidal fossils, the nomenclature of which is currently under study. The 2015 field season brought to light the first specimen of a multi-vaaned Ediacara-type fossil, so far unidentified. In addition, well-preserved *Hiemalora* are found, and *Palaeopascichnus* occur near the base of the Innerelva Member. This makes them the oldest non-stromatolite macroscopic fossils in Scandinavia. Hitherto the Innerelva Member has not yielded microfossils.

ORAL

### Local environmental controls on microbial Fe(II)-oxidation in seafloor hydrothermal deposits

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Microaerophilic Fe(II)-oxidizing bacteria form distinct twisted extracellular stalks that may function as biosignatures and indicators of palaeo-redox conditions in jaspers and iron formations. The identification of Fe(II)-oxidizing bacteria in the rock record is dependent on knowledge of the geological setting and local environment of Fe-deposition. Here we aim to shed light on the environmental factors governing microbial Fe(II)-oxidation and biomineralization by combining molecular, textural and geochemical analyses of modern stratified low-temperature hydrothermal Fe-deposits at the Jan Mayen Vent Fields, Arctic Mid-Ocean Ridge. Our results reveal that Fe(II) supplied by low-temperature hydrothermal fluids is utilized by a

microaerophilic Fe(II)-oxidizing community dominated by *Zetaproteobacteria*. The Fe-deposits are composed of biomineralized twisted stalks and branching sheaths with alternating MnO<sub>2</sub>- and sediment-rich horizons, cm-sized domal internal cavities and fibrous, organic-rich laminae. All laminae show negative Eu-anomalies, reflecting the low-temperature origin of the hydrothermal source fluid. Elevated P and REE contents in the fibrous laminae indicate that Fe(III)-reduction takes place in the underlying sediments and that hydrothermal fluid pulses supply recycled Fe(II) and adsorbed elements to the seafloor. Variations in textures and chemistry furthermore suggest that fluctuations in hydrothermal fluid discharge exert the primary control on the formation of laminae and constrain the spatial distribution of biomineralized extracellular stalks. We suggest that fossil low-temperature hydrothermal deposits represent the most promising archives for microaerophilic Fe(II)-oxidizing bacteria in the rock record. These deposits may be identified based on a combination of twisted and branching filament morphologies, Eu-depleted REE patterns and synchronous interlaminar variations in filament associations and contents of REE, P and MnO<sub>2</sub>.

ORAL

### Microbiological research on the Nornhraun lava field

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Newly formed lava fields are unique environments as they are the only naturally sterile (life-free) places on Earth. This makes fresh lava fields ideal research environments for studying microbial succession – colonization of the rock and development of viable microbial communities – that eventually leads to soil formation and development of higher life. Although the latest models suggest that life might have emerged on volcanic rocks in a formamide environment, nothing is known about the ability of modern microbes to thrive in previously uninhabited rocky environments.

The aim of this study is to reveal the microorganisms responsible for the transformation of the barren rock to a life-supporting ecosystem with soil and vegetation. Our research site is the Nornhraun lava field of the Bárðarbunga volcanic system in Iceland that formed during fissure eruptions between August 2014 and February 2015. The lava field covers ~85 km<sup>2</sup> and contains several microenvironments with different starting conditions (humidity, radiation, temperature, lava morphology, mineralogy) for microbes. Sampling included collection of rocks from different microenvironments and testing the eolian input of microbes with growth media plates deployed on the lava field. Plate experiments revealed the introduction of fungi and bacteria onto the lava field, with rain being probably a more important source than wind. Rock samples will be analysed for the presence of microbes and their specific metabolic properties. Only a limited number of species with special molecular properties are expected to survive on hostile lava fields with few available nutrients. Samples are also subjected to geochemical analysis to study the effects of different mineralogy on microbial colonization.. Sampling of the lava field is planned to continue annually for the purpose of long-term monitoring of the

colonization. The results will unravel the primary microbial succession in rocky environment and also build on our understanding of geochemical recycling as the first colonizers and the environments they create facilitate rock weathering and soil formation.

ORAL

### Origin of rod and dumbbell shaped phosphate precipitates in Namibian shelf sediments

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Microbial processes are thought to play an important role in modern marine phosphogenesis. Sulphur bacteria inhabiting modern shelves act as bacterial “pumps” leading to the phosphate concentrations needed for precipitation of Ca-phosphate minerals such as apatite (Schulz, 2005). Apatite precipitation is highly enhanced in the presence of suitable nucleation templates, such as organic matrices and bacterial ultrastructures.

The microstructure of phosphatic grains from modern Namibian shelf sediments was examined using scanning electron microscopy. The grains are composed of mostly pure Ca-phosphate and are highly porous. The pore walls are largely coated with rod-shaped microstructures of around 1 μm in length and 0.3 μm in diameter which co-occur with an organic matrix. The rods possess consistent shapes and sizes, and are composed of nanocrystallites arranged along the long axis. Superficially, they strongly resemble mineralized microbial cells. However, some morphological features are not consistent with microbial origin. Many of the rods intersect at angles close to 60 or 90 degrees. Together with other microstructures present in the grains, they seem to form a continuum from rods through dumbbells to semi-spherical. Remarkably similar aggregates, called biomimetic fluoroapatite-gelatine composites, have been described from laboratory experiments at high supersaturation (e.g. Busch 1999).



Our findings indicate that precaution must be taken while assessing the microbial origin of authigenic precipitates. Nevertheless, the common association of biomimetic apatite composites with organic matrices is consistent with the influence of biological processes on phosphate availability and precipitation.

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#### POSTER

### The Ordovician reefs of Baltica

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Widespread growth of reefs formed by a framework of biogenic constructors and of frame-lacking carbonate mounds started on Baltica during the Ordovician. Previously, Ordovician reef and mound development on Baltica was considered to be sporadic and local. A review of all known bioherm localities across the Baltic Basin reveals a more consistent pattern. Ordovician reefs and mounds grew in a wide E/W stretching belt across the Baltic Basin and occur in several places in Norway. The development started nearly abruptly and massively during the late Sandbian / early Katian interval and climaxed during the late Katian.

The current spatiotemporal distribution of bioherms is a result of interdependent factors of post depositional erosion, relative sea level and climate during the time of deposition. The likelihood that bioherms are preserved from long time erosion is higher when deposited during low sea level in deeper parts of the basin. At the same time, oceanographic conditions were likely more favorable during times of cooler global climates, low sea level and glacial episodes.

A main factor for the timing of the reef and mound evolution was Baltica's shift toward

palaeotropical latitudes during the Late Ordovician. The time equivalence between initial reef growth and the Guttenberg isotope carbon excursion (GICE) suggests that global climatic conditions were important. The long lasting stability, the resilience of individual mounds, and the increasing taxonomic diversity of the reefs/mounds suggest a significance of biological factors for the reef formation.

#### POSTER

### Magnetostratigraphic framework for the late Miocene mammalian fossils in Maragheh, NW Iran

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Maragheh in northwestern of Iran is a world famous Miocene fossil bearing area. The area has yielded classical late Miocene Turolian age fauna that has been collected and studied sporadically over the last 150 years.

However, most of these expeditions focused on the collection of fossils and description of new taxa, while much less effort was put on stratigraphy and age of the fossil occurrences. For example, magnetostratigraphy was not applied in the Maragheh area until preliminary work in the 1970's.

In order to provide a time frame for the late Neogene Maragheh sequence, we measured and sampled ca. 26-m-thick stratigraphic section at Dareh-e Gorg for paleomagnetic analysis. Paleomagnetic samples were collected every 20–50 cm and analyzed using alternating field and thermal demagnetisation methods. Samples yielded characteristic remanent magnetization (ChRM) carried by magnetite. Positive reversal test (McFadden and McElhinny, 1990) indicates that ChRM is primary and that it is not contaminated due to secondary components. Our data indicate that the sampled Dareh-e Gorg sequence consists of three magnetozones, the middle part of the section at around 15–21 metres showing reversed polarity, bounded by normal polarities above and below. Based on the paleontological constraints and recent K-Ar age determinations from the Maragheh Fm, two correlations

to the geomagnetic polarity time scale of Gradstein et al. (2012) seem possible. The first option places the magnetozones to C3Br.1n through C3Bn (7.285–7.140 Ma). Alternatively, the polarity sequence may be correlated to chrons C4n.1n to C3Br.2n (7.642–7.454 Ma).

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#### POSTER

### Ancient ecosystems in crystalline bedrock fractures

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The Fennoscandian crystalline bedrock fractures host microbial communities with versatile features. These communities thriving in isolated environments are possibly forming the oldest known ecosystems on Earth, as they are likely as old as the fracture fluids, up to 58 Ma [1]. Low cell numbers but high diversity is characteristic to the microbial communities of the Outokumpu deep subsurface in Finland [2-4]. *Comamonadaceae*, *Peptococcaceae* and *Anaerobrancheae* are prevalent bacterial members of the bacterial communities in the fracture fluids. Archaea are vertically distributed in Outokumpu fracture zones as they are in other Precambrian shields deep sites [5]. Archaeal species with versatile carbon metabolism are more abundant above 1500 m depth, as the hydrogenotrophic *Methanobacterium* dominates the communities below this depth [3-4]. Both bacterial and archaeal communities in Outokumpu fractures share features with other deep ecosystems. Dominant members of bacterial communities are similar to those detected from serpentinization-driven subterrestrial and surface aquifers. Sulfate-reducing microbial community shares features especially with Witwatersrand

deep biosphere [3]. SAGMEG archaea first characterized from gold mines in South Africa are especially abundant in the 967 m fracture in Outokumpu [3]. In addition, Outokumpu fractures present numerous phylotypes with low abundance, i.e. members of the rare biosphere with vast genetic potential to respond to possible environmental changes [3].

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## S9.2 What is the Anthropocene?

### KEYNOTE

#### The origin of the Anthropocene? Homo-induced collapse of East African carnivore guild, 2 mya.

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Studies of African mammalian carnivore fossils from the past seven million years show that the large members of this group have declined dramatically both in terms of the number of species and in ecological breadth, especially in the types of food and feeding behavior (functional richness). Prior to 2 million years ago, the community of large carnivores in eastern Africa ranged from those adapted to eating mostly plant foods (hypocarnivores) to those built for subsisting mainly on meat (hypercarnivores); today only few hypercarnivores remain (Werdelin and Lewis, 2013). The timing of the decline coincides with the rise of the *Homo erectus*-group of hominins, which were the first human ancestors to show biological adaptations trending towards those seen in modern humans, including the incorporation of significant amounts of meat in the diet. This suggests that competition with humans for access to prey drove many big carnivores to extinction (Werdelin, 2013). In addition, changes to the carnivore guild may have led to changes among the herbivores, through a trophic cascade. This is the earliest documented permanent (through extinctions) modification of the natural environment by the human lineage, pushing back the origin of the 'Palaeoanthropocene' (Foley et al., 2013) to ca 2 mya.

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### ORAL

#### A Tale of Ice and Campfires: Changes in the carnivoran guild of Britain during the Quaternary period influenced by hominids and climate change

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The order Carnivora is a diverse group of mammals that occupy a wide range of environments and ecological niches. This study looks at how the British carnivoran guild was affected during the Quaternary period when Britain underwent cycling glaciation events and colonisation by several hominid species. In addition to a gradual reduction in species number towards the present day, we find that the Beestonian glaciation (0.68-0.62 Ma) and the arrival of the early human *Homo heidelbergensis* during the following interglacial period (approx. 0.6 Ma) coincide with significant rapid changes in body size composition of the guild. Six small carnivorous species disappear during the Beestonian glacial period, whereas after the arrival of *Homo heidelbergensis* three large hypercarnivores (*Xenocyon lycanoides*, *Panthera gombaszoegensis* and *Pachycrocuta brevirostris*) disappear from the British record. Competition from related species and *H. heidelbergensis*, together with the reduction of prey caused by the disappearance of many large herbivore species during the Beestonian glaciation, are the likely drivers of this observed change in carnivoran guild composition. *H. heidelbergensis* is associated with substantial evidence of tool usage and possibly the use of fire. Interestingly, we see no change in carnivoran guild structure after the arrival of *Homo neanderthalensis* (approx. 0.4 Ma), known to have competed against carnivores elsewhere, but *H. heidelbergensis* disappears from the British record soon afterwards. Overall, the functional richness of the British carnivoran community declines towards the present, corresponding with the decline observed in the contemporaneous African carnivoran guild attributed to both changes in climate and competition with early *Homo* species.

The phylogenetic diversity of the British carnivoran guild also declines towards the present, and this corresponds with the decline observed in Eurasia during the same time period. However, the changes in Britain are more abrupt, reflecting its vulnerability as a peninsular/island ecosystem.

ORAL

### The chemical composition of the atmosphere in the Anthropocene

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During a substantial part of the Earth's history the atmosphere (Greek 'atmos'='vapour' + 'spharia'='ball') has been brought to thermodynamic disequilibrium by biological processes (Wayne, 2000). In fact, plants have played a crucial role in determining atmospheric change and hence the conditions on the planet we know today (Beerling, 2008). The epoch of Anthropocene is bringing with it large changes in the environment (Crutzen and Stoermer, 2000). These alterations cause perturbations in biogeochemical cycles that induce extensive further changes in the atmospheric chemical composition.

Although anthropogenic changes are driven by human induced emissions, atmospheric chemistry plays a large role in determining the burden and residence time of atmospheric constituents. In the atmosphere, a gaseous chemically active compound can be affected by interaction with other species in its immediate vicinity and interaction with solar radiation (photolysis). Atmospheric chemistry is characterized by many interactions and patterns of temporal or spatial variability, leading to significant nonlinearities and a wide range of time scales of importance (Isaksen et al., 2009). Most radiatively active compounds in the Earth's atmosphere are chemically active, meaning that atmospheric chemistry plays a large role in determining their burden and residence time and thus their forcing of climate change in the Anthropocene (Myhre et al., 2013).

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ORAL

### Duality of Anthropocene

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The concept of Anthropocene was coined by Stoermer and Crutzen in 2000 to mark a change from a world where Nature was dominating to a world where humans are an ecological force. The term was adopted quickly in various disciplines. The currently unfolding discourse on the Anthropocene represents a convergence of natural sciences and social sciences. In natural sciences the definition of the start of the Anthropocene period has become a hot topic. In social sciences the use of the term has varied from the implications of humans as an ecological force to the understanding of what constitutes societies and societal change (e.g. Moore 2015).

In the humanities, Anthropocene has come to denote an experiential change both on an individual and a collective level: paradoxically, Anthropocene is an epoch of total human planetary impact and a historical moment of awakening to a loss of control over our environment (e.g. Latour 2011). Therefore the concept of Anthropocene is supported by people of very different ideological persuasions. One advocates for business-as-usual driven by technological breakthroughs (e.g., saying the Anthropocene reveals that humanity is facing a never-seen-before predicament. The solution? Use more, and better, technologies, in order to better control nature.), another calls for a total transformation of humanity's relationship with nature (e.g. Bruno Latour (2011) uses the term—and the reality of human involvement in the climate—as a launching point to discuss the new politics required), yet another suggests that

it signifies that we need to put our differences aside, and face this challenge together, as one (e.g., that the ongoing changes affect the rich and the poor, and we should distribute wealth to increase resilience). In this presentation we review these different uses of Anthropocene and offer insights on the implications that the different uses of the term will have.

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ORAL

### The Anthropocene; a formal stratigraphical unit, an informal concept, or an interval of Holocene time?

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In recent years 'Anthropocene' has been proposed as an informal stratigraphic term to denote the current interval of anthropogenic global environmental change. A case is also been made for its consideration as a formal series/epoch, based on the recognition of a suitable marker horizon or event, such as the start of the Industrial Revolution in northern Europe. In order for the Anthropocene to merit designation as a formal stratigraphic unit, however, such an event would need to leave a global signature consistently distinct from that of the Holocene or of previous interglacials of the Pleistocene, and be marked by novel biotic (i.e. biostratigraphical), sedimentary and geochemical change. Although there is clear evidence in recent geological records of anthropogenic effects on the natural environment (atmospheric trace gas increase, sea-level rise, accelerated erosion, etc), it is far from certain that the stratigraphic signature of these trends is sufficiently distinct, consistent, and adequately dated at the global scale, for the proposal for a Holocene/Anthropocene boundary to be substantiated on stratigraphic grounds. As a consequence, there is a view within the Earth-science community that, if the term is to be employed, it

should remain an informal label. Here the Anthropocene will be considered in the context of the formal definition of geological time-scale units, particularly of the requirement for relating such units to unequivocal Global Stratigraphic Section and Point ('golden spike') localities, and that adoption of the term 'Anthropocene' will ultimately depend on whether such an event layer or horizon can be identified globally. In the absence of such a marker, it will be concluded that there is no justification for decoupling the Anthropocene from the Holocene, and that if the term Anthropocene is deemed to have utility, it should be as an informal historical designation rather than a formally-defined stratigraphic unit (of whatever status) within the Geological Time Scale.

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ORAL

### A Geologic Turn — Deep Time and Deep Futures in contemporary art

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The realization that anthropogenic impact is leading to planet wide transformations as well as to their readability and to repercussions in deep futures is not only discussed within natural science and the humanities. The anthropocene and specifically geological topics surface in contemporary artistic practices. We can see an increase in cultural responses which for example address geophenomena (Berger 2012), mining (Cohen and Van Balen 2014), global warming (HeHe 2008) or nuclear issues (Berger 2015) and their relation to deep time and deep futures from an artistic point of view. These artworks explore the dichotomy between human time perception and the time in biological, environmental, and geological processes of which we humans are part of.

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**POSTER**

**Co-occurrence of the pliopithecoid and  
 hominoid primates in the fossil record: an  
 ecometric analysis**

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Both pliopithecoid and hominoid primates were widely distributed throughout Eurasia during the Miocene, but are known to have coexisted only at a few localities. Special environmental conditions have been suggested as a reason for the rarity of this co-occurrence. Here, we study their co-occurrence using taxonomically-based palaeoecological diversity of associated fossil mammals as well as direct ecometric analysis based on hypsodonty of mammalian herbivores. Our results show that pliopithecoids had more persistently humid occurrence contexts compared to other primate groups studied, suggesting an inability to adapt to changing environmental conditions. The opportunity for co-occurrence of hominoids and pliopithecoids appears to have been restricted by this niche conservatism in the latter group. Co-occurrence is seen under apparently even more humid conditions than the occurrence of pliopithecoids alone, but the difference is not statistically significant. Direct ecometric analysis gives a better separation of the ecological preferences of primate clades than do analyses of taxonomically-based community structure.

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- Sukselainen, L., Fortelius, M., Harrison, T., 2015. Co-occurrence of pliopithecoid and hominoid primates in the fossil record: an ecometric analysis. *Journal of Human Evolution*, 84, 25-41.

## S10.1 Petrology general

### KEYNOTE

### Enriched continental basalts from depleted mantle melts: the issue of lithospheric contamination

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Magma-wallrock interaction (assimilation) is critical to the thermodynamic and chemical evolution of a magmatic system. While the most widely used quantification of AFC (assimilation-fractional crystallization) is DePaolo (1981), this approach is limited because it is not thermodynamically feasible. It mixes a compositionally fixed bulk contaminant into a magma body despite excellent documentation of partial melting processes at the contacts of intrusive rocks. Such limitations may significantly impact the mass balance of different sources in models of magmatic systems.

In our case study, we present contamination modeling of highly heterogeneous (e.g., initial  $\epsilon_{Nd}$  from -15 to +2) continental flood basalts from Vestfjella mountain range, Antarctica, which belong to the Jurassic ~180 Ma Karoo large igneous province. Previously presented AFC models implied that high amounts of crustal contribution (~20 wt. %) would be needed to explain the most enriched geochemical signatures. We show that by selecting viable representatives for crustal and mantle contaminants (Archean and Proterozoic crust and SCLM-derived melt i.e. lamproite) and by using the energy-constrained AFC (EC-AFC) modeling (Spera and Bohrsen, 2001), all Vestfjella lava types can be produced from a MORB-affinity parental melt with less than 5% of lithospheric contamination. This suggests an important role for a long-term depleted sublithospheric mantle source in their petrogenesis.

We encourage all igneous petrologists to learn to use EC-AFC equations in any model that involves contamination of a magma body with lithospheric components.

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### ORAL

### Mesoproterozoic diabase in Death Valley, California

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Mesoproterozoic diabase dikes and sills are widespread throughout the southwestern US. In the Death Valley region of SE California, diabase in sills a few meters to ~450 m thick, intrudes the Neoproterozoic Crystal Spring Formation. Baddeleyite from diabase in Crystal Spring and Saratoga Springs have ID-TIMS U-Pb ages of 1087±3 Ma and 1069±3 Ma, respectively (Heaman and Grotzinger, 1992). We have analyzed (by LA-ICPMS) the U-Pb isotope composition of tiny baddeleyite grains spotted in thin sections in search of a magmatic age of the Jupiter Hill diabase sill in the Kingston Range, southern Death Valley. Ten *in situ* spots define a weighted-average <sup>207</sup>Pb/<sup>206</sup>Pb age of 1101±12 Ma (MSWD 5.6). This age can be considered, within the experimental error involved, a reliable estimate of the emplacement age of the Jupiter Hill diabase sill. The upper unit of the Crystal Spring Formation is thus older than 1.1 Ga, contrary to recent detrital zircon U-Pb data released by Mahon et al. (2014). We have also analyzed three samples from the Jupiter Hill and Crystal Spring diabbases for Nd isotopes. These diabbases are transitional basaltic and moderately enriched in LREE with <sup>147</sup>Sm/<sup>144</sup>Nd of ~0.15. The initial  $\epsilon_{Nd}$  (at 1100 Ma) values for the Jupiter Hill sill are +2.9 (chilled margin) and +4.6 (sill interior) and that for the Crystal Spring sill -1.0. The two samples from Jupiter Hill are hydrothermally pervasively altered with only zircon, baddeleyite, and apatite as preserved magmatic minerals. It is likely, however, that the igneous values of

the conserved elements (e.g., REE) have been retained. The measurable difference ( $\sim 1 \epsilon$ -unit) of the initial  $\epsilon_{\text{Nd}}$  of the chilled margin and sill interior may have petrogenetic significance. The chilled margin is higher in  $\text{SiO}_2$  and  $\text{Mg/Fe}$ , and lower in total REE than the sill interior and may represent an earlier batch of basaltic magma derived from a mildly depleted lithospheric mantle source. The sill interior could have been crystallized from a less-contaminated basaltic magma from the same deep source, yet shielded from contamination by armored conduit margins. The Crystal Spring diabase presumably registers a local, more enriched, source in the subcontinental mantle of Mojavia.

ORAL

### The Pushtashan ophiolite: New Evidences for Iraq Zagros Suture Zone, Kurdistan Region, NE Iraq

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Fragmented ophiolite complexes are abundant in the Iraq Zagros Suture Zone, which marks the boundary between the Arabian and the Eurasian continents. These ophiolites were emplaced in two major episodes in Late Cretaceous and Paleogene times (Ismail et al. 2014). The Late Cretaceous Pushtashan ophiolite (POC) outcrop trends parallel to the Zagros belt and attains a width of six kilometres. There is a major structural break between the sequence underlying Tertiary Red Beds.

POC displays the classic ophiolite sequence and consists of three units. The topmost is volcanic rock, approximately 1000m thick, consisting of basalt and andesite. POC intrusive rocks approximately 140m thick form the middle part of the Pushtashan ophiolite and consist mainly of norite. Felsic igneous intrusions (mostly plagiogranite) are present in the upper part of the norite body. A small granitic sill is associated with plagiogranite. Ultramafic rocks make about 10% of the complex and form the lower unit. The maximum 40m ultramafic rocks consist of serpentized peridotite, sometimes altered to chrysotile asbestos and magnesite.

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Ismail S.A, Kettanah Y.A., Chalabi S.N. Ahmed A.H. and Arai S., 2014. Petrogenesis and PGE distribution in the Al- and Cr-rich chromitites of the Qalander ophiolite, northeastern Iraq: Implications for the tectonic environment of the Iraqi Zagros Suture Zone. *Lithos* 202–203 (2014) 21–36.

ORAL

### Magmatic age of the Norra Kärr alkaline complex determined by U–Pb and Lu–Hf isotopes of metasomatic zircon in fenite

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The Norra Kärr alkaline complex in southern Sweden is a small igneous intrusion of agpaitic nepheline syenites, which is characterised by complex magmatic Na–Ca–Zr–Ti–REE silicate minerals instead of conventional zircon and titanite. The wall rock—originally a TIB granite—was strongly affected by syn-magmatic alkali metasomatism (fenitisation) and now consists largely of albite and aggregates of biotite and aegirine(-augite). Here, abundant anhedral zircon (100–500  $\mu\text{m}$ ) and zircon inclusions (<10  $\mu\text{m}$ ) are associated with fluorite, aegirine(-augite), andradite, bastnäsite, xenotime, fluorapatite, and magnetite. We characterised zircon in the fenite to indirectly date the agpaitic magmatic activity.

U–Pb and Lu–Hf isotopic compositions of zircon and eudialyte (only Lu–Hf) were determined by LA-MC-ICP-MS at the Department of Geosciences, University of Oslo.

A reliable upper concordia intercept age of a mostly-concordant group of zircons gave  $1488 \pm 8 \text{ Ma}$  ( $2\sigma$ ,  $p = 0.86$ ,  $n = 23$ ), within error of the weighted mean  $^{207}\text{Pb}$ – $^{206}\text{Pb}$  age (reworked data, previously reported by Sjöqvist et al., 2014).

Lu–Hf systematics of zircon in the fenite and eudialyte in the nepheline syenites—in addition to mineral associations in the fenite—agree with a genetic link between the magmatic and metasomatic activity by showing identical initial  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios. The  $\epsilon_{\text{Hf}}$  for the fenite zircon at the time of formation (1.49 Ga) is  $6.44 \pm 0.5 (2\sigma)$ , which is significantly above the expected signature of Svecofennian crust at that time (ca.  $-5 \pm 2$ ), but is similar to a “mildly-depleted mantle”.



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## ORAL

### Pilanesberg, South Africa: The “forgotten” alkaline complex

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The Mesoproterozoic Pilanesberg Complex in the Northwest Province of South Africa is one of the largest alkaline intrusive complex on Earth. After initial studies in the early half of the 20<sup>th</sup> century, little research has been published on its petrology, mineralogy and geochemistry, despite its variety of rock associations and mineralogical features, and a potential for REE and Th mineralization.

The Pilanesberg consists of a series of concentric, ring-shaped hills, made up by intrusions that range from miaskitic syenite, through mildly agpaitic nepheline syenites (red and white foyaites) to highly agpaitic lujavrite (green foyaite). They are capped by lavas derived from the underlying intrusive. The overall structure of the intrusion is debated, and now considered to be a gently inward-dipping sheet. Subsequent injections of magma inflated an existing and evolving magma chamber rather than intruding into solid rocks.

Syenites and nepheline syenites in Pilanesberg are characterized by higher Mn/Fe and K/Na ratios and Ca content than is commonly seen in agpaitic complexes, and water activity during crystallization was high, resulting in considerable hydrothermal alteration.

Whereas the green foyaite is a classic agpaitic rock with rock-forming eudialyte, the white foyaite offers a rare opportunity to study a transition between miaskitic and agpaitic crystallization regimes, in which the different High Field Strength Elements show contrasting behaviour. Whereas Ti is hosted in a sequence of progressively more alkaline minerals (titanite, astrophyllite, aenigmatite, lorenzenite, rinkite), Zr remains hosted in clinopyroxene almost to the end of magmatic crystallization

## POSTER

### Naujakasite revisited

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The rare mineral naujakasite ( $\text{Na}_6\text{FeAl}_4\text{Si}_8\text{O}_{25}$ ) is rock forming in hyperagpaitic lujavrite in the Ilímaussaq complex, Greenland. From a chemographic analysis of naujakasite-bearing mineral assemblages in a much simplified model lujavrite system, Andersen and Sørensen (2005) inferred a very restricted stability field for naujakasite at extreme peralkalinity, low  $f_{\text{O}_2}$  and moderately elevated  $a_{\text{H}_2}$ , which is confirmed by modelling in a more realistic multi-component chemical system. The required conditions may not be commonly encountered in alkaline rocks. Agpaitic magma crystallizing eudialyte at an early stage (e.g. kakortokite magma in Ilímaussaq) is unlikely to reach the sodium enrichment needed to stabilize naujakasite by fractional crystallization. An alternative to closed system fractional crystallization to reach the very high sodium activity required by naujakasite is intraplutonic assimilation of sodalite by a lujavrite magma that may allow liquid compositions to tunnel through the eudialyte-arfvedsonite-albite-nepheline and aegirine-arfvedsonite-albite-nepheline barriers to develop further towards hyperagpaitic residuals that will eventually crystallize naujakasite.

Like the fractional crystallization scenario without aegirine suggested by Andersen and Sørensen (2005), this model requires special geological conditions to be able to operate: Late stage lujavrite magma in Ilímaussaq intruded into naujaite roof cumulate with abundant sodalite. Such a special geological setting may help explaining the global rarity of this mineral.

## References:

Andersen, T. and Sørensen, H., 2005. Stability of naujakasite in hyperagpaitic melts, and the petrology of naujakasite lujavrite in the Ilímaussaq alkaline complex, South Greenland. *Mineralogical Magazine* 69, 125-136.

## POSTER

### The stability of wöhlerite in agpaitic nepheline syenite: The effect of oxygen fugacity

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Wöhlerite is one of the most common zirconium disilicate minerals in nepheline syenite pegmatites in the Larvik Plutonic Complex (LPC) in the Oslo Rift (Sunde et al, this conference). It commonly occurs as euhedral to subhedral primary crystals formed during early magmatic crystallization, and is commonly intergrown with aegirine, amphibole and magnetite. Unlike related minerals such as hiortdahlite and lävenite, wöhlerite does not occur in stable coexistence with fluorite. Instead, assemblages with hiortdahlite + fluorite replace primary wöhlerite. These observations suggest that wöhlerite and fluorite, and possibly also wöhlerite and biotite, are unstable together, or that the stability field of the relevant assemblages are small and situated at physicochemical conditions not encountered in the pegmatites. The semiquantitative phase diagram in  $\log a_{Na_2Si_2O_5} - \log a_{H_2O} - \log a_{Hf} - \log a_{H_2O} - \log a_{Hf}$  space constructed by Andersen et al. (2010) assumed  $f_{O_2}$  controlled by coexisting microcline + biotite + magnetite. At higher  $f_{O_2}$  (microcline + magnetite without biotite), the stability fields of wöhlerite + fluorite and hiortdahlite + fluorite expand at the expense of lävenite and eudialyte. Since  $Fe^{2+}$  is essential for lävenite and eudialyte, the reason for this change of stability relationships is probably the lesser abundance of  $Fe^{2+}$  at higher levels of oxygen fugacity.

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Andersen, T., Erambert, M., Larsen, A.O., Selbekk, R. 2010. Petrology of nepheline syenite pegmatites in the Oslo Rift, Norway: Zirconium silicate mineral assemblages as indicators of alkalinity and volatile fugacity in mildly agpaitic magma. *Journal of Petrology*, 51, 2303-2325.

## POSTER

### Stability of hydrothermal tourmaline: insights from phase equilibria experiments in the system

MgO-(±FeO)-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O-NaCl-B<sub>2</sub>O<sub>3</sub> at 400-650 °C and 3 kbar

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Tourmaline occurs in a wide range of magmatic, metamorphic and hydrothermal environments, including granite-related magmatic-hydrothermal systems, granitic pegmatites, boron-rich metasediments and orogenic gold deposits. Naturally occurring tourmaline shows wide variations in major element composition, reflecting many cationic and anionic crystal-chemical substitutions. The potential of tourmaline as a petrogenetic indicator has been widely recognized, but quantitative modeling of natural tourmaline compositions is not yet possible due to the lack of reliable thermodynamic data for its end-members and insufficient experimental data for tourmaline phase equilibria. The stability of tourmalines has been addressed by experimental and geochemical modeling techniques, but phase equilibria studies involving Mg-Fe tourmaline solid-solutions have proven highly challenging.

We report the preliminary results of experimental phase equilibria studies in the system MgO-(±FeO)-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O-NaCl-B<sub>2</sub>O<sub>3</sub> the temperature range 400-650 °C and at a pressure of 3.0 kbar. The experiments used natural quartz, H<sub>2</sub>O, NaCl, H<sub>3</sub>BO<sub>3</sub> and oxide powders as starting materials and experiments were performed in gold capsules in cold-seal pressure vessels. Two series of experiments were performed, which are experiments in the pure Mg system and experiments along the Mg-Fe binary. The experiments in the Mg system were designed to investigate the Tschermak (Al-for-Si) exchange and to link the stability of tourmaline with that of coexisting Mg-chlorite. The experiments in the Mg-Fe system were designed to constrain the stability of tourmaline solid-solutions along the dravite-schorl binary and to yield Mg-Fe partitioning data between coexisting tourmaline and chlorite solid-solutions. The experimental results make it possible to construct the tourmaline phase

equilibria in the Mg and Mg-Fe systems. The data show clear temperature dependence of the extent of Tschermak substitution in the Mg system and of the Fe-for-Mg exchange in the Mg-Fe system. The new data will be used, in conjunction with experimental data from the literature and calorimetric data, to derive thermodynamic properties of key tourmaline end-members.

**POSTER****A general model for carbonatite petrogenesis in shallow alkaline intrusions**

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On Brava Island (Cape Verde) various silica undersaturated rocks form a continuous intrusive suite, which can be explained by fractional crystallization of olivine, clinopyroxene, perovskite, biotite, apatite, titanite, sodalite and FeTi-oxides. This fractionation leads to alkali enrichment and drives the melts into the carbonatite-silicate miscibility gap resulting in the formation of carbonatitic melts. On the other hand, early saturation in feldspatoids or feldspars would effectively prevent alkali-enrichment and hence also the formation of carbonatites. We also show that an initial CO<sub>2</sub>-content of as little as 0.4 wt % is sufficient to saturate in CO<sub>2</sub> and to unmix carbonatites from nephelinites.

This model of fractionation and unmixing is also supported by the mineral chemistry within the conjugate carbonatite and nephelinite rocks on Brava. The modeled carbonatite compositions also correspond well with the natural samples, albeit with a much lower alkali-contents in the latter. The alkali-poor character of carbonatites on Brava is likely a consequence of the release of alkali-rich fluids during the final stages of crystallization (resulting in fenitization of the surrounding country rocks).

We thus conclude that Brava documents a complete and continuous fractionation line from primitive melts to syenitic compositions, with repeated immiscibility events that produces carbonatitic liquids. We also propose that this process is not only restricted to Brava island but is likely to operate in many shallow alkaline intrusions around the world.

## S10.2 Chronicles of petrological processes: In-situ geochemical studies of minerals and melts

### KEYNOTE

#### Novel isotopic and geochemical applications of Secondary ion mass spectrometry

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An increasing number of high-spatial resolution analytical methods are available to the modern petrologist seeking to obtain information on small-scale geochemical and isotopic heterogeneities in rocks and minerals. Amongst these, Secondary Ion Mass Spectrometry (SIMS) remains largely unchallenged, in spatial/volume resolution as well as sensitivity and the ability to measure both positive and negative ions. This keynote will explore some of the well-established methodologies available to Nordic researchers using modern, state-of-the-art SIMS instruments such as the CAMECA IMS1280 instrument in Stockholm, including in situ analysis of volatiles, halogen contents (and Cl isotopes), and Pb isotopes. Additionally, newly developed methods utilising scanning ion imaging will be presented, showcasing an as yet little used, but highly versatile new tool.

### KEYNOTE

#### Laser ablation Rb/Sr dating by online chemical separation in a reaction cell

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In-situ dating based on the U/Pb system has flourished in the last decade, allowing reading the geological code on Earth history to unprecedented breadth and precision. Similar advances were not possible for in-situ dating based on the beta decay, e.g. Rb/Sr, as the decay of the parent isotope produces a daughter isotope of the same mass. The only option is to chemically separate both elements.

With the introduction of the Agilent 8800 ICP-MS it has become possible to do such chemical separation “on the fly”. Here, a reaction cell is sandwiched between two quadrupoles, so that in the first quadrupole only ions pass having the mass of interest (e.g., on mass 87 <sup>87</sup>Rb<sup>+</sup> and <sup>87</sup>Sr<sup>+</sup>). Those ions can react with a gas in a reaction cell, after which the reaction products separated (e.g., <sup>87</sup>Rb<sup>+</sup> does not react with oxygen, while the new-formed <sup>87</sup>SrO<sup>+</sup> ion is measured on mass 103).

At the Microgeochemistry lab in Gothenburg, we have coupled an Agilent 8800 with a laser ablation system and implemented a procedure for doing in-situ Rb/Sr dating. Using (1) oxygen as a reaction gas, (2) the glass standards NIST SRM610 and BCR-2G for quantification of <sup>87</sup>Rb/<sup>86</sup>Sr and <sup>87</sup>Sr/<sup>86</sup>Sr ratios and (3) biotites from the La Posta intrusion (91.6 Ma) to correct Rb/Sr ratios in biotites (for an update on Rb/Sr corrections, see Karlsson et al., this meeting), it is possible to routinely date a range of different rock types with accuracies comparable to in-situ U/Pb dating. For example, we obtain a Bt-Kfs-Pl isochron of 1260±13 Ma for the Ulvö gabbro intrusion, Sweden, identical to a TIMS U/Pb baddelyite age of 1256±1 Ma (Hogmalm et al., 2006 GFF 128, 1-6). This confirms not only the reliability of our method, but also proves that the Central Scandinavian Dolerite Group (CSDG) was not thermally reset after intrusion beyond temperatures of ca 350°C (approximate closure temperature of biotite). Additionally, we obtained imprecise, but accurate initial <sup>87</sup>Sr/<sup>86</sup>Sr ratios of 0.7044±14, confirming little to no crustal contamination for the CSDG.

In-situ dating holds great promise for the field of Rb/Sr geochronology. Most importantly, it is possible now to avoid inclusions and alteration in micas and feldspars. Furthermore, it will be possible to study expected Sr isotope zonation caused by slow cooling and reheating. Finally, this technique is ideal for provenance studies of pebble-size granite fragments (see Johansson et al., this meeting). Other beta decay systems (Lu/Hf, K/Ca) are within reach.

ORAL

### Augite and enstatite standards for SIMS oxygen isotope analysis and their application to Merapi volcano, Sunda arc, Indonesia

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Measurement of oxygen isotope ratios in common silicate minerals such as olivine, pyroxene, feldspar, garnet, and quartz is increasingly being performed by Secondary Ion Mass Spectrometry (SIMS). Many mineral groups exhibit solid solution, however, which leads to compositional uncertainty such as in calcic clino-pyroxenes [(Ca, Mg, Fe<sup>2+</sup>, Fe<sup>3+</sup>, Al)<sub>2</sub>(Si,Al)<sub>2</sub>O<sub>6</sub>] and magnesium-iron ortho-pyroxene [(Mg,Fe)<sub>2</sub>Si<sub>2</sub>O<sub>6</sub>]. Variations in mineral chemistry can lead to instrumental mass fractionation (IMF) during SIMS analysis, which must be corrected using repeated analysis of compositionally similar standards to ensure accurate results. Here we report on new augite and enstatite pyroxene standards sourced from Stromboli, Italy and Webster, North Carolina, USA (Swedish Museum of Natural History mineral collection) in order to widen the current applicability of SIMS to mineral compositions in common igneous rocks. Aliquots of the crystals were analysed independently by laser fluorination (LF) to establish their true  $\delta^{18}\text{O}$  values. Repeated SIMS measurements on randomly oriented fragments of the pyroxene crystals yielded a range in  $\delta^{18}\text{O}$  less than  $\pm 0.32\text{‰}$  ( $1\sigma$ ). The homogeneity tests also verified that the proposed standards do not show any crystallographic orientation bias and that they are sufficiently isotopically homogeneous on the 20  $\mu\text{m}$  scale to be used as routine mineral standards. We tested the utility of our new standards by analysing pyroxene in well-characterised basaltic-andesite samples from Merapi volcano, Indonesia. SIMS data for Merapi augite overlap and exceed the published range of  $\delta^{18}\text{O}$  values for Merapi bulk pyroxene separates, thus demonstrating that 20  $\mu\text{m}$  scale resolution  $\delta^{18}\text{O}$

analysis can reveal a level of isotopic detail that may be masked by bulk crystal or whole rock studies. This advance opens the possibility for rapid but detailed oxygen isotope crystal isotope stratigraphy on common igneous pyroxenes by SIMS.

ORAL

### Composition and evolution of plume melts in the lower crust; Seiland Igneous Province

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The Seiland Igneous Province (SIP), Northern Norway predominantly consists of large gabbroic and ultramafic intrusions. These formed through continued fluxing of large volumes of melt through the lower crust (25-30 km) within a short duration of time (10 Ma) (Roberts 2007). This region may therefore represent a rare glimpse at the plumbing system within a large igneous province.

The Reinfjord ultramafic complex in the south west of the SIP is mostly composed of modally and cryptically layered dunite-wehrlite-olivine clinopyroxenites intruded into pre-existing but cogenetic gabbro-norite. The intrusion also hosts a Ni-Cu-PGE sulphide deposit. Here, we measure trace element and major element compositions in olivine, clinopyroxene and orthopyroxene using LA-ICP-MS and EPMA.

The results show that the parent melts that formed the cumulates have nearly identical REE abundances as picrite dykes observed throughout the region. These have steep REE profiles with OIB affinity. High LREE/HREE ratios indicate that the mantle source region contained a significant component of residual garnet and clinopyroxene (i.e. garnet pyroxenite). Bulk rock analyses of gabbroic rocks in the SIP also have similar REE patterns (Roberts 2007). Analysis of cumulus and intercumulus clinopyroxene allow us to track the evolution of the parent melts as they fractionate at depth. We find that the melts do not undergo significant amounts of fractional crystallization at depth, meaning that

large volumes of magma must pass through the system to shallower crustal levels. Lower crustal ultramafic intrusions may therefore play a crucial role in the transport of magmas through the lower crust by acting as more localized conduit systems.

#### References:

Roberts, R.J., 2007, *Ph.D. thesis, Univ. of Witwatersrand, Johannesburg, South African Republic*, 225 pp.

ORAL

### A novel approach to in-situ rutile thermochronology

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Accessory mineral micro-analysis provides a diverse and versatile toolbox for deciphering the timing and conditions of petrological processes. Here we present a novel approach to using U-Pb thermochronology of rutile by exploring the use of Pb as a diffusive species in kinetics-based thermometry. Using the high spatial and analytical resolution of laser ablation multi-collector ICPMS, we constrain Pb diffusion profiles in rutile from the UHP zone of Western Gneiss Complex (WGC), Norway. These data, combined with Pb-based thermometry, allow us to constrain a full thermal history from single grains.

Millimeter-sized single crystals of rutile from a phlogopite vein in eclogite were mounted and polished to expose their geometric cores. Modern laser ablation systems allow for the analysis of transects of rectangular spots (c. 15x45 µm) ensuring ablation of a significant volume while maintaining the required radial spatial resolution. Transects yield well-defined Pb diffusion profiles, with U-Pb ages ranging from c. 415 Ma in the cores to c. 380 Ma in the outermost rims (±2%, 2σ on individual spots). Diffusion zoning length was used with well-established Pb diffusion parameters [1] to determine peak temperature conditions. The result, c. 810 ± 25°C, is consistent with 800 ± 25°C and c. 780°C estimated for the same sample using conventional and Zr-in-rutile thermometry, respectively. The cooling history is reconstructed through

age zoning analysis and diffusion modeling, and agrees with constraints from <sup>40</sup>Ar/<sup>39</sup>Ar dating.

The cooling history deduced from in-situ micro-analysis of single rutile crystals is consistent with, and further refines, that established for the WGC through decades of <sup>40</sup>Ar/<sup>39</sup>Ar dating. The recognition that both thermometric and thermochronologic constraints can be obtained from rutile U-Pb analysis demonstrates the great potential of this technique in lithosphere research.

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ORAL

### Nano-powder tablets of mineral standards as matrix-matched reference materials for Rb-Sr dating

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Currently there is no established homogeneous matrix-matched reference material for Rb-Sr dating. As of now the K-feldspar NBS SRM607 is the only mineral-based material used as a standard for isotopic determinations of Rb/Sr ratios and Sr isotopes. However Nebel & Mezger (2006) demonstrated that the NBS SRM607 standard is heterogeneous with respect to Rb/Sr ratios. To circumvent this problem they proposed to plot Rb/Sr ratios and Sr isotopes on an Rb-Sr model isochron.

As an alternative approach to overcome inherent heterogeneities of mineral standards, we are using the method described by Garbe-Schönberg & Müller (2014) to produce several nano-powder tablets of several widely available mineral standards.

Compared to NBS SRM607 the Mica-Fe and Mica-Mg reference materials are available from various suppliers for more affordable prices. The Rb/Sr ratio and Sr isotopic composition of Mica-Fe and Mica-Mg have previously been determined by Govindaraju (1979), however we will re-analyse these as nano-powders by MC-ICP-MS with the method described in Nebel & Mezger (2006).

One long-term motivation is recent advancements in LA-ICP-MS/MS enabling *in situ* Rb-Sr

dating by reaction cell online chemical separation as outlined by Zack (2015, this conference). The nano-powder tablets we will produce have the advantage of being well suited for this novel technique.

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ORAL

**In-situ Sr isotope of plagioclase and its implication in the study of mafic layered intrusions**

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Plagioclase has high Sr contents and extremely low Rb/Sr ratios, ideal for in-situ Sr isotope analyses by LA-MC-ICP-MS. We have applied this method to mafic layered intrusions to constrain the isotope composition of magma.

The in-situ data of plagioclase grains from the Upper Critical Zone (UCZ) of Bushveld is broadly consistent with whole rock data, but in some samples, is systematically higher than whole rock result. This could be explained by over age-correction for whole rock analyses, due to elevated Rb/Sr ratios in later stage alteration. We have found disequilibrium of initial <sup>87</sup>Sr/<sup>86</sup>Sr ratios (Sr<sub>i</sub>) isotopic compositions between cores and rims of plagioclase grains, and between cores of different cumulus plagioclase grains within thin sections. One potential contribution to the heterogeneity is from alteration effect of plagioclase. For example, the Kemi intrusion experienced relatively high alteration, which may have disturbed the Rb-Sr isotope system of plagioclase evidenced by the general negative correlation between Rb/Sr ratios and calculated Sr<sub>i</sub>. This could be interpreted by variable elevation of Rb in plagioclase by later fluid. This correlation could potentially be a criteria to evaluate whether later alteration has affected the determination of Sr<sub>i</sub>. In

contrast, the lack of a negative correlation between Rb/Sr ratio and Sr<sub>i</sub> in the Bushveld samples indicates that the primary isotopic signature of plagioclase has been preserved, possibly reflecting the involvement of magmas with different isotope composition. This is consistent with other later studies, showing that the degree of heterogeneity of Sr<sub>i</sub> in the intrusions is correlated with the degree of crustal contamination.

In future study, in-situ trace element, Sr isotope analyses of plagioclase, and textural analyses of cumulate rocks should be combined to constrain the magma composition.

ORAL

**Micro drill sampling in *in situ* mineral analysis**

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Different types of *in situ* analysis techniques are now routinely able to deliver spatially and texturally controlled mineral chemical information on the evolution of magmas. For example Sr isotope analysis of feldspar by laser ablation ICP-MS analysis has proven its power in resolving sub-mm scale within-crystal variation. However, due to Rb interference on mass 87, LA-ICP-MS-analysis of Sr isotopes is limited to low Rb/Sr phases, which necessitates a different approach when studying for example micas or alkali feldspar. To overcome this problem micro drilling (and milling) techniques, which enable chromatographic chemistry and complementary TIMS and ICP-MS -analysis of the sample material, have been developed.

Micro drill technique is also showing promise in providing high-resolution textural control to U-Pb zircon analysis. Large age differences in zircon populations (*i.e.* Archean vs. Proterozoic) can be deciphered from LAM-ICP-MS and SIMS data on traditionally processed samples. A growing amount of evidence, however, shows that high-precision U-Pb geochronology is riddled with sample heterogeneities on a far more subtle scale, which warrants for better textural control of sample material.

For example the effects of antecrystic zircon entrainment can be studied by micro drill sampling in a wide variety of sample materials. Coupled with SIMS or single crystal CA-ID-TIMS analyses strong

textural control can provide important *a priori* evidence for mineral population classification.

Micro drilling approach was utilized to study the potential zircon antecryst entrainment effects on the U-Pb geochronology of the ~1.63 Ga rapakivi granites of the Wiborg batholith in south-eastern Finland. Meticulous sampling and SIMS analysis was able to resolve analytically minute (~1 myr) but petrologically significant age differences between the zircon populations within the rapakivi texture-forming alkali feldspar ovoids and the corresponding groundmass zircon populations. Combined with zircon trace element analyses, this approach is able to provide detailed information about the multiple stages in the magmatic evolution of the Wiborg batholith.

ORAL

### Aillikite and Kimberlite Dike Emplacement as a Climax of Long-lived Magmatism in West Greenland

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Eruption of CO<sub>2</sub>-rich ultramafic magma involves rapid ascent of mantle-derived magmas loaded with mantle xenoliths and xenocrysts (>30 vol%). The dynamics and duration of such eruptions are increasingly well constrained; the causes are nevertheless largely unclear. To address this issue, we performed a petrological and speedometric analysis of well-preserved crustal xenoliths from aillikite dikes at Sisimiut and Sarfartôq alkaline provinces, W Greenland.

The xenoliths represent mafic granulites, scavenged from c. 25-36 km depth within the mid-to-lower crust. The rocks are infiltrated by various types of melt in grain boundaries, cracks and veins. Zirconium-in rutile thermometry and Fe-in-rutile speedometry indicate melt temperature of c. 1,015 °C and melt exposure time of c. 4 hours for the host aillikite, implying an average ascent rate of c. 2 m s<sup>-1</sup>. This is slower than average ascent rates of mantle cargo (4-40 m s<sup>-1</sup> [1]), suggesting a slowing-down of transport at shallow levels.

Local diffusive zoning in garnet indicates up to 6,000 years of melt-assisted mass transport. This demonstrates a two-stage magmatic process of rapid melt ascent preceded by a previously unrecognized long magmatic episode. Melt infiltration at Sisimiut lasted 10 times longer than at Sarfartôq, and unlike at Sarfartôq was initially associated with carbonate- and sulfide-rich melt. This contrast reflects a fundamental difference in the devolatilization efficiency of parental carbonatite magma. The rapid development of the Sarfartôq system is ascribed to the local lithospheric mantle being highly depleted and rich in the decarbonation reactant orthopyroxene [2]. A link is also proposed between this feature, and the occurrence of REE-carbonatite and diamond-bearing mantle cargo at that particular location.

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ORAL

### Reconstructing the plumbing system of Krakatau volcano

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Crustal contamination of ascending arc magmas is generally thought to be significant at lower to mid-crustal magma storage levels where magmas inherit their chemical and isotopic character by blending, assimilation and differentiation [1]. Anak Krakatau, like many other volcanoes, erupts shallow-level crustal xenoliths [2], indicating a potential role for upper crustal modification and hence late-stage changes to magma rheology and thus eruptive behaviour. Distinguishing deep vs. shallow crustal assimilation processes at Krakatau, and elsewhere, is therefore crucial to understand and assess pre-eruptive magmatic conditions and their associated hazard potential. Here we report on a multi-disciplinary approach to unravel the crustal



plumbing system of the persistently-active and dominantly explosive Anak Krakatau volcano [2, 3]. We employ rock-, mineral- and gas-isotope geochemistry and link these results with seismic tomography [4]. We show that pyroxene crystals formed at mid- and lower-crustal levels (9-11 km) and carry almost mantle-like isotope signatures (O, Sr, Nd, He), while feldspar crystals formed dominantly at shallow levels (< 5km) and display unequivocal isotopic evidence for late stage contamination (O, Sr, Nd). Coupled with tomographic evidence, the petrological and geochemical data place a significant element of magma-crust interaction (and hence magma storage) into the uppermost, sediment-rich crust beneath the volcano. Magma – sediment interaction in the uppermost crust therefore offers a likely explanation for the compositional variations in recent Krakatau magmas and most probably provides extra impetus to increased explosivity at Anak Krakatau.

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**POSTER**

**Chemical evolution of the Luumäki gem beryl pegmatite: Constraints from EPMA and LA-ICPMS mineral composition data**

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Granitic pegmatites are important hosts for economically important rare-element and gemstone deposits, but the magmatic and hydrothermal processes responsible for enrichment of rare-elements and formation of gem-bearing miarolitic pockets are not fully understood.

The Luumäki gem beryl-bearing pegmatite is located within the Wiborg batholith in SE Finland, about 20 km SW of the town of Lappeenranta. It consists of at least two exposed pegmatitic dikes, and one is being actively mined for yellow gem beryl (heliodor) by the Karelia Beryl Oy company. The pegmatite shows a well-developed zoning with border zone, wall zone, intermediate zone and quartz core (Lahti and Kinnunen, 1993). This magmatic

crystallization sequence is followed by miarolitic pockets, which contain euhedral crystal assemblage (smoky quartz, K-feldspar, biotite, gem beryl). The mineralogy of the different pegmatite zones has been characterized, including determination of the accessory minerals.

Key minerals (feldspars, micas, fluorite and quartz) have been studied for their chemical composition (electron-microprobe and LA-ICPMS analysis of major and trace elements) to reconstruct the compositional zoning and time-space evolution of the Luumäki pegmatite system. Fluorite REE data suggest that both exposed dikes are part of the same pegmatite system, but only one carries economic gem beryl mineralization. The feldspar trace element data suggest that the formation of beryl bearing miarolitic pockets was caused by exsolution of Be enriched hydrothermal fluids during the late stage of pegmatite formation.

The textural relations between the pegmatite border zone and the host rock rapakivi granite demonstrate that the pegmatite was emplaced while the rapakivi granite was still hot and partially molten. Ongoing studies focus on stable isotope geochemistry, fluid inclusion studies and trace element modeling. This aims at reconstructing the pressure-temperature conditions and chemical environment during formation of gem beryl pocket.

**References:**

Lahti, S. and Kinnunen, K., 1993. A new gem beryl locality: Luumäki, Finland. *Gems & Gemology* 29, 30-37.

**POSTER**

**Magmatic fractionation and episodic fluid exsolution of the Kymi topaz granite stock, SE Finland: Insights from biotite major and trace element chemistry**

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The Kymi monzogranite stock features the chemically most evolved rocks of the 1.65 Ga Wiborg rapakivi batholith. The stock has a well-developed zonation from center to rim, which correlates with the degree of magmatic fractiona-

tion. The key rock types are (1) least evolved porphyritic granite (porphyroblasts up to 5 cm and fine-grained matrix), (2) more evolved porphyritic granite (2-3 cm sized porphyroblasts and coarse-grained matrix), (3) equigranular topaz granite, and (4) the marginal stockscheider pegmatite. The well-developed zonation and the presence of abundant miarolitic cavities makes the Kymi stock a perfect target for quantitative studies of magmatic fractionation and fluid exsolution in highly evolved granitic systems. The mineral chemistry of biotites was investigated by EPMA and LA-ICPMS analysis and the data demonstrate clear fractionation trends, which can be explained by progressive magmatic fractionation coupled with episodic fluid exsolution. Biotites are siderophyllite for the porphyry granites and lithian-siderophyllite for the equigranular granite, stockscheider pegmatite and some miarolitic cavities. Fractionation trends within the biotites show increase in Si, Li and Mn content, and decrease in Fe and Mg on M sites. The Na, Rb and Cs concentrations increase towards the most evolved rocks, coupled with decrease of K, Ba and Sr on the I sites. Concentrations of Be, Tl and Zn decrease and those of Mo, Nb, and Ge increase systematically towards the most evolved rocks. The biotites are the main host of indium, and the highest concentrations are present in biotites from more evolved miarolitic cavities. The In concentrations correlate positively with Sn. The Cl/F ratios in biotite decrease systematically along the time sequence. In addition, there are distinct compositional gaps (showing approximately 10 times decrease in Cl/F) between each granite type. The biotites of the miarolitic cavities have Cl/F ratios which plot in between the compositional gaps observed between the three granite types. The more evolved topaz-bearing cavities have compositions similar to the equigranular granite and the stockscheider pegmatite. This suggests that at least three events of fluid exsolution occurred during the magmatic-hydrothermal evolution of the system, which are likely related to the formation of (1) the topaz-bearing cavities, (2) the barren hydrothermal veins and (3) the polymetallic hydrothermal veins.

## S10.3 Recent developments in metamorphic geology

### KEYNOTE

#### Continental Crustal Growth and Consolidation of Crust in Accretionary and Collisional Orogens: Trans-Euroasian Paleozoic System

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Both accretionary and collisional orogenic systems contribute to the growth of continents by contrasting mechanisms: Accretionary orogens are characterized by long-lasting additions of oceanic crustal fragments and scrapped ocean floor stratigraphy to the continental nuclei. In contrast, the collisional orogens result from closure of small oceanic basins and amalgamation of continental blocks. Magmatism and metamorphism related to ongoing oceanic and continental subduction are key processes forming lower crust by recycling of both old continental and freshly accreted juvenile crust. Thus, understanding mechanisms of vertical differentiation and lateral homogenization of accreted and collided blocks is a first order challenge of modern geodynamics. To fill the gap we compare geophysical and geological data from the Palaeozoic European Variscan and the Central Asian Orogenic belts, which contributed significantly to the final construction of the Pangea supercontinent. We show that in both cases the key process of continent construction is rélamination of orogenic lower crust derived from deeply subducted lower plate in the case of collisional Variscan belt. In contrast, in the accretionary Central Asian Orogenic Belt, it is the buried and re-molten arc and accretionary prism material, which are redistributed beneath upper plate crust. Both mechanisms are responsible for blurring of geophysical signal of originally accreted/amalgamated blocks by redistributing homogeneous layer of intermediate to felsic lower crust beneath heterogeneous upper crust. This anomalous lower crust is subsequently exhumed in form of giant granulite-migmatite domes which is the main

structural feature of both types of orogenic systems. We discuss the contribution of these processes to the building of mature continental crust and continental growth in general.

### ORAL

#### Thermodynamics, isochemical and pseudobinary systems: applications to some practical problems including the atmospheric CO<sub>2</sub> budget

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Thermodynamic data sets and computer programs are widely used for solving specific petrological problems. Here we present some examples of calculations which gives answers to more general questions, or illustrate how seemingly unexpected phenomenon faced in the field, thin sections etc. could actually be the expected ones.

Phase equilibria and mineral composition in dolomite marble – silica and peridotite systems are calculated in the presence of binary CO<sub>2</sub>-H<sub>2</sub>O fluid. Flow of silica bearing H<sub>2</sub>O rich fluid at constant P and T into the dolomite marble would cause mineralogical changes identical to those observed in the field occurrences. On the other hand, similar fluid is capable to transform peridotite to soapstone. Because both reaction series are relatively common and take place widely in field occurrences without any geological or structural relationship, we conclude that pervasive flow of water rich carbon dioxide bearing fluid through the whole crust cannot be excluded. This would have serious effect on the atmospheric CO<sub>2</sub> balance and should not be neglected from climate models. Phase equilibria and mineral composition of pelitic schists as function of excess oxygen are calculated. The results are consistent with natural assemblages suggesting that intensive oxidation took place in some shear system. Observed mineralogical changes could be explained by autoxidation by water resulting in the increased hydrogen content of the fluid. This will change the compatibility of metal complexes e.g. AuCl<sub>2</sub><sup>-</sup> and Au(HS)<sub>2</sub><sup>-</sup> in the fluid and could be one reason for

the generation of shear zone hosted ore deposits, regardless of the carrier species of gold. Phase equilibria calculation of generation and crystallization of silicate liquids indicates that peritectic reactions are to be expected to happen in some siliceous systems. Generation of corundum during melting of silica saturated pelite has consequence for gemstone exploration while crystallization of interstitial orthoclase during subsolidus cooling is a warning example of wrong petrographic interpretation of intergranular phases. Natural examples, consistent with the calculation are presented.

## ORAL

### Leucosome distribution method and geochemical melt modelling in Masku migmatites, SW Finland

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Partial melting processes have been shown to follow power law distribution (e.g. Soesoo et al., 2004) and behave as self-critical systems (Soesoo & Bons, 2015). Leucosome distribution in migmatites of metasedimentary origin often follows the simple power law function  $N_{>S} = kS^{-m}$ , where  $N_{>S}$  is the number of leucosomes thicker than width  $S$ ,  $k$  the number of leucosomes larger than unit size and  $m$  the distribution exponent (fractal dimension). If the power law exponent  $m$  is  $\sim 1$ , the melt extraction has been inefficient (majority of the melt is found in small leucosomes). If the exponent is about  $2/3$ , the melt extraction is effective ( $\sim 50\%$  of the melt is found in large melt batches).

Leucosomes of migmatites at the classical "Masku Riviera" outcrop, south-western Finland, were measured and their cumulative width distribution plotted on a log-log graph, after which a power-law function was fitted to the data. Our results evidence two power-law regimes with different power-law distributions. For larger leucosomes (width  $\geq 10$  mm) it seems that melt extraction was inefficient. However, the data for thinnest leucosomes (width  $\leq 9$  mm) suggest effective melt extraction.

Geochemical analysis of leucosome and palaeosome (assumed protolith) samples from the Masku

area shows that the leucosome is slightly enriched in REE, with the exception of HREE, in comparison to the palaeosome. Numerical models of modal batch melting of the palaeosome show that 60% melting of the paleosome results in about the same REE contents as the leucosome sample has.

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## POSTER

### Metamorphic map of Finland

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Metamorphic map is a layer in the new 1:1 000 000 bedrock data base of Finland. It is compiled both from previous metamorphic studies and from the results of new mapping in the years 2011-2014 at the Geological Survey of Finland. Roughly half of the Proterozoic bedrock in Finland consists of metagreywackes and metapelites which record low-variance mineral assemblages which are more sensitive to PT-changes than high-variance assemblages in mafic and felsic lithologies. Consequently the Proterozoic part of the map is based on the metamorphic features of peraluminous metasedimentary rocks. In the Archean metasedimentary rocks are found only locally, the bedrock mostly consisting of tonalitic-trondhjemitic-granodioritic gneisses and amphibolite migmatites. Therefore the classification of the Archean metamorphism is based on observations in metaigneous and metavolcanic rocks apart from those areas where metasedimentary rocks are more abundant. Classification tools are mineral assemblages, preservation of primary structures, grain size and the onset and degree of partial melting. Pseudosections showing the stability fields of stable mineral assemblages for a given whole rock composition are used to constrain approximate PT conditions for the metamorphic zones. The PT field of a certain mineral assemblage is shown in the PT pseudosection with a colour which corresponds to the same colour in the map.

The metamorphic zones are classified to low pressure, medium pressure and high pressure facies

series. The Svecofennian metamorphism is characterized by low pressure series with grade varying from low amphibolite to granulite facies, from andalusite schists to cordierite, garnet and sillimanite bearing migmatites. The Proterozoic cover sequence on the Archean and Proterozoic mobile zones in the Archean mostly represent medium pressure metamorphism with kyanite assemblages. The Archean metamorphism is mostly medium pressure type but both medium and low pressure granulites are found. An attempt was done to map the metamorphic age zones using the U-Pb age data on monazite, sphene and zircon from metamorphic rocks. For the Proterozoic metamorphism these data seem to indicate three events, low amphibolite facies Svecofennian schists and cover sequences mostly yielding 1.79-1.80 Ga monazite ages, migmatites in Southern Finland 1.81-1.83 Ga and migmatites in Central Finland 1.86-1.88 Ga. The strongest Archean metamorphic event was long-lasting, migmatites and granulites producing a spread of metamorphic ages from 2.70-2.60 Ga.

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**POSTER**

**<sup>40</sup>Ar/<sup>39</sup>Ar thermochronology of low-temperature alteration in a flood basalt pile during burial metamorphism**

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Celadonite is a low-temperature (<~50 °C) alteration mineral that fills voids and fractures within buried and metasomatized volcanic rocks. The common occurrence, mineral chemistry and structural properties of celadonite (K<sub>2</sub>O-rich and Ar retentive) make it attractive as a monitor of spatial and temporal variability of low-temperature hydrothermal fluid circulation and alteration.

The Neogene lava pile in E Iceland underwent burial metamorphism, tectonic tilting and subsequent glacial exhumation, and is today exposed with superimposed sub-horizontal regional zeolite facies mineral zones. From a single sample of the Skessa Tuff, a prominent welded pyroclastic

flow, we present new <sup>40</sup>Ar/<sup>39</sup>Ar incremental heating age determinations using the ARGUS-VI multi-collector mass spectrometer at OSU: plagioclase (10.26 ± 0.12 Ma), groundmass (10.15 ± 0.10 Ma), early-forming light green celadonite (9.73 ± 0.03 Ma) and later-forming dark blue-green celadonite (9.67 ± 0.03 Ma). The sample was collected at ~550 m above sea level (masl) near the Thingmuli volcano.

Cooling ages of plagioclase and groundmass separates are in close agreement and represent the eruption age of this pyroclastic flow. The geochronologic data and petrographic observations suggest homogeneous and relatively rapid crystallization of celadonite. The inferred original top of the lava pile is ~650 m (1400 masl) above the top of the analcime zone (~750 masl). Celadonite is predominantly found as early-stage lining of primary pore space, but overgrown by chlorite/smectite clays and zeolites at higher grades. Above ~750 masl vesicles are void of celadonite, and hence, celadonite precipitates in a narrow zone at ~650 m depth. Timing of eruption and burial to ~650 m depth are separated by ~600 ky, which suggests a burial rate of ~1100 m/m.y. This burial rate is 2x that of estimates from contemporaneous sections located away from central volcanoes. Considering proximity to Thingmuli it seems reasonable to expect a greater burial rate. Celadonite <sup>40</sup>Ar/<sup>39</sup>Ar dating can unravel tectono-magmatic processes active during flood basalt burial.

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**POSTER**

**Pentti Eskola – A Personal Outlook and Side Excursion to a 200-year History of Orthoamphibole**

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In 1956 en route home from petrologic study under Douglas Coombs in New Zealand, I had an accidental and friendly discussion of metamorphism with Pentti Eskola in Helsinki. In Massachusetts, 1958-1963, influenced by J. B. Thompson and Marland Billings, I focused on geologic mapping, graphic analysis of mineral assemblages, cordierite-anthophyllite rocks and gneiss domes, all subjects close to Eskola's heart. His Orijärvi Memoir was remarkable for its time, published in English in 1914 by the Russian Imperial Senate, based

on work 1908-1913, including maps, rock descriptions, mineral and rock analyses, and discussion of relationships with ore deposits. The follow-on bulletin, also 1914, but published in Swedish 1915, with English summary, was perhaps more influential. Even then, Eskola was aware of key work by Van Hise (1904) and Becke, Grubenmann, Niggli, and Goldschmidt (all 1911-1914). Here are headings 'Metamorphic Facies', 'Mineral Associations', 'Application of the Phase Rule', and a precise presentation of the ACF and AKF projections. His discussion concerning the diagrams contains warnings concerning behavior of components that occupied and vexed later users in decades to come. Thompson's 1957 muscovite projection was a direct spin-off from AKF. The diagrams were perfectly suited to graphic display of V. M. Goldschmidt's contact metamorphic assemblages near Oslo, Norway, as in his 1912 Ph. D. thesis (published in German), and in some later summaries were wrongly attributed to Goldschmidt himself.

The two came together in Oslo after WWI, when Eskola studied eclogites that he first thought of as an igneous facies. In 1963 I was on a field institute for American petrologists in Norway, Sweden, and Finland. The first day in Espoo, we met Eskola, then in his last year, but ready to autograph a copy of the 1915 bulletin then still available. My targets then were to see cordierite-anthophyllite rocks at Orijärvi and gneiss domes at Kuopio. We got one outcrop of each. Our leaders were more interested in the origin of granite. Among us was a small 'Eskola team', constantly seeking examples of his metamorphic facies, along the trail he set, that is still followed today.

Eskola focused on the origin of cordierite-anthophyllite rocks and eclogites. The former, brought attention to the strange history of the self-styled Karl Ludwig Giesecke, ~1791 an associate of W. A. Mozart in Vienna, and 1810 collector of "labradoriserende Hornblende" from the west Greenland coast, later reaching the Copenhagen Museum. There ~1924 the iridescence was studied by O. G. Bøggild and in 1971, in New England, its origin was elucidated by Robinson, Ross and Jaffe. In 1983-88 genesis of these rocks was described by J. C. Schumacher. When on such outcrops, the Magic Flute rings in the ears!!

## S10.4 Mafic-ultramafic intrusions and related ore deposits: Petrology and origin

### KEYNOTE

#### Mafic-ultramafic intrusions and related Ni-Cu-PGE deposits in the northern part of the Fennoscandian Shield

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In the northern part of the Fennoscandian Shield, magmatic Ni-Cu-PGE deposits are associated with ultramafic-mafic magmatism generated at four stages, ca. 2.82 Ga, 2.45-2.50 Ga, 2.06 Ga, and 1.98 Ga, with all of them thought to be related to mantle plume events. The parental magmas of the ore-bearing intrusions or lava flows vary from komatiites to high-siliceous magnesian basalts and ferropicrites.

In this presentation, most peculiar features of the Ni-Cu-PGE deposits are discussed. For example, their base and precious metal tenors and Pd/Pt show a very wide variation. At the other end, ultra-high Ni of more than 40 wt% in the sulfide phase has been recognized, which is reflected in the presence of a mineral paragenesis containing pyrite, millerite, and pentlandite. In some deposits, this seems to be the result of post-magmatic oxidation of sulfides and related sulfur loss whereas in some others, it is more likely a primary feature linked to an exceptional high Ni content of the magma.

Recently, multiple sulfur isotope analyses have provided a useful tool for detecting evidence for assimilation of external sulfur during ore formation. Consistent with the occurrence of mass-independent sulfur isotope fractionation (MIF-S) exclusively in pre-GOE (Great Oxygenation Event) sedimentary rocks, Archean komatiite-hosted Ni-Cu deposits in the Kuhmo greenstone belt show various levels of MIF-S, whereas no signs of MIF-S have so far been observed in Paleoproterozoic Ni-Cu deposits, such as Pechenga or Lomalampi, though it does not rule out contamination with Paleoproterozoic sedimentary sulfur.

ORAL

#### Nickel sulfide deposits related to 1.88 Ga mafic-ultramafic magmatism in Fennoscandian and Canadian Shields

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Nickel sulfide deposition took place in the Fennoscandian and Canadian Shields at 1.88 Ga. Examples include the Kotalahti and Vammala Nickel Belts in Finland, Västerbotten Nickel Belt in Sweden and Thompson and Cape Smith Nickel Belts in Canada. Most of the nickel-bearing mafic-ultramafic intrusions within the Finnish Svecofennian are found in the Kotalahti and Vammala Nickel Belts. The Kotalahti Nickel Belt lies close to the Archean/Proterozoic boundary similarly with the Thompson Belt while the Vammala Belt occurs further to the west and possibly continues to Västerbotten. The Fennoscandian and also part of the Canadian deposits are associated with amphibolite to granulite facies metamorphism and related migmatitic country rocks. The magmatism that produced the Finnish Svecofennian ore-bearing intrusions was coeval with the Svecofennian orogeny and the emplacement of the magma took place during the maximum intensity of deformation and metamorphism. The composition of the parental magma was basaltic with a MgO content usually around 12 wt.% (max. 15 wt.%). This is lower than the value of around 18 wt.% for the Thompson and Cape Smith belts. Also in the Västerbotten Belt in Sweden parental magma had locally higher MgO than within the Finnish nickel belts.

The total pre-mining resource of all the Finnish Svecofennian deposits known to date is about 73 Mt at 0.7 % Ni. Compared to the Thompson and Cape Smith Nickel Belts the nickel grade is distinctly lower. This is partly due to the remarkable lower mining cut-off value for the Svecofennian deposits but also to the lower MgO and thus lower Ni in the parental magma. The Cape Smith Belt extrusions host economic nickel deposits but nickel deposits in Svecofennian picrites in Finland are rare. In Sweden, however some picrite-hosted nickel deposits are found. Picrites, if proven to be comagmatic with the nickel-bearing intrusions, represent a notable rock type. They can be used as a reference

level for stratigraphic and geotectonic studies in and between the Fennoscandian and Canadian Shields. Also their regional distribution can guide nickel exploration.

ORAL

### Characterization and origin of dunitic rocks in the Ni-Cu sulfide-bearing Kevitsa intrusion: whole-rock and mineral compositional constrains

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The ca. 2.06 Ga mafic-ultramafic Kevitsa intrusion is located in the Central Lapland greenstone belt (CLGB). A large disseminated Ni-Cu-PGE sulfide ore deposit occurs within the ultramafic olivine-pyroxene cumulates. The intrusion is associated with a separate km-sized dunitic body (termed the Central Dunite) with an overall discordant relationship to the Kevitsa intrusive succession. In addition, dunitic and related ultramafic rocks occur as numerous inclusions within the Kevitsa intrusion, being most common in the mineralized zone. Two distinct types of inclusions are recognized: i) cumulate-textured (termed the Kevitsa Dunite) and ii) recrystallized ultramafic inclusions.

The Central Dunite and Kevitsa Dunite are texturally and mineralogically similar olivine-chromite cumulates and show comparable whole-rock and mineral compositions, suggesting that they are co-genetic. The parental magmas for the dunitic cumulates were probably picritic and relate to the picritic and basaltic volcanic rocks in the CLGB. The whole-rock major and trace element data and mineral compositions of the dunitic cumulates and Kevitsa olivine pyroxenites fall on the same linear trends and both record similar REE characteristics, indicating a genetic link between these two. A two-stage magmatic model is proposed to explain the field characteristics and compositional trends in the dunitic cumulates and Kevitsa ultramafic rocks.

Whole-rock and mineral chemical characteristics of the recrystallized inclusions suggest that they represent clasts of dunitic cumulates and dehydrated

(komatiitic) metavolcanic country rock xenoliths. A decrease in the flow rate of the Kevitsa magmas due to entrapment of a high number of inclusions is proposed as a mechanism to promote concentration of sulfides, contributing to the formation of the Ni-Cu-PGE ore.

ORAL

### Northern Fennoscandian komatiite-hosted Ni-Cu-PGE deposits: geochemistry and trace element composition of sulphides and oxides

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Magmatic Ni-Cu-PGE deposits are important resources of nickel, copper and platinum group elements (PGE). Experimental works and empirical observations have shown that the magmatic sulphide deposits are products of the segregation of an immiscible sulphide-rich liquid from a silicate melt. The sulphide liquid sequesters chalcophile metals from parental silicate melt, this process may lead to the formation of important ore deposits. One aspect addressed in this work, which has not been sufficiently studied in Finland, is the Re-Os isotope geochemistry and trace element contents of sulphides and oxides in magmatic Ni-Cu-PGE mineral systems

The main research targets of this study are the Ruossakero Ni-(Cu) deposit, Lomalampi PGE-(Ni-Cu) deposit, Tulppio dunite massive and related Ni-PGE mineralisation, Hietaharju Ni-(Cu-PGE) deposit, Vaara Ni-(Cu-PGE) deposit and Tainiovaara Ni-(Cu-PGE) deposit.

Analysis of sulphides and oxides provides information on the composition and origin of these minerals and conditions of ore formation. We have characterised trace element contents in oxides by using electron microprobe (EPMA). Our preliminary results show that the nickel contents in magnetite grains are elevated in mineralised samples, especially in magnetites associated with deposits with a high Ni content in the sulphide fraction. We propose that the occurrence of magnetites with more than 0.10 wt% Ni in moraine sample could be a good provenance-scale indicator of possible Ni sulphide-bearing source rock.



Analysis of Re-Os isotopes in the sulphide-bearing systems provides new insights into the ore-forming processes, including indications of country rock assimilation and new age constraints of the magmatic events. Chromite and sulphide separates from the studied deposits have been prepared and currently, the analytical work is being carried out. Results will be published later.

ORAL

**Long duration (130 Ma), mantle reservoirs (EM-1, OIB, E-MORB and N-MORB) and multistages history for PGE-bearing Paleoproterozoic layered intrusions in the N-E part of Fennoscandian Shield.**

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Layered Paleoproterozoic PGE intrusions located in the N-E part of the Fennoscandian Shield and have a total area about 2000 km<sup>2</sup>. Long multidisciplinary studies using isotope Nd-Sr, U-Pb and <sup>3</sup>He/<sup>4</sup>He systematic permit create a big bank of geochemistry data for different part of the intrusions: barren and main Cu-Ni-Cr-Ti-V and PGE phases, dykes complexes and host rocks. The primary reservoir for all precious and multimetal massifs are considered as enriched mantle EM-1 using  $\epsilon$ Nd- ISr system with negative  $\epsilon$ Nd values and low ISr data for whole rocks of the intrusions. Dyke complexes are presented as three groups: high Ti-ferrodolerites, low Ti and low Fe-gabbro-norites. Complex isotope (U-Pb, Sm-Nd) and geochemistry (REE,  $\epsilon$ Nd, ISr) data investigations reflect OIB, E-MORB and N-MORB reservoirs for its origin (Nerovich et al., 2014).

Isotope <sup>3</sup>He/<sup>4</sup>He and <sup>3</sup>He concentrations for accessory minerals (ilmenite, magnetite et. set) from the layered paleoproterozoic intrusions reflect significant lower mantle component and upper mantle contribution. According to the model of binary mixing there were calculated mantle and core component into plume magmatic reservoir connected with the origin of the PGE paleoproterozoic intrusions and mantle contributions lie in the interval from 85 to 93% (Jahn et al., 2000).

Based on U-Pb isotope data (on single baddeleyite and zircon) and Sm-Nd mineral isochrones (on rock-forming and sulphides minerals) there are distinguished long magmatic duration from 2.53 to 2.40 Ga. Using precise U-Pb and Sm-Nd data for different part of the intrusions there are established four main impulses: 2.53, 2.50, 2.45, and 2.40 Ga of magmatic (LIP) activities for gabbro-norite, anorthosite et. set. rocks. The very similar Sm-Nd data have been measured on the rocks of layered intrusions in Finland part of the Fennoscandian shield (Huhma et al., 2012).

We thank to G. Wasserburg for 205 Pb artificial spike, J. Ludden for 91500 and Temora standards, F. Corfu, V. Todt and U. Poller for assistance in the establishing of the U-Pb method for single zircon and baddeleyite grains.

All investigations are devoted to memory of academician RAS, professor F. Mitrofanov (Russia), he was a leader of scientific school for geology, geochemistry and metallogenesis of ore deposits.

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ORAL

**Otanmäki and Vuorokas  
iron-titanium-vanadium oxide deposits,  
Eastern Finland**

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Otanmäki area Fe-Ti-V oxide deposits are hosted by mafic to anorthositic intrusion complex (2065 ± 4 Ma) which is situated along with alkaline granitoids at the boundary between the Archaean Pudasjärvi and Iisalmi blocks, immediately to the west of the Palaeoproterozoic Kainuu schist belt.

The Otanmäki mine operated during 1953–1985 (Vuorokas Mine 1979–1985). In total, 30 Mt of ore was mined grading of 32–34% Fe, 5.5–7.6% Ti and 0.26% V (Puustinen 2003).

The average mineralogy of Otanmäki ore comprises of magnetite (35–40 wt. %), ilmenite (25–30 wt. %) and sulphides (1–2 wt. %). The main gangue minerals are chlorite, hornblende, and plagioclase. Magnetite and ilmenite occur mainly as granoblastic textured, separate 0.2–0.8 mm grains (Pääkkönen 1956). In parts, ilmenomagnetite is predominant containing ilmenite and spinel as exsolved lamellae and inclusions in magnetite.

The average vanadium content in magnetite is (0.62 wt.% V) and it varies slightly between the ore bodies (Kerkkonen 1979).

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#### ORAL

### PGE reefs in the Penikat Layered Intrusion, Northern Finland

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The Penikat Layered Intrusion, about 2440 m.y. old, is located in northern Finland. It is 23 km long and 1.5 to 3.5 km wide and it contains two main units: the marginal series and the layered series, the latter being further divided into five megacyclic units (MCU).

Three main PGE-enriched zones have been found in the Penikat Intrusion: the Sompujärvi (SJ), Ala-Penikka (AP) and Paasivaara (PV) Reefs, all of them are associated with MCU IV and only the SJ Reef occurs, in places, in the upper part of MCU III. The SJ Reef concentrations have been found to occur in association with either chromite, base metal sulphide disseminations or in silicate rocks without the disseminations mentioned above. The AP and PV Reefs are connected with base metal sulphide disseminations.

The late or post-magmatic fluid phase has been an important factor in the formation of all three PGE reefs. The volatile components of the magma diverged under appropriate conditions to release platinum metals and created the PGE reefs.

Two types of magma have intruded to the Penikat chamber: 1) boninitic or siliceous high-magnesian basalt (SHMB) affinity and 2) tholeiitic affinity. The source of the PGEs in all three reefs was the SHMB series of magmas, in which the PGEs moved upwards in the fluids of the residual magma along with volatile components.

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#### POSTER

### The Rein fjord Ultramafic complex; Petrology and Geochemistry

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The Rein fjord Ultramafic Complex is part of the 5500 km<sup>2</sup> Seiland Igneous Province (SIP), in northern Norway. The Rein fjord magmas intruded between 560-570 (Roberts 2006) Ma and the complex could represent a deep-seated plumbing system of a large igneous province (Larsen et al. 2012). The Rein fjord ultramafic complex (15 km<sup>2</sup>) is one out of four major ultramafic complexes in SIP, and consists of three series of ultramafic cumulates that formed Websterite (LLS), Lherzolite-Wehrlite (ULS) and dunite (CS) that are either modally and cryptically layered. Central parts of the intrusion are composed of cryptically layered dunite (Fo<sub>83-85</sub>), which contains one Ni-Cu reef with 0,38wt% Ni and 0,12wt% Cu and one Ni-Cu-PGE reef with 0,63ppm of total Pt+Pd+Au and 0,27wt% Ni.

The aim with this study is to understand the evolution of the dunite forming melts and to see if the cryptic variations leading to formation of a Ni-Cu reef may be linked to ore genesis. This will be done by analysing drill core and field samples with various geochemical analytic methods on whole rock samples and in situ studies of in olivine and pyroxene by SEM and EPMA. We also want to look at how the magma fractionate and the magma chamber processes leading to the formation of the cumulate sequence. The Rein fjord area is excellent due to

extremely fresh surfaces and primary features being well preserved. To improve our understanding of the evolution of the intrusion, the entire area was re-mapped. Major revisions from previous work include a reinterpretation of a large part of the intrusion and fault zones. Contrary to previous studies we see that the CS is larger than previously mapped, the ULS is smaller and large portions are assimilated by CS. Also the NE marginal series does not exist. A significant result of our studies so far is that the Reinfjord complex is a wide open magmatic system supporting >10 replenishment events. Fieldwork also unravelled what may be the roof zone of the intrusion in north east at 900 m.a.s.l.

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#### POSTER

### Chalcophile element geochemistry of komatiites and basalts in the Archean greenstone belts of Russian Karelian

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Archean komatiite and komatiitic basalt from the Hautavaara, Koikary, Palaselga and Sovdozero areas in the Vedlozero-Segozero greenstone belt, and the Irinozero and Khizovaara areas in the Northern Karelian greenstone belt has PGE contents in the range of other S undersaturated komatiites and komatiitic basalts globally, at 5-20 ppb Pt and Pd each, and Pd/Ir ratios range from <10 (komatiites) to > 15 (komatiitic basalts and basalts). The Iridium-group platinum group elements (IPGE) (Ir, Ru, Os) generally show compatible signature, decreasing with falling MgO content, whereas Pt, Pd and Rh (PPGE) exhibit incompatible behaviour. The poor correlation between Ir and MgO suggests that olivine does not control the IPGE contents. Pd, Cu and Au have behaved variably mobile during alteration

and metamorphism. Some samples from the Khizovaara belts have low Pt/Ti N ratios, low Ni, and high La/Sm, indicating localized sulfide saturation in response to crustal contamination. However, the potential of the Russian Karelian belts for Ni-sulfide mineralization is considered low, due to the absence of sulfide rich sedimentary rocks in the region, the lack of chalcophile element enrichment in any of the samples analysed, and the paucity of dynamic lava channel environment, indicated by a lack of high olivine adcumulates. Amongst the analysed belts, lavas in the Khizovaara area are considered to be the most prospective target for Ni sulfide mineralization due to their relatively enhanced crustal contamination and greater depletion of PGE.

#### POSTER

### The origin of internal reflectivity within the Kevitsa intrusion

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The Kevitsa mafic-ultramafic intrusion hosts large Ni-Cu-PGE disseminated sulfide deposit and is located within the Central Lapland Greenstone Belt in northern Finland. A vast number of geophysical and geological datasets, in particular extensive borehole data and 3D reflection seismic data used in this study, is available from Kevitsa.

Data mining approaches, such as Self-Organizing Map (SOM; Kohonen 2001) analysis, can be used for joint interpretation and objective analysis of the complex geophysical and geological datasets typical for mining camps. In this work, we are presenting initial results from SOM analysis of Kevitsa borehole data with the aim of understanding the origin of spatially constrained internal reflectivity within the Kevitsa intrusion, and its relationship to the Kevitsa Ni-Cu-PGE deposit. Earlier (e.g. Koivisto et al. 2015) it has been suggested that the internal reflectivity originates from contacts between the tops and bottoms of smaller-scale, laterally discontinuous and internally differentiated olivine pyroxenite pulses within the

intrusion, which have also been suggested to control the extent of the economic mineralization accumulated towards the bases of the pulses (Gregory et al. 2011). However, our initial results show that the origin of the internal reflectivity is more complicated. While the smaller-scale magmatic layers could potentially explain some of it, more detailed analyses are required to fully understand the origin of the reflectivity and its relationship to the Kevitsa Ni-Cu-PGE deposit.

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#### POSTER

### The Hunt for Platinum Group Minerals in the Rein fjord Intrusive Complex

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50 km W - NW of the Norwegian city of Alta in Troms region, is the Rein fjord Intrusive Complex (RIC), composed of three intrusive events that are approximately 560 - 570 Ma (Roberts, 2006). Drill holes from 2011 (RF-1 and RF-2) show two spikes for economic elements, one Cu-Ni reef low in PGE at depth of 86-93m and a PGE reef low in Cu-Ni at 107-113m. The Rein fjord deposit differs from other PGE deposits such as Norilsk (Russia) and the Merensky reef (South Africa), indicating a completely new type of PGE deposit.

The PGE spike in RF-1 is concentrated in a 6m thick Orthopyroxene pegmatite with plagioclase, amphibole, biotite, Dolomite and rutile. That shows a total amount of 0.79 ppm Pt+Pd+Au+Os (Iljina, 2012). When comparing the  $\delta^{34}\text{S}$  signature of the PGE reef with the Cu-Ni reef 20m above, it shows a distinct difference, -0.40 for the PGE reef and -4.56 for the Cu-Ni reef. This clearly indicates that the Sulphur has different sources.

This study looks into the details of the PGE's and their assembly, with the aim of identifying the process that forms this kind of a deposit. Thin section microscopy, SEM imaging, SEM mapping, EPMA and whole rock geochemistry are used to find cryptic variation from the Dunite host rock and into the PGE rich reef. BSE and EDS are used to detect and identify the PGE's. Thin sections, together with a thin section constructed from heavy element separation will give the highest probability of finding and identifying the PGE's. Current reflected light and SEM analysis have not revealed any PGE's. Therefore opening the possibility that the PGE's are substituting into pentlandite.

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#### POSTER

### Pt-Os geochronology constraints of a Cu-Pt-rich ore body in the Jinchuan intrusion, China: dating hydrothermal overprinting and the final emplacement of the deposit

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The Jinchuan ultramafic intrusion in northwest China is ranked the world's third largest magmatic Ni-Cu sulfide deposit. The Jinchuan intrusion has been dated at ca. 825 Ma by U-Pb method using zircon and baddeleyite. The age obtained by Re-Os method for massive ores is similar to the age of the intrusion. This age is considered to record the timing of crystallization of the intrusion and the main stage of ore formation. The Jinchuan intrusion shows a tectonic contact with its immediate country rocks and is believed to have been thrust to its present location by a regional tectonic event. Besides the main ore body consisting of

net-textured and disseminated sulfides, there is hydrothermal mineralization associated with sheared contact zones of the intrusion, which shows elevated Cu and Pt concentrations. In this study, we applied the Pt-Os chronometer to a Cu-Pt-rich ore body, yielding an isochron age of  $436 \pm 22$  Ma. This age is significantly younger than the main ore formation age of about 825 Ma, but similar to the continental collision event of the orogenic belt between the North China Craton and Qadam-Qilian Block. This indicates that the intrusion may have been uplifted to the present location in the orogenic process, which generated the Cu-Pt-rich hydrothermal ore body. Our new data provide the first precise age indicating the time when the Jinchuan deposit was thrust to its present location from depth. This study shows that the Pt-Os isotope system is a powerful tool for dating hydrothermal overprinting of Ni-Cu-(PGE) sulfide deposits.

## S10.5 Precambrian granitic systems of Fennoscandia: From genesis to emplacement

ORAL

### Formation mechanism and age of the Särkilahti garnet-cordierite leucogranite, SE Finland

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A Svecofennian Grt-Crd leucogranite (~80 km<sup>2</sup>) is located in the Särkilahti region, 35 km south of the town of Savonlinna in SE Finland (Nykänen 1988; Selonen 1988; Lavikainen et al. 1992). It occurs in a granulite terrain, which is composed of Grt-Crd migmatites with lesser Grt-Opx gneisses, Opx-Bt metatonalites and granite pegmatite dykes. The leucogranite is slightly heterogeneous and coarse-grained, having Grt, Crd, Bt and reddish alteration product as mafic minerals (~5%). This granite was injected into the migmatites on its southern and western margins, as veins often parallel to the banding of the country rocks. In the same areas, it contains supracrustal restites and metatonalite inclusions. The NE margin involves a shear zone. U-Pb ages made by LA-ICP-MS on monazite for two leucogranite samples yielded 1793±10 Ma and 1786±10 Ma.

We suggest that the leucogranite represents a late Svecofennian magma layer below the "melting interface" (MI, Chen and Grapes 2007), which divides the convection (below MI) and conduction (above MI) heat flow modes in the crust. The layer has replaced its roof migmatites by partial melting. Compositional differences between the leucogranite and the country rocks evidently are due to gravitational sinking of restitic roof rock fragments in the partial melting region, supported by upward displacement of granite magma. The Särkilahti Grt-Crd leucogranite could be a new lithodeme in the plutonic suites of Finland.

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ORAL

### Rapakivi texture in the Wiborg batholith

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The origin of rapakivi texture, the formation of plagioclase-rimmed alkali feldspar ovoids in particular, has drawn attention since rapakivi granites were first described by J. J. Sederholm in the late 19<sup>th</sup> century. Over a hundred years later there are still several competing genetic models: sub-isothermal decompression, magma mixing, and exsolution processes among the most popular ones.

This study comprises petrographic analysis of ~60 ovoids from 6 different sample sites of the three major rapakivi types (dark wiborgite, wiborgite and pyterlite) of the *locus classicus* ~1.63 Ga Wiborg batholith in southeastern Finland. The aim is to describe and compare petrographic features and determine chemical compositions of the alkali feldspar ovoids as well as the inclusion minerals.

All ovoids are perthitic and have concave and rod-like quartz, hypidiomorphic or slightly resorbed plagioclase (often with partial quartz rim), zircon, biotite, apatite, ilmenite and/or magnetite as inclusions. The ovoids of the more mafic rapakivi types have also hornblende and sometimes fayalitic olivine and clinopyroxene as inclusions while the more felsic types have abundant fluorite. Although the basic features of all ovoid types are the same, each sample location seems to have specific characteristics, for example ragged biotite, symplectitic hornblende or myrmekitic margins of plagioclase.

The studied ovoids fall into 3 main groups based on their margin texture: 1) ovoids with plagioclase rim, 2) ovoids with symplectitic, "lace-like", quartz, and 3) ovoids interlocked with groundmass. Rock type or location does not seem to be significant (except for pyterlites that often lack plagioclase rims) as all three types may coexist almost next to each other in any single location. Plagioclase rims can be continuous or partial, and they may consist of a

single grain or of numerous grains. They are antiperthitic and have small grains of quartz, fluorite, apatite, biotite, and sometimes also hornblende and zircon as inclusions.

It is noteworthy that the groundmass feldspars are clearly different from the ovoids: there are hardly any inclusions, and minor exsolutions, if present, are different. K-feldspar may be heavily twinned. These petrographic observations indicate that the ovoids crystallized not only from distinct magmas but most likely also in a varying (P-T) environment.

ORAL

### ***In situ* zircon U-Pb ages and $\delta^{18}\text{O}_{\text{VSMOW}}$ values of alkali feldspar syenites and topaz granites from the Suomenniemi batholith**

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The Suomenniemi rapakivi granite batholith in SE Finland is the host of peraluminous topaz-bearing granites and peralkaline alkali feldspar syenites. As these rock types are commonly related to important commodities (e.g., Sn and REE), perception of their petrogenesis is crucial in gaining further insights into the metallogenic potential of rapakivi granites.

Zircon O and U-Pb isotope data from three alkali feldspar syenites and two topaz granites were obtained by *in situ* secondary ion mass spectrometry. The  $\delta^{18}\text{O}_{\text{VSMOW}}$  values of these syenites and granites show no marked differences [ $\delta^{18}\text{O}_{\text{VSMOW}}$  of  $8.17 \pm 0.17$  ‰ (n=45) and  $8.04 \pm 0.17$  ‰ (n=30), respectively]. The weighted average  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of the alkali feldspar syenites are  $1642 \pm 4$  Ma (n=20),  $1644 \pm 4$  Ma (n=19) and  $1645 \pm 5$  Ma (n=19). The average  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of the topaz granites are  $1635 \pm 6$  Ma (n=23) and  $1641 \pm 4$  Ma (n=20).

Our data show that the zircon U-Pb ages and O isotope compositions of the alkali feldspar syenites and topaz granites are identical within the experimental error. Moreover, they do not markedly differ from those of the main granite phases of the Suomenniemi batholith (Elliott et al. 2005, Miner.

Petrol. 85, 223-241; Rämö and Mänttari 2015, Bull. Geol. Soc. Finland 87, 25-45), and imply a source with a prominent crustal component in both the sub-aluminous granites and peralkaline syenites of the batholith.

ORAL

### **Polybaric crystallization of the Ahvenisto anorthosite**

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The recent confirmation of high-aluminum orthopyroxene megacrysts (HAOM) in the ~1.64 Ga Ahvenisto rapakivi granite – massif-type anorthosite complex provides further evidence to support the suggested mantle-derived origin for the anorthositic rocks of the complex.

Fieldwork in the northwestern flank of the Ahvenisto complex revealed two morphologically different types of HAOM embedded in leucogabbroic rocks. The “type 1” HAOMs commonly display a complex rim structure comprised of plagioclase, low-Al orthopyroxene, olivine (mostly altered) and sulphides. “Type 2” HAOMs have less well-developed rim structures and are associated with megacrystic plagioclase.

An “Al-in-opx”-geobarometer was used to evaluate crystallization pressures of orthopyroxene in different textural positions of the studied rocks. A three-stage polybaric evolution was observed. The highest recorded Al-abundances from the cores of the HAOM (~7.6 wt. %) correspond to crystallization pressures up to ~1.1 GPa and depths of ~34 km. The rims have crystallized in much lower pressures (maximum of ~0.5 GPa/20 km) and the highest estimates within barometer calibration for the host rock orthopyroxene were ~0.2 GPa (<10 km).

This suggests that the inner parts of the HAOMs have crystallized in high-pressure conditions at lower crustal levels. The reaction rims have most likely formed during initial igneous cooling and in the presence of some melt, followed by a subsequent hydration of the system. The occurrence of magmatic olivine within the rim may reflect the effects of pressure decrease in the ternary Fo-An-Si system, which stabilized olivine over orthopyroxene in the late stages of crystallization. Groundmass orthopyroxene composition is concurrent with late low pressure crystallization at intrusion depth.

Additionally, these results offer constraints for intrusion depth estimates for the whole Fennoscandian rapakivi suite; specifically the early emplacement stages (~1.64 Ga) of the Wiborg batholith.

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**POSTER**
**Net-veined and pillow structures in the 1.64 Ga Ahvenisto complex, southeastern Finland**

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Net-veined and pillow structures are typical features of plutonic systems where magmas of different compositions, viscosities, and temperatures (e.g. felsic–mafic) have existed contemporaneously. The bimodal Ahvenisto massif-type anorthosite complex in southeastern Finland comprises a granitic batholith surrounded by a horseshoe shaped arc of anorthositic and monzodioritic rocks, which have intruded the Svecofennian country rocks rather simultaneously at ~1.64 Ga. U–Pb geochronology has not been able to distinguish between the ages of granite and anorthositic rocks, but field relations show that when their contacts are sharp, the granites have always intruded the anorthositic rocks.

Recent field work has, however, uncovered prominent mingling structures between monzodioritic and granitic rocks in the Ahvenisto complex in two locations: on the northwestern flank in the Tulinieniemi region and in the southeastern Pärnäjärvä area. In both locations the mingling regions form domains that are several hundreds of meters thick and located structurally between the anorthositic rocks and what have been interpreted as early hbl-granites that have intruded between the country rocks and the anorthositic arc. This suggests that the monzodioritic magmas represent the latest stages of mafic magmatism that overlapped with the earliest silicic magmatism in the Ahvenisto complex.

In more detail, the mingling structures are formed by sparsely plagioclase-porphyric, fine-grained monzodiorite pillows which are intruded by thin finger-like granitic dykes forming locally net-veined structures.

Field work, detailed mapping, and geochemical (whole-rock XRF) and petrographic analyses combined with melt viscosity modeling will be used to

document the features and extent of the locations and to study the origin of the structures.

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**POSTER**
**The age of the Wiborg batholith**

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Recent studies on upper crustal granitic plutons suggest that igneous processes in silicic volcanic systems with shallow plutonic roots develop in two distinct time scales: incremental buildup stage of up to several m.y. and subsequent rapid remobilization/eruption stage of possibly even less than 1 k.y. High-precision geochronological data demonstrate that zircon can saturate at multiple points during the lifetime of a subvolcanic system and is able to record this history.

Six samples were collected from different localities of representative rapakivi-textured rock types of the Paleoproterozoic Wiborg rapakivi batholith in southeastern Finland to acquire detailed knowledge of their crystallization history. Zircon was sampled using a micro drill technique from within the rapakivi-texture forming alkali feldspar ovoids and by standard crushing and separation methods from the groundmasses of the corresponding samples.

U–Pb SIMS ages and LAQ-ICP-MS trace element analyses of these texturally controlled zircon populations reveal that the ovoid material of rapakivi granites was most likely crystallized earlier (by up to several millions of years) and from magmas with dissimilar compositions than their respective groundmasses. The groundmass ages of all the samples are at ca. 1628 Ma (weighted mean <sup>207</sup>Pb/<sup>206</sup>Pb age 1628±1.5 Ma; n = 134; MSWD = 1.1).

These observations suggest that: a) a substantial amount of the batholith volume was accreted incrementally through successive injections of magmas into the upper crust and b) the actual emplacement and final crystallization of the batholith took place during a rather narrow time interval. The minimum magmatic flux estimated based on these data (ca. 30% groundmass volume over 3 Ma; 70% ovoid



volume over 20 Ma) was substantially higher during final crystallization ( $> 0.01 \text{ km}^3/\text{a}$ ) than amalgamation ( $< 0.01 \text{ km}^3/\text{a}$ ), which points to a relatively large magmatic event that may have led to a silicic supereruption at the late stages of Wiborg rapakivi magmatism.

## POSTER

### Age of the late stage magmatic phases of the Ahvenisto rapakivi granite batholith

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The ~1640 Ma Ahvenisto AMCG complex in southeastern Finland includes a granite batholith with diverse rapakivi granites from hornblende-biotite granite to more evolved biotite granites and topaz granites (Eden, 1991, Alviola et al., 1999). According to the previous U-Pb ID-TIMS dating on zircon and baddeleyite the crystallization of the complex took place during a relatively short period of time from 1629 to 1644 Ma, but the most evolved phase, topaz granite, was not dated (Heinonen et al., 2010). We have dated monazites from drill core samples from the most differentiated magmatic body of the rapakivi granite batholith i.e. biotite and topaz granites by LA-SC-HR-ICPMS. The preliminary age data indicate two distinct ages; ~1600 Ma for the topaz granites and ~1630 Ma for the biotite granites, suggesting that the crystallization of the complex has taken longer than previously anticipated.

Monazites are characterized by a high level of common Pb, which is always challenging for the U-Pb technique. In situ measurements of Pb isotopes from co-genetic K-feldspars will be performed to improve the common Pb correction.

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## POSTER

### Three stages to form and stabilize an arc-collisional batholith – an example from the Svecofennian orogen

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Arc-collisional batholiths may record their magmatic history from an arc to arc-collision zone, hence the batholiths mirrors the underlying crustal evolution. Change in the geochemical composition, age and structure can give direct and indirect information of the changing tectonic setting. We have used the Central Finland granitoid complex (CFGK) in the central part of the Paleoproterozoic Svecofennian orogen as a proxy for a batholith, which has evolved in an arc-continent collision and has experienced gravitational spreading. The CFGK can be divided into three groups based on geochemistry and geochronology: 1) calcic group at ca. 1890 Ma, 2) calc-alkalic group at ca. 1884 Ma and 3) alkalic to alkali-calcic group at ca. 1880 Ma. The degree of deformation varies from undeformed to local or pervasive deformation within the three groups and is not dependent on U-Pb zircon ages. Therefore deformation was omitted in the group division.

We suggest that Group 1 granitoids represent the first arc-collisional crustal melts. Emplacement age of Group 1 suggests that there was approximately 20 my delay in the partial melt formation after the collision at 1910 Ma. Group 2 granitoids represent the partial melts of middle crust that was weakened by collision and crustal thickening. The Group 2 underwent lateral flow during crystallization, hence we propose that gravitational spreading was already active at that time. Group 3 represents new phase of melt formation, which emplaced during gravitational spreading. We suggest that the Group 3 plutons were transported from lower crust via arc and terrane boundaries, and were deformed by localized shear zones at 1975-1860 Ma due to the gravitational spreading. Overall, gravitational spreading was active in the CFGK area up to 24 my. Variation on degree of deformation likely reflects different exhumation levels.

## S11.1 Glacial geology — processes, deposits and landforms

### KEYNOTE

#### Active subglacial drumlins at Múlajökull, Iceland

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The drumlin field at the Múlajökull surge-type glacier, Iceland, consists of 142 exposed drumlins, as mapped from a 2013 LiDAR DEM. It is an active field in that partly and fully ice-covered drumlins are being shaped by the current glacier regime. Sedimentological exposures and ground penetrating radar (GPR) profiles show that the drumlins consists of several till units where the youngest till commonly truncates older tills on the drumlin flanks and proximal slope. Along with clast and AMS fabrics, this suggests that the drumlins form by a combination of deposition during surges and erosion in interdumlin areas and adjacent drumlin flanks during quiescent phases. This implies that the drumlins become more elongate and even migrate down-ice with time. This is supported by studies of drumlin morphometry which shows that drumlins are more elongate in parts of the forefield where more surges have occurred. A GPR survey shows that the drumlin field extends under the current ice c. 500 m up from the 2015 ice margin, most likely towards the downglacier-edge of a subglacial over-deepening.

A conceptual model suggests that radial crevasses create spatial heterogeneity in normal stress on the bed so that drainage, sediment transport and deposition is favoured beneath crevasses and erosion in adjacent areas. Consequently, the crevasse pattern of the glacier controls the location of proto-drumlins. A feedback mechanism leads to

continued crevassing and increased sedimentation at the location of the proto-drumlins. Drumlin relief and elongation ratio increases as the glacier erodes the sides and drapes a new till over the landform through successive surge cycles.

The Múlajökull drumlin field, with its well-known glaciological conditions, can serve as an analogue to Pleistocene drumlin fields where glaciological conditions could not be observed.

### ORAL

#### Conceptual model: Erosional origin of drumlins and mega-scale glacial lineations

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The erodent layer hypothesis (EHL) argues that drumlinization leaves no substantial stratigraphic record because it is primarily an erosional process that creates a low-friction surface at the base of accelerating ice. The wide variety of hard and stiff cores of drumlins and associated megaridges (flutings) within tracts of mega-scale glacially lineated (MSGSL) terrain does not support models where bedforms grow upwards by vertical accretion ('emergence') from deforming subglacial till ('soft beds'). Drumlins and megaflyte ridges predominantly have autochthonous cores of antecedent till(s), other stiff and coarse-grained sediment and rock or any combination thereof explaining the close juxtaposition (and common origin) of rock and sediment drumlins within the same flow sets ('mixed beds'). EHL argues that drumlins and megaflytings are remnant features that did not 'grow upwards' from soft till beds but 'grew down' by erosional carving of pre-existing stiff till, sediment and/or rock, by abrasive subglacial streams of deforming subglacial debris. This process is well known to the science of tribology (science of wear) where remnant 'microdrumlins', ridges and grooves (wear tracks) directly comparable to MSGSL are cut by a thin abrasive 'erodent layer' on surfaces in relative motion. In the subglacial setting the erodent layer is thin (<1m) and comprises deforming diamict containing harder 'erodents' such as boulders, clast rich zones or frozen rafts.

Drumlins and megaflytings form a continuum in many flow sets recording 'bisection' (cloning) of parent ovoid drumlins as the bed is progressively

lowered to create a low friction, low slip surface, which is reflected megafaultings. Limiting factors in this evolutionary continuum are the duration of fast ice flow and subglacial sediment thickness; the latter controls the extent of bed lowering; in areas of thin drift, megagrooves and ridges may become stencilled into rock as it becomes exposed by erosion. EHL predicts 'transient subglacial storage' of tills deposited as non-streamlined till plains during sluggish 'steady state' flow for long periods earlier in the glacial cycle and subsequently eroded into a low friction 'self-organized' streamlined surface during a late, short-lived episode of fast ice flow. This presentation recognizes that till is a *glacial cataclasite* and that there is a fundamental commonality of all forms of erosional wear on sliding interfaces from the microscopic scale to the geological. They are examples of textured 'self-organized' shear surfaces meaning that there is no unique glacial explanation for MSGL.

ORAL

### Subglacial sediment homogenization by clast ploughing

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Large Pleistocene ice sheets moved primarily by some combination of basal sliding and bed deformation. The latter process, besides contributing to the forward movement of ice, has been suggested to effectively mix the subglacial material by intergranular advection producing homogeneous basal tills as depositional end-products. Pervasive deformation in a soft, water-saturated, several-metres-thick basal sediment layer that yielded in response to glacier stress has been postulated as a widespread process under the Scandinavian, British-Irish and Laurentide ice sheets.

Here we investigate in detail properties of a massive basal till of Weichselian glaciation at Sønderby, western Denmark in a single vertical profile spanning over 5 m of the till thickness and sampled in 26 closely spaced intervals. Grain-size distribution, fine-gravel composition, macroscopic

and AMS till fabrics, micromorphological structures, and grain-shape characteristics all exhibit remarkably low variability indicating profound mixing of the material by a common and consistent process. We suggest that the mixing was primarily caused by clasts projecting from the ice sole that ploughed the bed before they were lodged and stabilized. Such clasts, typically with flattened and striated upper surfaces ubiquitously occur in the Sønderby till. Calculations show that every part of the till during its formation must have experienced multiple ploughing events that cumulatively generated a well-mixed, homogenous basal till.

These results question the model of pervasive subglacial sediment deformation inferred from till properties as the predominant mechanism of ice-sheet movement and subglacial sediment transport in favour of localized and non-pervasive, yet efficient, clast ploughing.

ORAL

### The role of sub-glacial hydraulic conditions for the formation of fractures in basal tills, examples from recent Icelandic tills and Pleistocene tills in Denmark

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Generally glaciotectonic fractures forms as a result of sub-glacial load and shearing of the sub-surface. However sub glacial hydraulic conditions highly affect the formation of fractures in tills. These conditions depends on three major factors; 1; local hydraulic properties of the till (matrix permeability and thickness) 2; Drainage conditions below the till, and 3; the sub-glacial recharge of melt-water (depending on annual melt water recharge cycles, controlled by local climatic conditions).

In order to investigate the formation of fractures under well-known climatic conditions, a number of basal tills was studied in front of Kötlujökull and Slettjökull, Iceland (Klint et al 2010), and compared with the formation of fractures at a significant number of locations in Danish clay tills.

Several types of fractures were forming depending on a number of factors. Generally sub glacial water-saturated areas favour the formation of hydraulic fractures and water-escape structures.

In contrast un-saturated conditions favours the formation of sub horizontal shear-fractures and low to steeply dipping conjugate sets of shear fractures striking perpendicular or parallel to the ice-movement direction.

These observations have formed the background for evaluating fracture distributions in Danish clay tills based on primarily till thickness, till-type, texture and geo-morphology (Klint et al 2013), thus allowing some general assumptions for risk-assessment of groundwater reservoirs covered by till.

#### References:

Klint K.E.S., Nilsson B., Trolldborg L. and Jakobsen PR. 2013: A Poly Morphological Concept for hydrogeological applications in heterogeneous glacial sediments. *Hydrogeology Journal*: Volume 21, Issue 6 (2013), Page 1247-1264.

Klint K.E.S., Richardt N. and Krüger J. 2010: Evidence for subglacial deformation and deposition during a complete advance-stagnation cycle of Kötlujökull, Iceland – a case study. In *The Myrdalsjökull Ice Cap, Iceland, 13, Glacial Processes, Sediments and Landforms on an Active Volcano*. Ed. Schomacker A, Johannes Krüger J, Kjaer K. pp 145-159.

ORAL

### Different styles of glaciotectionism during an active retreat of a marine terminating glacier – examples from W-Iceland

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Glacier induced deformation commonly takes place below and in front of oscillating glaciers and ice sheets. Resulting glaciotectionic landforms and structures come in a variety of types and sizes, reflecting the ice dynamics during formation. Therefore, interpretation and analyses of these structures can provide valuable information on the deformation events that created them. The information can be used together with sedimentological studies to reconstruct past dynamics and histories of glaciers and ice sheets.

This study focuses on polydeformed marine sediments exposed in the Belgsholt, Melabakkar-Ásbakkar and Skipanes coastal cliffs in the lower Borgarfjörður area, W-Iceland. These glaciotectionic sequences were formed in Late-Weichselian

between c.11,000 and 14,000 cal. yr BP when glaciers advanced off the coast in the area resulting in a large-scale deformation. These formations are now exposed subaerially due to isostatic rebound after the deglaciation.

Documentation of the stratigraphy and structures in the sections has revealed a series of highly deformed zones and ridges, most likely formed during readvances or still-stands as the glacier retreated northwards from its maximum extent. The zones are separated by in-filled basins of stratified and undeformed, marine sediments. Detailed analyses of these zones were performed in order to obtain information about the glacial processes that formed them. These data will be used to construct a model of sedimentological- and deformational processes and placed in context with the regional glacial history. The model may have implications for the subglacial and ice-marginal processes of marine terminating glaciers.

ORAL

### Surge-type glaciers in Svalbard identified through remote sensing

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Identifying glaciers that exhibit surge-type behaviour is important as we aim to use evidence of ice front fluctuations as a proxy for reconstructing past climate oscillations. The relationship between surge activity and climatically controlled glacial mass balance is not entirely clear. This project identifies previously undocumented surge-type glaciers in Svalbard, based on the presence of crevasse squeeze ridges (CSRs; also called fill ridges) visible in glacier forelands. Crevasse squeeze ridges are believed to be a landform unique to surge behaviour. Although it is acknowledged that many Svalbard outlet glaciers surge, estimates vary greatly as to the actual number of surge-type glaciers, and their distribution pattern is not well understood. A detailed survey of recent (2008-2012), high-resolution

aerial imagery from Toposvalbard, provided by the Norwegian Polar Institute, allowed for a rapid analysis of forelands of Svalbard glaciers. Using CSRs as indicators of surge behaviour has almost tripled the amount of potential surge-type glaciers in Svalbard. Limits to the CSR identification method are discussed. Additionally, as the forelands of previously reported surge type glaciers were analysed for CSRs, it was evident that the unique surge landforms were not present in approximately a third of the known surge-type glacier forelands. Numerous factors control the formation and preservation of CSRs including glacier size, bedrock lithology, subglacial sediments and clast size as well as glacial fluvial run-off. This presentation will focus on the controlling factors for CSR formation and preservation as well as the relation between surge activity and climate on Svalbard.

ORAL

### Rates of glacio-isostatic uplift as an age modelling tool

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The relatively rapid reduction of contemporary glaciers in Iceland and subsequent glacio-isostatic uplift has been observed to be progressing at rates as high as +35 mm a<sup>-1</sup>. Earlier on, during the late Weichselian deglaciation of Iceland, the coastal areas were uplifted at rates between +34 mm a<sup>-1</sup> (Pre-boreal) and at least +159 mm a<sup>-1</sup> (Bølling). The rates of uplift were also contemporaneously different within an area and, thus, with time they produced uplifted shorelines and ice-lake strandlines with different gradients of different age, due to variable rates of glacio-isostatic uplift.

It has been recognized that a decrease of strandline gradients towards the end of uplift is preferably described with an exponential expression:

$$\partial g = \partial g_0 \cdot e^{-k \cdot t_0}$$

where  $\delta g$  is a change in gradient over a known period of time;  $\delta g_0$  is a reference level (0.01 m km<sup>-1</sup>);  $k$  is a litho- and asthenospheric dependent

constant;  $t_0$  is duration of uplift. Solving the equation for Iceland returns  $k = 2.1810^{-3}$ . Applying this equation to uplifted ice-lake strandlines in East Iceland shows that a strandline gradient of 0.7 m km<sup>-1</sup> was produced during a period of 1,955 years prior to the end of glacio-isostatic uplift at about 9,500 cal BP.

ORAL

### Holocene glacier extent and ELA reconstructions of paleoglaciers in Sarek National Park, northern Sweden

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In this study recently published high resolution LiDAR data is used for the first time to reconstruct equilibrium line altitudes (ELAs) of Holocene paleoglaciers in Sarek National Park, northern Sweden. Trimlines, marginal meltwater channels, end moraines and lateral moraines were mapped to define past extent of the paleoglaciers. The glaciers are often fronted by several imbricated, closely spaced end moraines, most of which are thought to be formed during the Little Ice Age (LIA) but some moraines might be of early- and mid Holocene age (Karlén & Denton, 1976).

ELAs were calculated using the Accumulation Area Ratio (AAR), Area Altitude (AA) and the Area Altitude Balance Ratio (AABR) methods. Calculated ELAs for the paleo glaciers ranges between 1340-1460 m.a.s.l. when applying an AAR of 0.6, 1350-1490 m.a.s.l. with the AA-method and 1280-1490 m.a.s.l. for AABRs of 0.8-3.0. These paleo-ELAs are approximately 100-200 m lower than measured 21th century ELAs in the adjacent Kebnekaise area.

The results in this study identify periods when glacier extent cannot be explained by reconstructed summer temperatures alone and therefore indicate high winter precipitation at the time. These findings are potentially of major importance for paleoglaciological reconstructions in Sweden as summer balance have previously been assumed to be more important than winter balance on net mass balance of Swedish glaciers. Resulting in discrepancies between glacier reconstructions and the moraine-based glacier chronologies. The existing

glacier chronologies in northern Sweden are, however, mainly based on highly extended lichen growth curves. The maps produced in this study are hence needed to pinpoint locations for future exposure dating as a revision of the glacier chronologies will enable correlations with possible climate forcings.

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ORAL

### Glacial sequence stratigraphy reveal the Weichselian glacial history of the SE sector of the Eurasian Ice Sheet

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Reconstructions of the last Weichselian glacial cycle 117,000-11,700 years (kyr) ago propose that S Finland, adjacent Russia and the Baltic countries in the SE sector of the Eurasian Ice Sheet (EIS), were glaciated during the Middle Weichselian time [marine isotope stage (MIS) 4, 71-57 kyr ago] and that this glaciation was preceded in S Finland by an Early Weichselian interstadial (MIS 5c, 105-93 kyr ago) with pine forest.

Here glacial sequence stratigraphy (Powell and Cooper 2002) is applied to isolated Late Pleistocene onshore outcrop sections in S Finland. The analysed sedimentary records have traditionally been investigated, interpreted and published separately by different authors without an attempt to a methodologically more systematic survey. By putting new field data and old observations into a regional sequence stratigraphic framework it is shown how previously unnoticed regularities can be found in the lithofacies and fossil successions.

It is shown that the proposed Middle Weichselian glaciation or the pine dominated interstadial did not take place at all (Räsänen et al. 2015). The one Late Weichselian glaciation (MIS 2, 29-11 kyr ago) at the SE sector of EIS was preceded in S Finland by a nearly 90 kyr long still poorly known non-glacial period, featuring tundra with permafrost and probably birch forest. The new Middle Weichselian paleoenvironmental scenario revises the configuration and hydrology of the S part of EIS and gives new setting for the evolution of Scandinavian biota.

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ORAL

### Spatial changes in distribution of suspended matter from the tidewater glacier in Hansbukta, Hornsund Fjord (Spitsbergen)

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In polar regions we can observe the tidewater glaciers that affect the fjords. Glaciers activity includes the outflows, which deliver the freshwater and sediments into the fjords. The lower density of these outflows causes that they are lifted up to the surface of sea. They form the plumes of suspended sediment concentration (SSC) which are transported by dynamic marine processes. The sediments gradually fall on the seabed. The amounts of sediments depend on the season, weather and oceanographic conditions.

The main goals of our work are to analyse the changes of distribution of the SSC, the direction of suspension movements, and localization of sources of these plumes and the amount of SSC in the water column during ablation season. In this purpose, we analysed the results of the field measurements of SSC, oceanographic conditions (CTD and ADCP measurements), and the satellite images for the two bays Isbjørnhamna and Hansbukta in Hornsund Fjord (Spitsbergen).

## ORAL

### Combining terrestrial and marine glacial archives – a geomorphological map of Nordenskiöldbreen forefield, Svalbard

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Nordenskiöldbreen is a polythermal, tidewater glacier located in inner Billefjorden, central Spitsbergen, where it terminates in Adolfbukta bay. This on-going MSc project aims to produce a high-resolution geomorphological map of the recently deglaciated area in front of Nordenskiöldbreen and a landsystem model for a polythermal tidewater glacier, with descriptions and interpretations of sediment-landform associations.

A holistic approach is taken, and the map is created in ArcGIS software based on analysis of aerial images (2009) and high-resolution swath bathymetry (2009) from the fjord. Ground-truthing was carried out through field campaigns in August 2014 and 2015. Glacier front position lines are reconstructed from historical data, aerial imagery and satellite images.

The study contributes to an improved understanding of Svalbard glaciers and their response to climate fluctuations and is a part of the larger research project: “Holocene history of Svalbard Ice Caps and Glaciers” (see Research in Svalbard (RIS) database at: <http://www.researchinsvalbard.no/project/7567>).

## POSTER

### Microtextural and heavy mineral constraints on the oscillations of the late Pleistocene Scandinavian Ice Sheet

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Microtextural and heavy mineral characteristics of the upper sediments of the Rautuvaara terrestrial succession in NW Finland is studied to better understand the Scandinavian Ice Sheet (SIS) dynamics during the late Pleistocene. Investigation of the SIS evolution has become particularly relevant since the recent research concluded that the Rautuvaara sediments are much younger than previously assumed; the entire succession deposited during the Weichselian Stage in at least three glacial ice advance-retreat cycles and glaciolacustrine conditions existed between the cycles. In this framework we analyse quartz grain surface microtextural and heavy mineral contents of the Rautuvaara sediments to interpret their origin and processes of sediment transport. Focus is on the upper 7 m of the section where two uppermost tills and the interbedded sediments are exposed.

Preliminary microtextural analyses show that the sediments have been subjected to subglacial, fluvial and chemical processes during transportation and sedimentation. A strong subglacial signal exist at lower till bed accompanied by upwards intensifying fluvial signal. Subsequently, fluvial signal become dominant in the following ripple- and horizontally bedded sand and massive fine sand/silt beds. In the lower part of massive fine sand/silt bed, there is, however, a considerable increase in subglacial and reduce in chemical signal as compared to the sand beneath. These findings may indicate change in sediment source and geochemical environment. Observations of dropstones support sedimentation by iceberg rainout. Heavy mineral analyses will provide further detailed information of mineralogical source characteristics of tills and interbedded sediments.

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**POSTER**

### Provenance of glacial sediments by detrital geochronology from Kapp Ekholm, Svalbard

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This study aims to present inter-comparative provenance data from the Saalian to Late Weichselian till units preserved in the Kapp Ekholm stratigraphy, located in inner Isfjorden on the west coast of Svalbard.

Here we attempt to distinguish sediment sources by coupling individual detrital grains to geochronological data. In recent years the paradigm of ice sheet behavior has shifted towards the concept of highly dynamic fast flowing ice-streams with inactive inter-ice-stream areas. Northern hemispheric ice sheet configurations are known to have differed considerably throughout the late Quaternary (Svendsen et al. 2004), and probably shifted to more channelled erosive regimes constrained to fjord settings in the mid-Pleistocene (Gjermundsen et al. 2015). Lack of preserved landforms leaves reconstructions of older glacial cycles contingent on data from preserved glacial sediments. Provenance data from this study might yield information reflecting distinct ice flow patterns, while providing a testing ground for geochronological provenance studies.

Recent advancements in LA-ICP-MS enables <sup>87</sup>Rb/<sup>87</sup>Sr geochronology without prior isotopic separation and sample dissolution (Zack et al. this conference). In-situ <sup>87</sup>Rb/<sup>87</sup>Sr geochronology may provide a key provenance tool for reconstructing ice flow dynamics throughout the Pleistocene, and should also be applicable within similar sedimentological contexts.

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**POSTER**

### Evolution of saltwater intrusions in coastal aquifers during the past and the future

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Today, groundwater is the main source of water supply in Denmark. Aquifers in low lying areas near the Wadden Sea in Southern Denmark are vulnerable to saltwater intrusion, which is likely to intensify due to relative sea level rise. To understand the dynamics and development of this complex flow system, the initial hydrodynamic conditions imposed by the last Scandinavian Ice Sheet (SIS) must be taken into account (Piotrowski 2007).

We investigate the influence of SIS during the Weichselian glaciation on the current groundwater flow pattern and the development of salt water intrusions in the coastal aquifers due to postglacial sea level rise. It is likely that the groundwater-flow dynamics, driven by the postglacial hydraulic head drop and the relative sea level rise are not yet equilibrated and, enhanced by the potential future sea level rise due to climate change, contamination of fresh-water aquifers will continue.

Based on a geological voxel model spanning Miocene through Quaternary deposits (Jørgensen et al. 2015) a large-scale 3D finite-difference numerical groundwater flow and transport model, including density-driven flow is used to simulate the distribution of the current saltwater intrusion and to investigate the evolution of saltwater intrusion during the last 15000 and future 200 years.

In a field campaign in February 2015, groundwater samples from Miocene and Quaternary aquifers were collected for isotope age dating that is used to calibrate and validate the numerical transport model. Chemical and isotopic composition of



groundwater will be used to determine its the origin. Where the collected data and simulations indicate groundwater recharged during the last glaciation analyses of heavy noble gases will be carried out in order to estimate recharge temperatures and evaluate the recharge mechanism.

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Piotrowski, J.A., 2007. Groundwater Under Ice Sheets and Glaciers. In: Knight, P.G. (ed.) *Glacier Science and Environmental Change*. Blackwell Publishing, Oxford, UK, pp. 50–60.

#### POSTER

### Internal structure and drainage conduits in a cold Svalbard glacier

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A combination of speleological exploration and high-resolution radar survey was applied to investigate the englacial and subglacial drainage system of Longyearbreen, a cold glacier in Svalbard. Direct observations were compiled with remotely-sensed data in a 3D visualization of the glacier system using Petrel software package. In addition, a radar survey covering the entire glacier provided information on changes in the glacier thermal regime over time.

Previous studies assumed that, in cold glaciers, no englacial and subglacial drainage systems form because cold ice acts as a barrier to water flow (Hodgkins 1997; see also the classical model of the evolution of the englacial meltwater system of Shreve 1972). However, the meltwater conduits present in Longyearbreen show that englacial and subglacial drainage channels indeed can develop in an un-crevassed, cold glacier, and we suggest that they formed through the cut-and-closure process as in the conceptual model of Gulley (2009).

In the view of the present global temperature rise, investigating whether meltwater may reach the bed through a cold surface layer is vital for the understanding of glacier dynamics and stability. Valley glaciers in Spitsbergen such as Longyearbreen are potentially important contributors to the near-future sea level rise (Meier et al. 2007).

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#### POSTER

### Glacial landscapes carved by subglacial meltwater erosion under the Scandinavian Ice Sheet

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The impact of subglacial meltwater erosion on shaping glacial landscapes is contentious and often difficult to constrain due to the lack of unequivocal diagnostic criteria. The same holds for the role of subglacial meltwater in glacier movement processes and sediment transport and deposition.

Here we present new evidence of widespread channelized erosion under the southern, soft-bedded fringe of the last Scandinavian Ice Sheet (SIS) based on high-resolution terrain analysis with LiDAR imagery. We identify several tens of sites with “glacial curvilinearation” landscapes first recognized by Lesemann et al. (2010, 2014) and considered as evidence of erosion by turbulent meltwater flows at the ice/bed interface.

The “glacial curvilinearation” landscapes mapped here consist of sets of parallel, winding ridges typically several metres high and up to several kilometres long occupying glacial overdeepenings and tunnel valleys. The ridges are aligned approximately perpendicular to the past ice sheet margins and they are composed of various deposits often pre-dating the last ice advance. We interpret them as erosional remnants of older landscapes dissected by high-energy subglacial meltwater flows. These findings suggest that the palaeoglaciological significance of meltwater drainage under the southern portion of SIS may have been grossly underestimated.

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## POSTER

### Thickness of superficial deposits in Finland

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A superficial deposits thickness map database was produced by Geological Survey of Finland. It represents the loose Quaternary deposits thickness over the bedrock. The overburden thickness is typically only some meters in Finland.

The Map Database will be used in several applications including geoenergy surveys (underground thermal energy), engineering geology for urban planning and environmental research.

The thickness of superficial deposits is based on direct and indirect bedrock elevation observations from the databases of Geological Survey of Finland. In addition, the database of the national borehole register (Pohjatutkimus-rekisteri) has been used. Data has been interpolated to raster grid with a cell size of 500 m by 500 m. This grid layer has been combined with bedrock area (outcrops and thin overburden) polygons from 1:200 000 scale Quaternary geology map and superficial deposits polygons from 1:1 000 000 scale Quaternary geology map. The latter have been classified into depth classes of typical values for each superficial deposit type in different regions of Finland.

The resulting raster image shows thickness of superficial deposits classified into five classes: < 1m, 1–10 m, 10–30 m, 30–50 m and > 50m.

The Map Database is intended to provide regional, generalized and averaged information. It is not intended to be used at a higher resolution, for example for a site-specific evaluation overburden thickness.

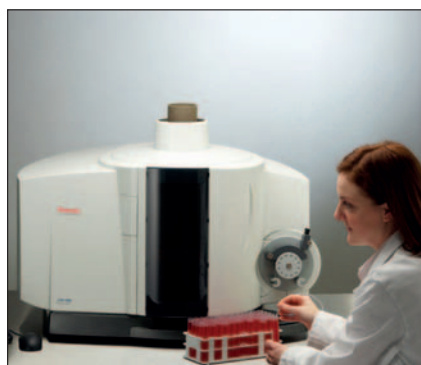
Raster image (.jpeg) is available to download at the website of Geological survey of Finland <http://hakku.gtk.fi/>

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### Metallianalyytikon työkalut

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## S11.2 Glacial history of Scandinavia

### KEYNOTE

#### The Scandinavian Ice Sheet – History and dynamics

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The Scandinavian mountains have repeatedly been the inception center for large ice sheets throughout the Quaternary. At full scale glaciations such as the Last Glacial Maximum, the distance to the western ice margin on the continental shelf was about one-fourth of the distance to its eastern counterpart in NW Russia. Asymmetric build-up and eastwards migration of the main ice-divide was suggested more than 60 years ago (Ljungner 1949). It follows that the maximum ice margin is not a synchronous line. In fact, it may be as much as 10,000 years between oldest and youngest maxima in different ice-sheet sectors (Hughes et al. 2015). Warm based, subglacially formed and cold based, relict landforms group systematically in the area of the former ice sheet (Ottesen et al. 2002; Kleman et al. 2008). The subglacial thermal regime and ice-bed interactions associated with these landforms hold information about ice-flow mechanisms from which relative velocity distribution can be deduced (Larsen et al. 2014). All this adds to the explanation of the asynchronous glacial maxima.

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### ORAL

#### A new Middle Pleistocene interglacial occurrence in Copenhagen, Denmark

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Only a few non-marine interglacial occurrences have been recorded from eastern Denmark. In connection with borings and excavations for a new metro line in Copenhagen, a new occurrence could be sampled. The succession at the new site consists of Danian limestone, glaciofluvial sand and gravel, a gyttja layer, a lower till bed, glaciofluvial sand and gravel, an upper till bed and glaciofluvial sand. The gyttja layer is up to 0.5 m thick and rich in plant remains; it also contains flattened tree logs. The interglacial layer is located in a channel-like depression and has probably been protected from erosion.

The new occurrence is located 1.4 km from an interglacial occurrence discovered in the free port in 1892, and the stratigraphy as well as the fossil flora and fauna show marked similarities. Hence we suggest that these occurrences represent the same interglacial stage.

The flora includes the trees *Pinus*, *Picea*, *Betula*, *Alnus*, *Quercus*, *Tilia*, *Ulmus*, *Corylus* and *Populus* and the shrubs *Cornus*, *Salix*, *Rubus* and *Empetrum*. These species show that the region was forested but included some light-demanding species. The flora also includes a number of warmth-demanding species. One of them, the small water plant *Najas minor*, has a northern geographical limit in Germany at present, and points to slightly higher summer temperatures than at present.

The fauna includes a small extinct bivalve species, *Pisidium clessini*, which is unknown from Eemian or younger deposits. This species was also recorded from the free port. The free port fauna includes the bivalve *Corbicula fluminalis*. This is an extant species that currently lives in Asia and Africa. It is recorded from many interglacial deposits in NW Europe, but not from Eemian deposits. These bivalves indicate a fluvial palaeoenvironment, but the fine-grained nature of the deposit

shows that it was deposited in a low-energy environment, perhaps an oxbow lake.

Attempts are made to date the occurrence by pollen analyses, optically stimulated luminescence dating and amino acid analyses on opercula of the snail *Bithynia tentaculata*.

ORAL

### Early Weichselian glacial history in western Finland

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Glacial history of Fennoscandia and adjacent areas are mainly based on litho-, bio and chronostratigraphical evidence. Several ice advance events across Finland have caused erosion and subglacial deformation of previously deposited sediments. Therefore, most of the pre-Late Weichselian sediments have been eroded completely or severely glaciotectionised and subglacially deformed complicating attempts to reconstruct a firm glacial history for Finland. However, in western Finland (Ostrobothnia) and central Finnish Lapland the pre-Late Weichselian sediments occurring beneath the Late Weichselian till are more abundant compared to the rest of Finland and sediments from these areas provide the best opportunity to shed light on the glacial history of Finland. Here an attempt is made to critically analyse the events that took place during the Early Weichselian in western Finland. For this purpose new litho-, bio- and geochronological results of the multiple till successions, interbedded with interstadial sediments, at Koivusaarenneva and Muhos, in central western Finland adjacent to the Gulf of Bothnia are presented. The results of these sites are compared to previously published and also new data from other pre-Weichselian sites in western Finland in order to have a comprehensive picture of the Weichselian history of the area.

ORAL

### OSL dating of Weichselian ice-free periods at Skorgenes, western Norway

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During recent years, many sites with pre-LGM sediments have been identified in the formerly glaciated areas. As more and better dates are presented from these sites, we see increasing evidence for an active and dynamic Scandinavian ice sheet.

In this study, we revisited the site Skorgenes in western Norway. Here sediments from three periods with ice-free conditions have been found interbedded with tills, and they provide a record of several generations of ice advances and retreats. The youngest of these sediments, a pro-glacial delta succession, has been linked to the final deglaciation of the site but the ages of the older units are more problematic.

Here we present an updated chronology for the Skorgenes site, based on 10 new OSL dates, and discuss possible correlations with other sites in western Norway and their relation to other important sites in Scandinavia.

ORAL

### Sequential development of Jutulhogget canyon, southern Norway

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Jökulhlaups or glacial lake outburst floods (GLOFs) are recurrent phenomena in glacial areas. They are often related to periods of deglaciation

or retreating glaciers when there is an excess of glacial meltwater. The largest water floods on Earth are assumed to be related to the drainage of the enormous glacier dammed lakes which formed in front of the continental ice sheets in North-America and northern Eurasia during the glaciations. Jutulhogget canyon in southern Norway is one of northern Europe's largest canyons with a length of 2.4 km and a depth of 250 m. During glaciations, when the ice sheet divide was situated south of the main watershed in southern Norway, large glacier dammed lakes formed in the upstream ends of the eastern valleys. Jutulhogget canyon was formed by cataclysmic floods during the emptying of glacial lake Nedre Glåmsjø.

A new survey of the erosional deposits at the mouth of the canyon shows terraces with ice-contact features, subaerial drainage channels and plunge pools at different elevations. We suggest that this indicate a sequential development of the canyon through at least four distinct jökulhlaup events. The timing of the events is not yet resolved, but OSL dating of fine sediments suggest that Nedre Glåmsjø also existed during MIS3 prior to the last glacial maximum, and that the canyon formed between c. 30 and 10 ka.

ORAL

### Deglaciation of the southwestern Scandinavian Ice Sheet using $^{10}\text{Be}$ dating

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We present a number of  $^{10}\text{Be}$  ages from glacial erratic boulders along the major fjord systems of Boknafjorden and Hardangerfjorden to constrain the dimension of the Scandinavian Ice Sheet in southwest Norway during deglaciation. The results complement our previous findings that the Norwegian Channel Ice Stream collapsed during as early as  $\sim 20$  ka (Svendsen et al. 2015). A second pulse of deglaciation started at  $\sim 16$  ka when the ice front retreated towards the head of Boknafjorden. Two younger glacier advances culminated during the Older and Younger Dryas cold spells (Briner

et al. 2014). The ice sheet profiles during deglaciation seem to have been rather steep with typical gradients  $\sim 30$  m/km.

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Svendsen, J.I., Briner, J., P., Mangerud, J., Young, N.E. 2015: Early break-up of the Norwegian Channel Ice Stream during the Last Glacial Maximum. *Quaternary Science Review* 107, 231-242.

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ORAL

### Extent and timing of the Late Weichselian Scandinavian ice-sheet maximum and the following deglaciation in northern Atndalen, east-central southern Norway

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Atndalen is a valley orientated N-S east of Rondane in east-central southern Norway, and is located between the former ice divide and the present main watershed to the north within the suggested cold-based ice sheet region of central Scandinavia. In northern Atndalen there exist extensive lateral meltwater channels and eskers after downwasting ice sheets from the final stages of deglaciation. Except for cirque glaciation at an altitude well below the present glaciation limit, there are no clear indications of erosive valley glaciers since the vertical downwasting of the Late Weichselian Scandinavian ice-sheet maximum (20-18 ka) started, and the final deglaciation.

The general deglaciation pattern of northern Atndalen has been reconstructed by mapping of lateral meltwater channels and related overflow gaps, ice-dammed lakes, the occurrence of low-altitude cirque glaciation and stratigraphical investigations. The timing of events has been dated by using three independent methods; optically stimulated luminescence (OSL), terrestrial cosmogenic nuclides (TCN) and AMS radiocarbon dating on terrestrial

plant macrofossils. Suggested to be the result of precipitation starvation, the vertical extent of the late Weichselian glacial maximum of the Scandinavian ice sheet in northern Atndalen is much less than previously suggested, and except for cirque glaciation, no or limited glacier activity took place during the Younger Dryas. Deglaciation events in northern Atndalen may be linked to contemporaneous events along the coastal ice margins of southern Norway during the Allerød, Younger Dryas and Preboreal chronozones.

## ORAL

### Dynamics of and controls on post-Younger Dryas retreat of a Bothnian Sea ice stream

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The Gulf of Bothnia has variably played host to interior portions of the Fennoscandian Ice Sheet; the onset, trunk and retreat zones of Baltic and Finnish ice streams; and marine ice sheet retreat and the subsequent development of an 'inland' marine basin. These glacial dynamics and environments have, hitherto, been inferred from terrestrial, peripheral evidence. The Gulf of Bothnia itself has been little investigated and its glacial geological archives are virtually unknown.

Recent acquisition of high resolution multi-beam echo-sounding data across the Gulf of Bothnia reveals, for the first time, the glacial landforms associated with flow and retreat of ice through the basin. A late-stage ice stream, with onset over Kvarken and the Västerbotten coast, flowed southward through the Bothnian Sea in a narrow corridor of fast flow. A vast field of crevasse squeeze ridges indicates ice flow under high extension, which likely enabled large supraglacial melt volumes to penetrate to the bed and develop an extensive, channelised and well-connected basal hydrological network. Stimulated by our geomorphological observations, we use a physically-based numerical ice

flowband model (Nick et al., 2010) to examine the sensitivity of ice retreat to atmospheric warming (surface melt), calving and sea level change. We further explore the coupling between rapid extensional ice flow, basal crevassing and ice margin stability during deglaciation of the Bothnian Sea.

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## ORAL

### What happened during the formation of the Salpausselkä ice marginal formations

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Recently public interest to the origin of Salpausselkä ice marginal formations has grown and science fiction theories has been put forward (Isomäki 2015).

This is a story what really happened when Salpausselkä where deposited (Nenonen 1995).

Southern and central Finland were covered by the continental ice sheet during marine isotope stages 3 and 2, from 54 ka to 13 ka BP. Abrupt climatic variations of the last glaciations are clearly visible in the oxygen isotope record of the long GRIP ice cores from Greenland. The front of the melting ice sheet withdrew to the south coast of Finland about 13 000 years ago.

According to the varved clay chronology the ice front reached Lappeenranta about 11 600-12 800 years ago. Till-covered deposits of varved clay and silt on the proximal side of the Salpausselkä deposited when the ice front withdrew to a position possible up to 50 -80 km north of what is now Salpausselkä I, during the Heinola Deglaciation.

The Heinola deglaciation occurred during the warm Allerød interstadial at the beginning of oxygen isotope stage 1. Beneath Salpausselkä I in Lahti and in the basal parts of clays on the distal side of Salpausselkä I, there are deposits compatible with the Allerød chron in vegetation.

Salpausselkä I and II formed during the Younger Dryas chron, at 11 600-12 800 <sup>14</sup>C yr BP, when the climate suddenly cooled back to the glacial level. Re advance of the continental ice sheet where triggered by the cooling climate and by the changes in relative sea level of the Baltic basin, evidently

caused by discharge of cold ice lake water to North Atlantic. The drop of Pre-Baltic Ice Lake level has probably been even in order of 25 - 50 meters during several steps over a century, when the Billingen corridor opened first time during Allerød interstadial and 8000- 16 000 cubic kilometers of cold fresh water drained to North Atlantic in a relatively short time. Simultaneously the North American Laurentide ice sheet discharged glacial lake waters to Labrador Sea and North Atlantic.

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Keijo Nenonen 1995. Pleistocene stratigraphy and reference sections in southern and western Finland. Kuopio: Geological Survey of Finland, 205 s.

ORAL

### Fluctuations of the Scandinavian Ice Sheet during Bølling-Younger Dryas were very different in Western Norway compared with Sweden-Finland

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Distinct Younger Dryas (YD) moraines are mapped more-or-less continuously around the entire Scandinavian Ice Sheet. In most areas there is no evidence to suggest that a major glacial re-advance took place during the YD. In contrast we here present 90 radiocarbon dates from 35 different sites that were overrun by a major ice sheet advance in the area between Hardangerfjorden and Sognefjorden, SW Norway. The re-growth commenced during the Allerød interstadial and expanded along 600-800 m deep fjords reaching a thickness of up to 2000 m during the YD. We present time-distance diagrams for two lobes; for both the outermost coast became ice free close to 15 cal ka BP, i.e. at the onset of the Bølling. Both lobes reached their most retreated position before re-advancing at 13.5-13.0 ka and obtained their maximum extent at the Herdla-Halsnøy moraines at the very end of the YD, at 11.5

ka. The late culmination of the advance is accurately dated and differs from most of the Scandinavian Ice Sheet margin where the maximum was reached during early or middle YD. The Herdla-Halsnøy moraines are located only shortly inland of Bølling the ice-margin position, again contrasting eastern parts of the ice sheet.

ORAL

### Dating the response of methane hydrate systems in the Barents and Norwegian Seas to collapse of the Scandinavian Ice Sheet

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CH<sub>4</sub>-derived authigenic carbonate (MDAC) crusts exhibiting characteristic <sup>13</sup>C-depleted isotopic signatures were collected from five seepage sites of the Norwegian and Barents Sea, areas that were characterised by thick (>1km) grounded ice during the last glacial maximum. Modelling of the gas hydrate stability zone in grounded ice margin indicate the potential for significant CH<sub>4</sub> hydrate accumulations during glacial maximum. U-Th dating of MDAC has been attempted on early generation carbonate phases that cement sandy and gravelly sediments as well as late generation phases occurring as botryoidal laminae that fill cavities within carbonate cemented sediments. U-Th dates indicate that the formation of the early generation carbonate cements in studied crust samples was coincident with the deglaciation of the area and collapse of the Scandinavian Ice Sheet (ca. 17 ka). The CH<sub>4</sub> flux for the carbonate crust formation was likely provided by the dissociation of CH<sub>4</sub> hydrates that formed in underlying sediments during the last glacial period due to ice sheet loading, but became unstable due to pressure release associated with ice sheet retreat and collapse. The main episode of CH<sub>4</sub> seepage and carbonate crust formation that was initiated by the ice sheet collapse continued for 7-10 kyr after deglaciation as the gas hydrate stability zone continued to thin in response to sea-level

change, isostatic rebound and bottom water warming. These data provide constrain in the timescale of CH<sub>4</sub> efflux in basins which were ice grounded during glacial maximum but underwent rapid ice sheet collapse.

## ORAL

### Jan Mayen – The Pleistocene-Holocene glacial history of an active volcanic island

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The volcanic island of Jan Mayen, situated in the Norwegian – Greenland Sea, has an arctic – maritime climate influenced by the northwards flowing Atlantic current and the southwards flowing East Greenland current. Small shifts in these current systems will likely influence the climate on Jan Mayen which suggests that the island could be very sensitive to climate change. In 2015 we started a project funded by the Research Council of Norway to investigate glacial and climate history of the island. Below we report preliminary results of the glacial history.

Presently, the active volcano Beerenberg has an ice cap with several outlets, some of them reaching down to sea-level. The Little Ice Age (LIA) marginal moraines are well developed, and preliminary <sup>36</sup>Cl cosmogenic dates give reasonable LIA ages. Whether or not the entire island has been ice-covered previously has been a matter of controversy. A moraine ridge at present sea-level with an associated marine terrace are interpreted to represent the Last Glacial Maximum (LGM) and the marine limit, respectively. This, in addition to other geomorphological observations, are taken to indicate that the entire island was ice-covered, and that glaciers extended at least down to present sea level. <sup>36</sup>Cl cosmogenic dates indicate that glaciers had retreated considerably by some 18 – 19 ka BP.

Stratigraphic investigations indicate that the island of Jan Mayen was covered by ice also prior to LGM. In coastal sections at several locations, glaciogenic diamictites at stratigraphic position below LGM are found in association with lava flows.

Interaction between glaciers and volcanic eruptions cause complex sediment associations, but also provide opportunity for dating glacial events.

## POSTER

### DATED-2: updates to the Eurasian ice sheet chronology and time-slice reconstructions

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We present on-going work to update, maintain and develop the DATED database of dates and time-slice reconstructions of the build-up and retreat of the Eurasian (British-Irish, Scandinavian, Svalbard-Barents-Kara Sea) ice sheets during the last glacial cycle (40-10 ka). Our first compilation and assessment of dates (DATED-1; census 1 January 2013; Hughes *et al.* 2015) demonstrated that the timing of maximum extent and both the timing and rates of ice advance and retreat were spatially variable across the ice sheet complex. Despite the wealth of information accumulated over several decades, it is possible to precisely define the ice sheet margin in only a few sectors and time-slices. In some locations and time-slices uncertainty in the placement of the ice margin position is as much as several 100 km and some instances of contradictory evidence also occur. Even in just three years since the DATED-1 census, the volume of new information (from both dates and pattern information) has grown significantly requiring a reassessment of the ice-sheet margin positions. Here we discuss the implications of these additional data and present preliminary revised time-slice maps (DATED-2). We heartily invite scientists to inform us about dates and other information missing in DATED-1, and to criticise our interpretation of the data.

## References:

Hughes, A. L. C., Gyllencreutz, R., Lohne, Ø. S., Mangerud, J., Svendsen, J. I. 2015. The last Eurasian ice sheets – a chronological database and time-slice reconstruction, DATED-1. *Boreas*. 10.1111/bor.12142



## POSTER

**Lake Nordlaguna, Jan Mayen: The potential for a palaeoclimate record from the island**E. LARSEN<sup>1,2\*</sup>, A. LYSÅ<sup>1</sup> AND M. LUDVIGSEN<sup>3</sup>

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The arctic island of Jan Mayen situated in the Norwegian – Greenland Sea, has an arctic – maritime climate influenced by the northwards flowing Atlantic current and the southwards flowing East Greenland current. It is hypothesized that small shifts in these current systems will greatly influence the climate on Jan Mayen. It follows that the island might be very sensitive to climate change. Therefore lake coring will be performed in April of 2016.

The only lake on the island suitable for coring is Nordlaguna situated ca. 2 m a.s.l. on the western coast. It is separated from the sea by a long and wide beach ridge. Jan Mayen has active volcanism, but it appears likely that no Holocene lava flows entered the lake. Preliminary data indicates that the lake area was just inside the the Last Glacial Maximum limit. Thus, in theory, the lake might hold a long Late Weichselian – Holocene palaeoclimate record. In order to prepare for the drilling we have mapped lake bathymetry, bottom sediments and sediment sources around the lake.

An AUV mounted side scan sonar including other sensors combined with ROV mounted video cameras revealed that the lake is less than 40 m deep and has a very gentle/flat bottom topography in the southwestern part. Mainly fine-grained bottom sediments are found, with occasional blocks. Driftwood that are thrown over the beach ridge in heavy storms are quite frequent. GPR profiling across and along the beach ridge provides evidence that it developed in an end moraine. The postglacial relative sea-level history of Jan Mayen is unknown. Nevertheless, marine sediments is expected in the sediment sequence.

## S11.3 Recent developments in Quaternary dating methods

ORAL

### Finding a good place to date

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The luminescence characteristics of quartz, one of the main minerals used for luminescence dating, vary greatly from region to region, and this is reflected in how easy Quaternary sediments from different areas are to date with optically stimulated luminescence (OSL), and in the accuracy or precision of final ages. The cause of ‘good’ or ‘bad’ luminescence characteristics seems to largely be the geological history of the quartz, e.g. the number of erosional-depositional cycles it has been through.

Large parts of Scandinavia unfortunately seem to provide quartz with less than ideal luminescence characteristics, but a few years ago Alexanderson & Murray (2012) put up a hypothesis that the Proterozoic Dala sandstone in Sweden was a source of ‘good quality quartz’ for OSL dating of Quaternary deposits. This hypothesis has now been tested and preliminary results suggest that the hypothesis is correct. Sediments derived largely from the Dala sandstone (Late Quaternary glacial/aeolian deposits near Mora, Dalarna; see presentation by Bernhardson & Alexanderson) as well as large clasts of Dala sandstone have been analysed with OSL. Crushed Dala sandstone, untreated and treated Quaternary sediment all showed excellent luminescence characteristics. The good agreement between measurements of untreated material (so called range-finder OSL; Roberts et al. 2009) and fully treated material (standard OSL) show that relative chronologies, based on range-finder OSL, can rapidly (a few days of measurement) be established in areas such as this.

To identify other areas of potentially good or bad luminescence source rocks, and ideally to provide some insight into the origin of good OSL, quartz-rich rocks from other parts of Sweden and from Svalbard, ranging in age from Proterozoic to Paleogene, have been tested and compared with results of OSL analysis of sediments derived largely from these rocks. The results may give some hints

of areas where OSL dating may be easier, and which areas to preferably avoid!

### References:

Alexanderson, H. & Murray, A. S. 2012: Problems and potential of OSL dating Weichselian and Holocene sediments in Sweden. *Quat. Sci. Rev.* 44, 37-50.

Roberts, H. M., Durcan, J. A. & Duller, G. A. 2009: Exploring procedures for the rapid assessment of optically stimulated luminescence range-finder ages. *Rad. Meas.* 44, 582-587.

ORAL

### Bayesian chronological tools in event reconstruction – case study of Vuoksi breakthrough

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In archaeology Bayesian chronological tools have been considered to be even another revolution in understanding cultural evolution. In this work, we present a case in which Bayesian chronological modelling is used in transdisciplinary study to reveal most probable event sequence of geological anomaly and nearly contemporaneous cultural development.

Particularly, we show that an abrupt water level decline of an ancient Lake Saimaa nearly 6000 years ago preceded a cultural change bringing in the most influential of the past cultures into the eastern Finland – the Typical Comb Ware. The change was accompanied by an increased usage of moose, consistent with the ecological development of new residual wetlands and with the observed population maximum within the area. The methodological approach described allowed the reconstruction of past natural and cultural events, and demonstrated how they can be causally intertwined.

## References:

Oinonen M et al 2014. Event reconstruction through Bayesian chronology: Massive mid-Holocene lake-burst triggered large-scale ecological and cultural change. *The Holocene* 24(11): 1419-1427.

## POSTER

### Cosmogenic surface exposure dating with $^{36}\text{Cl}$ on Jan Mayen

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Jan Mayen is the northernmost island on the North Atlantic ridge, situated 550 km north of Iceland. Glacial sediments and landforms are relatively common on the island but so far only the youngest moraine system, corresponding to the little ice age, have been dated.

In this project we use cosmogenic surface exposure dating with  $^{36}\text{Cl}$  to extend the glacial chronology on Jan Mayen. So far 23 samples, sampled from landforms ranging from the fresh little ice age moraines to the older till surfaces on central Jan Mayen, have been analyzed. The samples give mostly reasonable ages that are consistent with the relative ages of the landforms. However, the lack of independent age control and the limited knowledge of the paleoenvironmental history of Jan Mayen means that it is challenging to constrain key variables such as local production rate, isostatic rebound or erosion. Here we discuss the problems and potential for  $^{36}\text{Cl}$  dating on Jan Mayen and the implications for the precision of the chronology.

## POSTER

### Quantifying the past, present and future at the Laboratory of Chronology

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The Laboratory of Chronology at the Finnish Museum of Natural History, University of Helsinki, operates in a multidisciplinary field of science based on three cornerstones:  $^{14}\text{C}$ -AMS dating, luminescence dating and stable isotope measurements. Frequently upgraded OASIS database ([www.oasisnorth.org](http://www.oasisnorth.org)) provides a reflection of the work containing presently the published University of Helsinki  $^{14}\text{C}$  measurements and northern dietary isotopic data of multiple sources.

During its >45 years of existence, over 7000 radiocarbon analyses have been processed. Collaborative efforts of the Laboratory of Chronology together with the Department of Physics (Univ. of Helsinki) has led to the establishment of Radiocarbon Analytics Finland (RACAF) – a common umbrella under which all the phases of  $^{14}\text{C}$  analytics are now performed within even less than  $\pm 20$  year statistical uncertainty.

Luminescence measurement provide a tool to extend the time span of research to reach the last glacial and post-glacial era that has shaped the environment we presently live in. In the Laboratory of Chronology is made about 50 age determination/year from archaeological or geological samples. The luminescence datings are based mostly on Optically Stimulated Luminescence method (OSL).

The laboratory houses two IRMSs for analysis of light stable isotopes, with EA-, TC/EA-, GasBenchII-, and PreCon- peripherals. The main avenues of investigations comprise climate and ecology in the past, present and future. Current major projects deal with 1) studying climate anomalies using carbon and oxygen isotopes of pine tree-rings from Northern Finland 2) subsistence of Iron Age people in Finland; 3) the paleoecology of the Wrangel Island mammoth population.

## POSTER

**Askja 1875 tephra in lake sediment in Southern Finland**

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Tephra from Icelandic volcano eruptions is known to be carried to Northern Europe, but no tephra has previously been found or reported in Finnish peats or lake sediments. We report a recent finding of a cryptotephra layer in lakes Kalattomanlammi, Pernunjärvi and Ahvenuslammi in Southern Finland.

Lake sediment samples from three lakes, located in the fall-out zone of the Hekla 1947 eruption, were investigated for presence of tephra shards in order to assess the possibilities of tephrochronology in Finland. Tephra shards were extracted from lake sediment using heavy liquid separation method, and electron probe microanalysis of main elements was conducted on single shards. The results of geochemical analysis show that the tephra originates from an eruption of Askja in 1875, thus extending the known distribution of the Askja 1875 tephra towards east.

Our results confirm that the size of cryptotephra particles and the shard concentrations in Finnish sites are sufficient for tephrochronological work. The presence of the Askja 1875 tephra in our study sites suggests that high-resolution studies of the recent environmental change in Finland could greatly benefit from using tephrochronology as a dating method. Additionally, the absence of the Hekla 1947 tephra from sites located in the previously inferred fall-out zone is an important implication of the complexity of tephra deposition and needs to be investigated further.

## POSTER

**Trondheim radiocarbon laboratory – performance results and future plans**

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Radiocarbon dating is probably the most important dating technique in Quaternary geology, and the accuracy and precision of the ages are critical for our possibilities to make high-resolution records of the Late Quaternary history. To ensure that the results are reproducible between different radiocarbon laboratories, several international inter-comparison studies have been made. However, these inter-comparisons are only relevant as long as no major changes are made to the equipment or protocols used. The National Laboratory for Age Determination at NTNU, Trondheim, has recently re-opened after a major renovation including the installation of a new 1 MV AMS system and a new graphitization line. Thus it is timely to present the new systems and procedures, and show that they are capable of producing reproducible and accurate results e.g. when tested on reference material of known age. Furthermore, we will show our background levels, which are limiting the range of our dates. We will also discuss our future plans for the laboratory, such as the possibility to start measuring <sup>10</sup>Be for cosmogenic surface exposure dating.

## S12.1 Sedimentology

ORAL

### On the evolution of glaciated continental margins

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Glaciated continental margins at both northern and southern high-latitudes are areas of repeated shelf-wide glaciations. Their evolution are in several aspects different from their low-latitude counterparts where eustatic sea-level variations possess a fundamental control and where fluvial systems provide the main sediment input. From studies of the Norwegian – Barents Sea – Svalbard and NE Greenland continental margins we propose the following factors as the main control on the evolution of glaciated continental margins: 1) Continental margin morphology including both pre-glacial and glacial relief controlling accommodation space and influencing sediment routing on long timescales, 2) Ice sheet glaciology including the location of fast-flowing ice streams where source area morphology exerts a fundamental control, 3) Composition of the glacial sediments, e.g. the importance of clay content, and 4) Sea-level controlled both by eustasy and isostasy. From three case studies (western Barents Sea, north and mid-Norwegian margin) the influence on these factors on the sea-floor morphology, sedimentary processes (continental slope to deep sea) and continental margin architecture will be discussed.

ORAL

### Last glacial ice sheet dynamics and deglaciation on Svalbard inferred from fjord records

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Various glacial landforms and sedimentary processes identified in the Spitsbergen fjords provide valuable insights into the dynamics of the northwestern parts of the Svalbard-Barents Sea Ice Sheet during the last glacial.

Glacial linear features oriented parallel to most fjord axes provide evidence of locally fast-flowing grounded ice draining the northwestern parts of the Svalbard-Barents Sea Ice Sheet to the shelf breaks off north and west Svalbard. Eskers overlying glacial lineations reveal the existence of englacial or sub-glacial drainage systems that developed after the termination of fast ice flow. Iceberg ploughmarks suggest that parts of the deglaciation occurred by iceberg calving. Multiple transverse ridges, e.g. grounding zone wedges and moraines, indicate that multiple halts and/or readvances interrupted the deglaciations of the fjords. This includes relatively small moraines, probably deposited during halts and/or readvances in consecutive winters, thus, allowing the calculation of annual retreat rates of the ice fronts in certain fjord areas. Their regular spacing may suggest that e.g. parts of Billefjorden, Smeerenburgfjorden and Woodfjorden were deglaciated at relatively constant rates of at least 140 m/year. However, the deglaciation of van Keulenfjorden accelerated from approx. 80 m/year to about 190 m/year.

Lithological analyses allow the study of sub-glacial, glacier-proximal and glacier-distal sedimentary processes and environments, as well as the identification of influences from various sediment sources. They reveal, furthermore, that the

deglaciations of multiple fjords terminated quasi-synchronously around 11,200 cal. years BP, but that significant local delays of up to several thousand years occurred.

ORAL

### Provenance analysis of the Late Glacial – Holocene SW Barents Sea sediments

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The Barents Sea region can be seen as the confluence area between the Scandinavian (SIS) and Barents Sea (BSIS) ice sheets, thus the onset of deglaciation and the following development can be evaluated by determining the sediment provenance changes and prevailed transport agents along time.

Three sediment cores from Nordkappbanken, SW Barents Sea have been studied for sediment components including clay and heavy minerals to reconstruct behaviour of the ice sheets around the Barents Sea region in relationship with the sediment provenance changes over the Late Glacial–Holocene time. These sediments consist of glaciomarine sediments and diamictons overlain by a thin layer of Holocene sediments.

We studied variations in terrigenous input, including clay minerals distribution, geochemical composition of heavy minerals and occurrence of ice-rafted debris (IRD) to obtain critical information on distribution, transport, pathways and sources of the Barents Sea sediments which are still relatively sparsely known. Mineralogical analysis includes main clay minerals content by X-ray diffraction, IRD counting from X-ray radiographs and source rocks indicative heavy minerals compositions obtained by Electron Probe Microanalyzer (EPMA).

Results show variations in contents of clay minerals as well as heavy minerals through Late Glacial–Holocene time that gives an evidence of changes of source areas and types of transportation agents of sediments including sea ice, icebergs, and open sea. The further comparison of our results with the constructed source rock database from land allows identifying precise provenances around Barents Sea region.

ORAL

### Reservoir Quality of Lower-Middle Jurassic sandstones within the Johan Castberg Field in the SW Barents Sea

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The Johan Castberg Field is located on the western margin of Loppa High in the south-western Barents Sea and comprises a reservoir in Lower-Middle Jurassic sandstones of Stø and Nordmela formations containing both oil and gas. Cored intervals, 15 samples (well 7220/5-1) and wells log data (7219/8-1, 7219/9-1, 7220/8-1 and 7220/7-1) have been used for petrophysical and petrographical study of sandstone reservoirs. Reservoir properties are preserved significantly due to uplifting and erosion of the entire region. Sandstone diagenesis is a function of burial rate, mineralogical composition and texture, climate, and hydrodynamic and geothermal gradients.

X-ray diffraction (XRD), Optical Microscopy, Scanning Electron Microscopy (SEM) and Core logging have been performed to investigate the depositional environment, clay mineralogy, role of sediments composition, facies distribution, and provenance of the reservoir sandstones. Petrographical study has been carried out to find the diagenetic clay and microquartz coatings, quartz cementation and its distribution in the sandstone reservoirs.

The estimation of porosity and Intergranular Volume (IGV) values reflecting mechanical compaction of sandstone reservoirs were the main objectives during this research work. Quartz cementation has very limited effect on the porosity loss. In addition to mechanical compaction, the authigenic kaolinite and depositional matrix filling the pore space caused some porosity reduction.

Lower-Middle Jurassic sandstones are moderate to well sorted, fine to medium grained and are mineralogical mature. Sandstones are deposited in prograding coastal regime whereas shale interval indicates regional transgressive pulses during deposition. The porosity and IGV values of sandstones range 6-26% and 25-34% respectively. The porosity is still well preserved and reservoir quality of Lower-Middle Jurassic sandstones in well 7220/5-1 is very good.

Keywords: IGV, authigenic clays and porosity, facies distribution, quartz cementation, SEM, XRD

## ORAL

**Palaeogeography of the main carbonate reservoir, the Late Carboniferous-Early Permian Gipsdalen Group, Norwegian Barents Sea.**

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Globally carbonates store approximately 50% of the world hydrocarbon resources although these rocks comprise only c. 15% of the world sedimentary rocks. In the Norwegian Barents Sea exploration drillings during the later years have proven recoverable oils in Upper Palaeozoic carbonate reservoirs.

The most promising carbonate reservoirs are present in dolomitized and leached inner and middle ramp carbonates of the Gipsdalen Group. The group was deposited in an arid and warm climate in an ice-house world characterized by high frequency and – amplitude glacio-eustatic sea level changes. The 2D seismic structure mapping of the Gipsdalen Group shows a complex mosaic of basins and highs in the Norwegian Barents Sea. During the latest Serpukovian-Kasimovian trans-arctic rifting led to the development of a complex NE-SW and N-S trending basin and high structures in the Barents Sea. During the earliest and most active rifting stage erosion of the highs supplied siliciclastics into the adjacent basins. The sediments were deposited as reddish-brown coloured coarse-grained alluvial fans along the basin margins and associated floodplain fines in more distal part of the basins. The basins were gradually flooded from the east during the Bashkirian and onwards and led to a complex interfingering of alluvial red beds and shallow marine siliciclastics along basin margins contemporaneous with carbonate ramp development in shallow-marine areas, sulphate evaporites in enclosed middle and outer ramps and halite in the deeper basins. The overall rise in sea level gradually led to flooding of the palaeo-highs and by end Carboniferous only the inner part of the Finnmark Platform were sub-aerially exposed. Consequently there is a gradual change from siliciclastic to carbonate dominated facies during the deposition of the Gipsdalen Group.

In order to construct the palaeogeographic maps, detailed facies and structural mapping have been performed by using all 2D seismic data from

the Barents Sea. The facies interpretation was calibrated to all wells penetrating the Gipsdalen Group. High-amplitude seismic facies calibrate to outer ramp mixed carbonate and sulphate-evaporite deposits and basinal halite deposits in the Nordkapp-, Ottar-, Maud-, Bjørnøya and Tromsø basins. The low-amplitude carbonates comprise mounded, clinoform, parallel and hummocky seismic facies representing various carbonate deposits. Among the carbonates, mounded seismic facies, interpreted as carbonate build-ups, were a key seismic facies. Based on wells and onshore analogues the build-ups represent shallow marine middle and outer ramp carbonates. Clinoform facies probably represent prograding inner ramp grainy lithologies.

Analogue data show that potential reservoir facies are present in inner and middle ramp setting and include palaeoaplysiniid-phyllloid algal build-ups and higher energy grainy dolomitized facies. Potential source rocks include basinal evaporites, carbonates and siliciclastic mudrocks and sabkha mudrocks/carbonates in inner ramp settings. Prominent top seal are evaporites, tight carbonates and siliciclastic mudrocks.

## POSTER

**The Early to Middle Cenozoic paleoenvironment and sediment yield of the southwestern Barents Sea margin**

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2D and 3D seismic data and results from 6 exploration wells have been utilized to study the development of the Lower to Middle Cenozoic deposits in the southwestern Barents Sea. The western Barents Sea margin shows a complex history of structural configuration of highs and basins related to the Greenland and Eurasian plate movement and subsequent sea floor spreading of the Norwegian-Greenland Sea.

At the Paleocene and Lower Eocene interval, the sediment infill of the Sørvestnaget basin is dominated by offshore shale as shown in the wells 7316/5-1 and 7216/11-1. The Middle Eocene strata in the basin includes shelf-edge delta and deepwater sandy fan deposits, sourced from the Stappen High

area. Oligocene-Miocene sediments represents a shallow marine setting.

At least two major uplift and erosion event occurred in the Early to Middle Cenozoic; (1) at the Early Eocene time which resulted in uplift of the intrabasinal highs and deposition of major volcanics strata in the Vestbakken Volcanic Province. This event is related to the continental break-up. (2) at Oligocene-Miocene period probably related to a major change in plate reorganization coupled with global sea-level fall due to the opening of the Fram Strait. Sediments of assumed Miocene age are seen downlapping to the uplifted marginal high in the west. Notable compression structures can be observed from seismic data suggesting a period of structural inversion that also affected the intrabasinal highs at this Neogene period.

Isopach maps were generated to calculate the volume of sediments deposited. Sediment yield of the Lower to Middle Cenozoic were also estimated. These result will be presented and discussed.



## S13.1 Burial, uplift and exhumation of Scandinavia and surrounding regions: Timing, magnitude and mechanisms

### KEYNOTE

#### The Norwegian strandflat: Insights into an old weathering front

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Reusch introduced the term 'strandflat' in 1894 to describe the flat-lying low relief landscape along and off the Norwegian coast. This landscape is only observed in the Arctic region with additional examples from e.g. western Greenland and is commonly excepted to be the product of Quaternary wave- and ice- abrasion. We suggest that repeated periods of deep weathering altered the basement such that it was subsequently easy to erode. Deeply weathered bedrock on the Norwegian strandflat is similar to weathering occurring beneath Mesozoic strata at offshore basement highs (e.g. the Utsira and Frøya highs) indicating this surface has an older origin. Initial K/Ar age dating of saprolite remnants confirm Mesozoic ages and some localities on Andøya reveal even older, Carboniferous ages. Geophysical measurements on the strandflat indicate the existence of remaining thick packages of weathered bedrock, which are mostly preserved in joints and fractures. We thus argue that the present day strandflat is an old weathering front, that has been stripped in quite recent geological time through Quaternary erosional processes. Mapping potential deep weathering along the Norwegian strandflat shows an obvious correlation with tectonic fault systems on the shelf and indicate a relation between deep weathering and the development of the Norwegian margin. Rifting along the margin and fractured basement rocks could have facilitated deep weathering and increased weathering rates. Main observed weathering difference is between western and mid Norway and the Lofoten-Vesterålen-Vestfjorden region, which we suggest is due to the location relative to the rifting in the North Sea and the Norwegian Sea.

The greater Vestfjorden region constitutes a part of the Mesozoic rift system with an abundance of uplifted and rotated fault blocks, whilst mid Norway was located more remotely relative to the rift centres in the Møre-Haltenbanken area. Consequently, we find the remnants of deep weathering on rotated fault blocks in Lofoten–Vesterålen whereas saprolite occur in the more gentle landscape along the coast of Trøndelag. We suggest that the deep weathering in the Hamarøya, Lofoten and Vesterålen areas is preserved because of the young uplift and erosion of this area (Late Pleistocene age). Most of the ice was transported in ice streams through Vestfjorden and Andfjorden leaving the interior of the mainland and the inner Lofoten–Vesterålen archipelago relatively unaffected, whilst along the coast of Nordland and Lofoten-Vesterålen a wide and extensive strandflat zone has been exhumed due to Quaternary erosion.

### ORAL

#### The Scandinavian highlands and Miocene to Pliocene sea levels

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The summit level of the Scandinavian highlands is bounded by the sub-Cambrian peneplain to the east and by a weathered and block-faulted Mesozoic surface to the west. The development of paleovalleys and younger surfaces eroded into these surfaces has been studied in relation to Miocene and Pliocene deposits in the Norwegian Continental Shelf. A middle Miocene phase of compression is marked by anticlinal and synclinal structures in the Central Graben in the North Sea, in the Norwegian Sea, by the large scale uplift of the southern and northern Scandes Domes and the corresponding subsidence of the North Sea and Lofoten Basins.

In the North Sea, there is a break in deposition and a change in depocenters between the Skade Fm and the Eir fm at about 16 Ma. The sandy Middle Miocene Eir formation shales out to the east and south. Middle Miocene marine shales occur in most of the Norwegian sector. Planktonic foraminifera and Bolboforma are abundant throughout and indicate deposition in an open sea. Middle Miocene

sandy erosional products from the southern Scandes make up thick deposits in Jutland and the adjacent offshore area. The sandy Utsira Formation consists of a lower unit (12.5-6 Ma) restricted to the depocenters and an upper unit (5-3.5 Ma) with a wider distribution. In the north the upper unit is developed as a sheet of glauconite sand (5 Ma) overlying an erosional unconformity. Our new interpretation relates the erosion to the sea level drop in the Late Miocene due to the Messinian salinity crisis and it should not be correlated with the Middle Miocene compression.

#### References:

<http://www.npd.no/no/Publikasjoner/NPD-bulletin/Bulletin-10/>, and references therein.

ORAL

### Uplift and faulting of the Utsira High basement: evidence from low-T thermochronology

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The Utsira High is a basement horst in the northern North Sea, flanked to the west and east by the Viking Graben and Stord Basin respectively, and composed of Caledonian granitic and gabbroic rocks. Since Caledonian times, the North Sea region has been affected by extensional tectonics leading to rifting, active fault tectonics and uplift of basement blocks. Extensive drilling due to recent hydrocarbon exploration has made the basement of the Utsira High accessible for thermochronological investigations that aim to reconstruct its tectonic history.

Zircon (U-Th)/He, apatite fission track and apatite (U-Th)/He dating on seven samples yielded Middle-Late Devonian, Late Permian-Late Jurassic and Middle Jurassic-Pliocene ages respectively, tracking cooling through successively lower closure temperatures and subsequent re-heating during sedimentary burial since the Jurassic. Generally basement rocks of the Utsira High reached near surface temperatures already in Carboniferous-Triassic

times, much earlier than the oldest overlying sediments (Middle Jurassic-Cretaceous) might indicate. Surface exposure already in the late Paleozoic-early Mesozoic is in good agreement with clay formation in saprolites, dated at ca. 240-230 Ma (Fredin et al., 2012). The Utsira High is dissected by faults into several fault-bound basement blocks. Differences in cooling history between some of these blocks suggest that the faults were active in the late Paleozoic and Mesozoic. This is confirmed by K/Ar illite dating of fault gouge material recovered from one basement core, indicating a Jurassic age for that fault.

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ORAL

### Burial and exhumation history of southernmost Norway estimated from apatite fission-track analysis data and geological constraints

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We present new apatite fission-track analysis (AFTA) data from 27 basement samples from Norway south of ~60°N. The data define three events of cooling and exhumation that overlap in time with events defined from AFTA in southern Sweden (Japsen et al., 2015).

The samples cooled below palaeotemperatures of ~100°C in a major episode of Triassic cooling as also reported by previous studies (Rohrman et al., 1995). Our study area is just south of the Hardangervidda where Cambrian sediments and Caledonian nappes are present. We thus infer that these palaeotemperatures reflect heating below a cover that had accumulated during the Palaeozoic and Triassic. By Late Triassic, this cover had been removed from the Utsira High, off SW Norway, resulting in deep weathering of a granitic landscape (Fredin et al., 2014).

Palaeotemperatures reached ~80°C prior to a second phase of cooling and exhumation in the

Jurassic, probably after a phase of Late Triassic – Jurassic burial. Upper Jurassic sandstones rest on basement near Bergen, NW of our study area (Fossen et al., 1997), and we infer that the Jurassic event led to complete removal of the Phanerozoic cover in the region adjacent to the evolving rift system prior to Late Jurassic subsidence and burial.

The data reveal a third phase of cooling in the early Miocene when samples that are now near sea level cooled below palaeotemperatures of  $\sim 60^{\circ}\text{C}$ . For likely values of the palaeogeothermal gradient, such palaeotemperatures correspond to burial below rock columns that reach well above the present-day landscape where elevations rarely exceed 1 km above sea level.

This implies that the present-day landscape was shaped by Neogene erosion, in agreement with previous suggestions that the near-horizontal Palaeozoic surfaces of southern Norway are the result of Cenozoic erosion to sea level followed by uplift to their present elevations in a fourth event that is not detected by the AFTA data (Lidmar-Bergström et al., 2013).

ORAL

### Uplift Record in Hydrocarbons and Sulphides in South Norway

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When a small, but once economic gold deposit in southeast Norway returned different Re-Os ages for occurrence-specific pyrite and hydrocarbon samples in a study ten years ago, some questioned the credibility of Re-Os dating. With one Re-Os isochron age less than ten million years for one sample, eyebrows were raised. Ten years on, additional field work and dating affirms an array of ages in the Phanerozoic, and teaches us that old and deep crustal wounds may never heal. That is, tectonic reactivation through uplift exploits old pathways. Now, with additional data, new thinking, and a database carrying consistently young ages from other studies in the region, we must embrace an on-shore Mesozoic-Cenozoic history in Scandinavian bedrock.

The accuracy of Re-Os ages from small veinlets and fractures, with or without sulphide, can be

safely and soundly interpreted in a geologic context rooted in the uplift history of Scandinavia. The most comprehensive Re-Os data set is from one locality in southeast Norway, the Eidsvoll gold deposit. Other localities return ages with highly anomalous Re concentrations in their molybdenite indicating uplift and loss of volatiles at regional scales. Still other locations in Norway, and on other continents, preserve molybdenite in stylonite-like structures. In such cases, expected replication of Re-Os ages may be compromised. Other samples presented as molybdenite for Re-Os dating are in fact samples where shear and frictional heating during faulting in organic-rich shales has produced a hard, polished mirror-like surface. Re-Os dating of these surfaces provides ages for frictional heating of organic-rich shale along glide planes. Although these samples may look like molybdenite on casual glance, their high common Os and context indicates faulted shale in organic-rich source rocks. This feature is common at some Paleoproterozoic gold mines in northern Finland.

The AIRIE Program continues to make sense of unusual occurrences of bitumen, pyrobitumen, and hydrocarbon both on-shore and off-shore Norway to reconstruct the uplift history of this critically important region for oil. Both sulphides, hydrocarbons and shales are candidates for tracking pore and fracture filling, and post-depositional faulting.

ORAL

### Phanerozoic denudation across the Kola Peninsula

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Contrasting views exist on the stability of the Earth's shield regions over the last 1 Ga that have major implications for reconstructing erosion patterns on shields and the supply of sediment to intracratonic and marginal basins. This contribution explores Phanerozoic denudation rates and patterns on the northern part of the Fennoscandian Shield in the Kola Peninsula, Northwest Russia. This shield region was intruded by magmatic rocks of the Kola Alkaline Province (KAP) in the Devonian and Early Carboniferous. The KAP was emplaced at various depths in the crust and allows assessment of depths and rates of erosion during and since the KAP magmatic episode.

Post-Devonian denudation rates on the shield rocks of the Kola Peninsula have varied in space and time. Around the periphery of the Kola Peninsula, low long-term denudation of shield rocks is indicated by the survival of Riphean cover rocks and Late Devonian lavas, kimberlite crater facies and near-surface emplacement of dykes. In contrast, in the main belts of KAP intrusions, 4–6 km of rock was removed in response to doming between 460 and 360 Ma. Deep denudation is indicated by the emplacement depths of alkaline intrusions and Phoscorite–Carbonatite pipes (PCPs). Erosion on the Kola Peninsula since 360 Ma has been far more limited. Extensive, shallow, late-stage magmatism associated with PCPs, dykes and the large alkaline intrusions in the KAP indicates that erosion depths nowhere exceeded 2 km. Post-Devonian denudation has removed <1 km of rock from the margins of the Kola Peninsula and from the backslope of the Saariselkä–Karelia scarp in northern Finland. AFT data point to an important phase of erosion in the early Mesozoic but depths of unroofing of 3–5 km based on AFT cooling ages for this later phase are in conflict with the evidence of lesser erosion provided by the late-stage KAP intrusions and also require unrealistic depths of former Devonian to Triassic cover rocks.

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Hall, A.M., 2015. Phanerozoic denudation across the Kola Peninsula, northwest Russia: implications for long term stability of Precambrian shield margins. *Norw. J. Geol.* 95, 27–43.

ORAL

### Mass-balance of an Induan (Early Triassic) Fennoscandian-derived clinoform package in the Barents Sea: Implications for Early Triassic landscape and exhumation

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During the Permian the Norwegian part of the Barents Sea Basin was relatively stable and dominated by sparse siliciclastic input and carbonate deposition. In the Triassic, siliciclastic sediments sourced mainly from the Uralian Orogen prograded into the basin and left behind large-scale wedges across the basin. However, seismic data show at

least three fan-shaped units c. 150 m thick, recognizable as arcuate clinoform packages, prograding from the Fennoscandian Shield during the lower Induan stage (Early Triassic), prior to arrival of the large Uralian sedimentary systems. Channel- and clinoform geometries from seismic amplitude maps, along with thickness trends, show that one of these fans-shaped units prograded c. 100 km into the basin from an apex near the mouth of the present day Tana Fjord. The volume of this fan has been constrained using seismic, core and well data, and the sediment supply rate through the fan apex has been calculated using velocity and density data derived from well logs, in combination with biostratigraphic datings.

Drainage patterns and sediment loads in the Triassic Barents Sea were analogous to the modern day Bay of Bengal, which comprises a major fluvial system draining the Himalayan orogen, and several smaller fluvial systems draining the nearby Indian craton. Furthermore, application of the empirical BQART model (Syvitski and Milliman, 2007) which explains magnitude of sediment transport in modern rivers, indicates that the drainage basin of this fan-shaped unit drained a modest but significant part of the Fennoscandian Shield (c. 1/10) and that the catchment consisted of sedimentary rocks. These results indicate the presence of remnants of Caledonian foreland basin deposits on Fennoscandia during the Early Triassic. Calculated denudation rates were likely enough to remove this sedimentary cover during the (lower) Triassic.

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Syvitski, P.M. and Milliman J.D., 2007. Geology, Geography and Humans Battle for Dominance over the Delivery of Fluvial Sediment to the Coastal Ocean. *The Journal of Geology*, 115, p. 1-19

ORAL

### Burial stress and burial strain

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Burial stress on a sediment or sedimentary rock is relevant for predicting compaction or failure caused by changes in, e.g., pore pressure in the

subsurface. For this purpose, the stress is conventionally expressed in terms of its effect: “the effective stress” defined as the consequent elastic strain multiplied by the rock frame modulus. We cannot measure the strain directly in the subsurface, but from the data on bulk density and P-wave velocity, we can estimate the rock frame modulus and Biot’s coefficient and then calculate the “effective vertical stress” as the total vertical stress minus the product of pore pressure and Biot’s coefficient. We can now calculate the elastic strain by dividing “effective stress” with the rock frame modulus. By this procedure, the degree of elastic deformation at a given time and depth can be directly expressed. This facilitates the discussion of the deformation mechanisms. The principle is illustrated by comparing carbonate sediments and sedimentary rocks from the North Sea Basin and three oceanic settings: a relatively shallow water setting dominated by coarse carbonate packstones and grainstones and two deep water settings dominated by fine-grained carbonate mudstones and wackestones.

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ORAL

### 3D Stress Modelling of a Neotectonically Active Area in Northwestern Norway

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The Nordland area in NW Norway is one of the tectonically most active areas in Fennoscandia. It exhibits patterns of extension, which are in contradiction to the first-order regional stress pattern which reflects compression from ridge-push. The regional stress field stems from the interaction of ridge push and GIA (glacial isostatic adjustment); the local stress field mainly results from gravitational stresses as well as the flexural effects of sediment erosion and re-deposition. Whereas the first three effects are fairly well constrained, the latter is only poorly known and is the focus of this study.

A number of data sets are collected within the project: Seismicity is monitored by a 2-year local

seismic network. Surface deformation is recorded by a dense GPS network and DInSAR satellites. In-situ stresses are measured in a couple of relevant boreholes.

We develop 3D finite element numerical models of crustal scale, using existing geometric constraints from previous geophysical studies. Internal body forces (e.g. variations in topography) already yield significant deviatoric stresses, which are often omitted in stress models. We apply the far-field stress fields (GIA, ridge-push, sediment redistribution) as effective force boundary conditions to the sides or base of the model. This way, we can account for all stress sources at once, but can also vary them separately in order to examine their relative contributions to the observed stress and strain rate fields.

We develop a best-fit model using the different seismological and geodetic data sets collected and compiled within the project. Effects of lateral density changes and pre-existing weakness zones on stress localization are studied in connection to observed clusters of enhanced seismic activity.

ORAL

### Process-oriented gravity modelling of the Northern Scandes

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The Northern Scandes are associated with a prominent isostatic gravity low located westward of the main topography. Different origins have been proposed as a connection to the Transscandinavian Igneous Belt or a deep crustal origin. A shallow origin is often preferred from gravity and magnetic data. Earlier studies along the Blue Road profiles showed only a moderate increase of crustal thickness from the coast beneath the mountains. The profile is, however, located at the southern end of the isostatic gravity anomaly.

New crustal thickness estimates based on the receiver experiments Scanlips -2 and Scanlips-3D show that the isostatic anomaly is underlain by a very thick crust, which explains most of the gravity anomaly. The area is however not in isostatic equilibrium with respect to simple local isostasy.

An additional factor is the flexural rigidity of the lithosphere, which might have prevented local

isostatic equilibrium and kept parts of the Northern Scandes geometry unaffected by later tectonic events, as for example the collapse of the Caledonides. We discuss the consequences and implications and illustrate the evolution of the crustal geometry by process-oriented gravity modelling.

ORAL

### Isostatic and dynamic support of high passive margin topography in southwestern Scandinavia

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Substantial controversy surrounds the origin and recent evolution of high topography along passive continental margins in the North Atlantic, with suggested age of formation ranging from early Paleozoic Caledonian orogenesis to Neogene uplift of a Mesozoic peneplain. Here we focus on the well-documented high passive margin in southwestern Scandinavia, and quantify the relative contributions of crustal isostasy and dynamic topography in controlling the present topography. We find that most topography is compensated by the crustal structure, suggesting a topographic age related to ~400 Myr old Caledonian orogenesis. In addition, we infer that dynamic uplift (~300 m) has rejuvenated existing topography locally in coastal region within the last ~10 Myr due to mantle convection. Such uplift has, in combination with a general eustatic sea-level fall and concurrent erosion-driven isostatic rock-column uplift, the potential to increase erosion of coastal-near regions and explain observations that have traditionally been interpreted in favor of the peneplain uplift model. We conclude that high topography along the Scandinavian margin cannot represent remnants of a peneplain uplifted within the last ~20 Myr. Topography must have been high since the Caledonian orogeny.

ORAL

### “For the mountains may be removed and the hills may shake...”

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Albeit separated in time from rifting itself, the post-rift evolution of landscapes at rifted margins is fundamentally rooted in the processes of crustal extension. During the main phase of crustal thinning at the Norwegian margin, coupling of deformation between crust and mantle left behind a linear transition that separates the part of the margin where deformation became coupled from the part where it was not. This transition is manifested in the subsurface by the outermost part of the tapering crystalline crust wedge that outlines the inner boundary of the highly thinned distal margin. We call this the taper break. It is located at a rift-related zone of permanent weakness, and acts as a point of flexural coupling that exerts a fundamental control over Scandinavian topography. The absolute height of the onshore mountain envelope is inversely proportional to its local distance from the taper break (Apparent Taper Length, or ATL). Coastal denudation, landscape elements such as the degree of preservation or excision of paleosurfaces, and fault reactivation also correlate with the ATL. Although the taper break was created around the Jurassic-Cretaceous boundary, the crust in its vicinity is seismically active at present day. Rapid loading by Plio-Pleistocene sediments augmented by onshore erosion, seaward-directed gravitational potential energy, and post-glacial rebound engender a lithospheric flexure that downwarps at the taper break. Sequential stress patterns develop, transitioning from 1) compression offshore, 2) through a neutral zone, to 3) tension at the innermost part of the proximal margin domain. There, tensile stress is sufficient to reactivate favorably-oriented faults in normal mode and to uplift their footwalls. Thus do Scandinavia's earthquakes – products of mountains long since removed – shake the hills even as they raise mountains anew.

## S13.2 Dynamics and evolution of the lithosphere from Archean to present

**KEYNOTE**

### Plate Tectonics: Past and Present

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Over the last century, our portrayal of the movement and deformation of the Earth's outer layer evolved from the hypothesis of Continental Drift into Sea-Floor Spreading and then to the paradigm of Plate Tectonics. The onset of convergent plate interaction, plate tectonics, and ultimately supercontinents, are leading questions in Earth history. Early Earth was certainly very different from the planet we know today, the mantle was clearly hotter than the modern mantle, plumes of very hot magma were abundant, and the lithosphere was thinner and more buoyant. The Archean remains the most popular time-frame for the onset of plate tectonics but this question critically depends on how plate tectonics is defined. The prevalence of eclogitic diamond compositions at around 3 Ga suggest a major change in the geodynamic regime at that time and perhaps the onset of plate tectonics. Rb/Sr ratios in juvenile continental crust also increased around this time, suggesting that the newly formed crust became more silica-rich and therefore probably also thicker. A gradually cooling mantle and the onset of cold, deep and steep subduction (ultra-high pressure – UHP - metamorphic conditions) comparable with the present-day first occurred in Neoproterozoic times. Western Norway is a prime example of a large UHP terrane shaped through the Late Silurian collision of Baltica with Laurentia, and which was subsequently exhumed relatively rapidly during the Early Devonian.

**ORAL**

### Garnet: a key to unraveling Earth's dynamic lithosphere

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The Pamir-Himalaya-Tibet Orogen is the ultimate natural laboratory for the development and testing of models for the dynamics of collisional orogens. Significant achievements in various fields of geoscience have greatly advanced the knowledge on the Cenozoic evolution of the region. In spite of this, the most fundamental aspect to the development of the region – the India-Eurasia collision – is poorly understood and timed. Plate reconstructions indicate collision and slowing-down of convergence at 55-50 Ma. Deformation and thickening of the crust, however, cannot be traced back further than 35 Ma. The 15-20 million year hiatus is largely uncharacterized, impeding progress in the development of tectonic models. To address this issue, we performed Lu-Hf garnet dating on deep crustal rocks of Indian and Eurasian affinity exposed in Central Tibet and the Pamir, respectively.

Garnet from high-grade rocks now exposed in the North Himalayan Gneiss Domes in Central Tibet commenced in the early Eocene (54-49 Ma). This result is the first to confirm an 'old' age for the onset of crustal thickening and contraction in the Tibetan Himalaya. The result is identical to the age of collision as determined by plate reconstructions, erasing a decades-long controversy on India-Asia collision timing. Garnet dating and thermometry, and rutile U-Pb thermochronology on high-grade rocks in Pamir revealed a history of heating to 750-830 °C. This process commenced at 37 Ma in the South Pamir and occurred progressively later northward until 22 Ma, when the crust switched to wholesale collapse by orogen-parallel extension. The latter study advocates a causal link between Indian slab break-off to the south and progressive prograde heating and ductilification of the subduction

hanging wall. Both studies demonstrate the ability of garnet to characterize the crucially important, yet typically difficult to constrain, early stages of crustal tectonics in orogenic cycles.

ORAL

### Orogen-parallel mass transport along the arcuate Himalayan front into Nanga Parbat and the western Himalayan syntaxis

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Quaternary rates of rock exhumation in the western Himalayan syntaxis region are more than twice those observed along strike in the central Himalaya, yet the elevation of mountain peaks in both regions are comparable. This apparent disconnect suggests the western Himalayan syntaxis area requires an additional flux of crustal mass into the region to maintain high-elevation topography. One potential source of crustal mass is strain partitioning along strike in the arcuate orogen, where the orogen-parallel component of oblique convergence is accommodated on a strike-slip fault system at the rear of the Himalayan orogenic wedge resulting in an orogen-parallel mass flux into the syntaxis region, where the convergence obliquity then decreases and the mass accumulates.

Using a combination of analytical calculations and 3D numerical geodynamic models, I demonstrate that strain partitioning is expected for an arcuate Himalaya-like orogen and that the magnitude of orogen-parallel mass transport can balance rapid surface erosion in the western Himalayan syntaxis. Strain partitioning in the analytical force balance is driven by the shear force along the base of the orogenic wedge and resisted by the shear force on a strike-slip shear zone at the back of the wedge, and normal- and reverse-sense shear zones at the lateral ends of the obliquely convergent segment of the orogen. The force balance suggests strain partitioning will only occur when the rear shear zone is weak, with an internal angle of friction of  $\phi_r < 5^\circ$ . This result is supported by generic 3D numerical geodynamic models with a Himalaya-like geometry in which strain partitioning is observed when

$\phi_r = 1 - 2^\circ$  and oblique thrusting (no partitioning) is observed for  $\phi_r = 5^\circ$ . When strain partitioning occurs in the models, I observe rates of orogen-parallel mass transport of 5-7 mm/a that produce local uplift rates in the western Himalayan syntaxis of 10-12 mm/a, comparable to the Quaternary rates of rock exhumation in this region. In addition, a strike-slip shear zone cutting obliquely across the orogen forms at the distal end from the syntaxis with a geometry remarkably like that of the recently documented Western Nepal Fault System. Combined, this suggests strain partitioning is a viable mechanism for supplying crustal mass to the western Himalayan syntaxis.

ORAL

### Rheological behaviour on the crust of the northern Fennoscandian shield

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The continental lithosphere is usually old, cold, having a multilayer rheology and its rheological behaviour is determined by the brittle and ductile properties of the constitutive rocks that form the lithosphere. Rheological strength was derived for the seismic POLAR profile based on the seismic velocity structure (Janik et al., 2009; Moisio and Kaikkonen, 2013). Relations between the focal depths of the earthquakes and the rheological strengths were analyzed especially the factors that have influence on the brittle strength favouring the observed distribution of the earthquakes.

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ORAL

### Structural and geochronological studies on the crustal-scale Pajala Deformation Zone, northern Sweden

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Geological and geophysical investigations were conducted to constrain the tectonic history along the Pajala Deformation Zone (PDZ). The PDZ is a 50 km wide deformation zone that strikes along the border between northern Sweden and Finland. Recently, it has been postulated that the PDZ marks an old suture zone between the continents Norrbotten and Karelia (Lahtinen et al. 2015).

Interpretations of the geophysical data (VLF, magnetics, gravity) reveals a series of steeply dipping shear zones and faults, which are striking N-S to NW-SE. These structures bound strongly elongated tectonic lenses composed of tightly folded migmatites and paragneisses. Geological field mapping and 3D structural modelling indicates a dome geometry of the tectonic lenses, which we interpret as large-scale, steeply plunging sheath folds that became progressively flattened during E-W to NE-SW shortening.

The westernmost shear zone of the PDZ is considered to be the main tectonic boundary accommodating several kilometers of vertical displacement that juxtaposed rocks affected by metamorphism of medium grade to the west and high grade to the east.

The timing of metamorphism within the PDZ is constrained to 1820-1780 Ma (Bergman et al. 2006). A formation age of  $1804 \pm 5$  Ma was obtained in this study by U-Pb SIMS zircon dating of a strongly foliated quartz monzonite, which suggests that at least part of the shearing along the PDZ occurred after 1800 Ma.

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ORAL

### Evolution of the Crustal Structure of the Svecofennian Orogen

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We have studied the evolution of the Svecofennian orogen using a conceptual PURC orogenic model developed by Jamiesson and Beaumont (2013) to help in identifying the similarities and the differences in the architecture of the various areas. The Svecofennian orogen is characterized by LP-HT metamorphism that usually develops in transitional to plateau stages. Deep seismic reflection profiles BABEL and FIRE are interpreted using PURC concepts: prowedge, retrowedge, uplifted plug, subduction conduit and elevated plateau.

A pronounced super-infra structure, typical of plateau stage, is imaged along FIRE3 and FIRE12. The Central Finland Granitoid Complex could represent an elevated plateau underlain by a midcrustal flow structure. The Bothnian belt could be either a retrowedge or a prowedge. The Raahe-Ladoga zone shows signs of both uplifted plug and of a transform zone. Pirkanmaa belt could represent a prowedge.

BABEL1 and BABEL3&4 profiles image a less well-developed orogenic domain, where a prowedge (Bothnian belt), an uplifted plug (Vaasa dome) and a retrocontinent (Skellefte and Savo belts) would have developed just prior to freezing of the collisional process.

BABELB, C and 1 profiles image a transitional orogen. Southern Sweden would comprise prowedge underlain protocontinent whereas the Södermanland basin, the Bergslagen area, the Häme belt would comprise retrowedge underlain by retrocontinent.

Altogether the architecture suggests a long-lived south-westerly retreating subduction system, with continental back-arc formation in its rear parts and well developed system of prowedge-retrowedge-uplifted plug close to a subduction conduit. Changes in the relative velocities of the upper and lower plate may have resulted in repetitive extensional and compressional phases of the orogeny as has previously been suggested for the southern part of the Svecofennian orogen.

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**ORAL**

### Crustal conductors in the Central Fennoscandia – constraints for a complex accretionary Svecofennian orogen

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We have studied conductivity structures within the Svecofennian orogen, a complex accretionary orogen in the Fennoscandian Shield. The accreting units comprise a subducting plate carrying passive margin sequences and two island arc complexes with possible forearc, backarc and accretionary prism sequences. Conductors are interpreted as representing different types of closed basins and thus mark the boundaries between the accreting units. We have compiled old and new data from seven broad-band MT-profiles transecting palaeo-basins: the Kiihimäki, Bothnian, Savo, and Kainuu belts in the central part of the orogen.

The data comprise c. 240 BMT soundings. Older data from 1980's were inverted for the first time. The new inversions of the old and new data revealed the sets of conductors with opposing dips. Conductors associated with the passive margin dip W/SW-wards whereas arc-affiliated conductors dip E/SE-ward. The Botnian belt represents a palaeo-accretionary prism within which a large dome structure with a granitic core (Vaasa dome) has developed. The eastern part of the dome is characterized by deep conductors dipping E and below the neighbouring tectonic unit. On the surface, the prism sequences are dipping W-wards at low angles. Sub-horizontal conductors mark the bottom of the granitic core of the dome. A comparison of the conductivity models with airborne electromagnetic and seismic data and lithological maps suggest that upper to middle crustal conductors are composed of graphite- and/or sulphide-bearing metasedimentary

rocks and lower crustal conductor under the Central Finland Granitoid Complex probably of oxides.

**POSTER**

### Monazite and zircon dating of the plagiogranites in the Mawat Ophiolite Complex, NE Iraq

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The Mawat Ophiolite Complex (MOC) in NE Iraq belongs to the Zagros Orogen (ZO) which is a member of the Alpine - Himalayan Orogenic Belt. The ZO is ~ 3000 km long and was formed during the closure of the Neo-Tethyan Ocean and subsequent oblique collision between the Afro-Arabian plate and the Eurasian continents. The belt contains numerous ophiolites, e.g. the well-known Troodos and Oman ophiolites. The MOC displays the classical ophiolite sequence, which consists of three units; volcanic rocks on the top, mafic rocks in the middle and ultramafic rocks in the lower part. Nine leucogranite and plagiogranite dykes have been discovered over an area 4km<sup>2</sup>. The width of these dykes varies from a few tens of centimetres to tens of metres, and they have intruded into massive and altered dunites rocks. The dykes are mostly peraluminous and plot the trondhjemite field in the normative An-Ab-Or diagram.

U-Pb dating was conducted on zircons and monazites from the dykes using a Laser-Ablation-ICP-MS on separated grains mounted in epoxy. The preliminary results indicate that the MOC was formed at c. 95-92 Ma contemporaneously with and within the same tectonic framework as the other, more well studied members of the Tethyan ophiolites, (e.g., Dilek and Thy, 2009). This is the first U-Pb age estimate of the plagiogranites in the MOC.

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## POSTER

### Consistent top-to-the-foreland directed deformation from floor to roof in the Seve Nappe Complex (SNC), Jämtland, Sweden

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The recent COSC-1 drilling programme (Lorenz et al., 2015), discovery of microdiamonds (Majka et al., 2014) and discussion of extrusion-wedge tectonics (Grimmer et al., 2015) outline the importance of the Seve Nappe Complex (SNC) and its key role during the Caledonian orogeny. The kinematic evolution of the SNC is crucial for better understanding the entire mountain belt. Thorough structural mapping of the SNC and adjacent units was conducted in western and northern Jämtland, central Sweden. Complementary microstructural investigations strengthen the field observations and show consistent top-to-the-SE directed movement through all studied tectonic units. Amphibolite-facies deformation can be inferred from fabrics in the SNC, which are overprinted by greenschist-facies structures showing the same kinematics throughout the studied section of the nappe stack. These data indicate persistence of the same foreland-directed kinematics over a wide range of pressure–temperature conditions in space and time. Currently proposed models for exhuming high-grade metamorphic rocks in collisional orogens fail to explain these observations and highlight the need for discussing new tectonic concepts for the Scandinavian Caledonides.

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## POSTER

### Structural framework of Paleoproterozoic rocks northeast of Kiruna, Sweden

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The Paleoproterozoic, supracrustal rocks in the Kiruna area in northern Sweden host large, well-known ore deposits. Yet, the structural framework and deformation history of these rocks is poorly understood. Although a number of studies try to unravel the deformation patterns observed in the bedrock around Kiruna (e.g. Vollmer et al., 1984; Witschard, 1984; Forsell, 1987; Talbot and Koyi, 1995), a generally accepted model for the structural evolution of these rocks is lacking. Further, information on the deformational history of the rocks to the northeast of Kiruna is sparse. There, the rocks are affected by folding and faulting within the Kiruna-Naimakka deformation zone (Bergman et al., 2001), but it is unclear through which structure(s) these rocks connect to the supracrustal rocks closer to Kiruna. Considering the ore potential of these rocks, it is important to investigate this.

In the context of the Barents project (<http://www.sgu.se/en/mineral-resources/barents-project/>), integrated geological and geophysical field studies were undertaken in order to understand the deformation patterns observed in the supracrustal rocks. Here, we present results and a preliminary model of the structural framework focusing on the rocks to the northeast of Kiruna.

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## POSTER

### Controls on continental strain partitioning above an oblique subduction zone, Northern Andes

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Strain partitioning is a common process at obliquely convergent plate margins, dividing oblique convergence into margin-normal slip on the plate-bounding fault and horizontal shearing on a strike-slip system parallel to the subduction margin. Plate convergence is oblique along much of the western margin of South America, yet strain partitioning is only observed along part of that length, possibly related to variations in the convergence obliquity angle, subducting plate dip or presence of a volcanic arc. This raises the question, to what extent do subduction zone characteristics control strain partitioning in the overriding continental plate?

We address this question using a lithospheric scale 3D numerical geodynamic model to investigate the relationship between subduction dip angle, convergence obliquity, weaknesses in the crust owing to the volcanic arc and strain partitioning behavior. The model design is based on the Northern Volcanic Zone of the Andes (5°N - 2°S), where strain partitioning is observed. This region is characterized by steep subduction (approx. 35°), convergence obliquity between 31°-45° and extensive arc volcanism. The relatively high angle of convergence obliquity suggests strain should be close to partitioning in this region, but preliminary model results show no strain partitioning for a uniform continental crustal strength. However, strain partitioning does occur when including a weak zone in the continental crust resulting from arc volcanic activity.

## POSTER

### Basement deformation during continental collision: a modelling example of the Swedish central Caledonides.

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Recent geophysical investigations (Hedin et al., 2012; Yan et al., 2015; Juhlin et al., 2015), carried out as part of the Collisional Orogeny in the Scandinavian Caledonides (COSC) project, provide an improved picture of the upper crust over the central Swedish Caledonides. The geometry and lithology of the basal detachment (surface to 1-2 km depth) are relatively well constrained by various observations

(Seismic reflection, magneto-telluric, field observations ...), whereas deeper structures (> 1-2 km depth) observed in the Precambrian autochthonous basement are more ambiguous and may be interpreted as possible deformation zones or dolerite intrusions (dykes).

In this study we interpret these structures as shear zones formed during a pre- or syn-Caledonian convergence event, at the boundaries of strong layers (e.g.: dolerites dykes) intruding the basement. In this collisional context, shear zones would work as thrust sheets accommodating the shortening, while the dolerite intrusions would rotate but remain mostly undeformed.

We use a two-dimensional thermal-mechanical model to test this hypothesis. Our model is set up as follows: a 200km x 30km rectangular box composed of a sedimentary cover (5-7km thick) and a weak alum shale layer (100-500 m thick), overlying a continental basement intruded by vertical dolerite dykes and horizontal sills. Shortening velocities are applied on the right and bottom boundaries while the left side is fixed and the top boundary defined as a free surface. We use a visco-elasto-plastic rheology to characterize the three layers that compose the model and use consistent thermal parameters to define the temperature field. The governing equations of momentum, energy, and mass conservation are solved using COMSOL Multiphysics, a finite element software.

The three main objectives of this study are to:  
1) Analyze the localization and distribution of deformation in the basement and in the overlying lay-

ers. 2) Quantify the amount of shortening/strain required to form the shear zones and rotate the dolerite dykes 3) Study the role of the alum shale in the decoupling between the Lower Allochthon cover and the Precambrian basement.

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**POSTER**
**The rock matrix: formation and evolution of rocks in polyphase metamorphic basements**

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Let us accept that each metamorphic tectonite basically displays a dual property: the **mineral assemblage** of a specific **metamorphic stage** and its expression into **fabrics**; both properties are, in time, subjected to changes. The metamorphic re-equilibration history may form, during geologic time, **n** mineral assemblages (metamorphic stages). Considering **k** fabric types (e.g. coronite, tectonite and mylonite fabrics), **k × n** different **basic fabrics** can appear. By the superposition of these basic fabrics, metamorphic stage after metamorphic stage, **petrostructural fabric types** (i.e. rocks) are produced.

Namely, they are all the combination of basic fabric types (of length  $\leq n$ ) that each basic fabric can produce, with the restriction that the row index is strictly increasing. That is, the  $k$  fabric type at  $n$  cannot form before  $k$  type at  $n - 1$  time, in implicit accord with time evolution of metamorphic transformations. Imagine now considering only the combination of length  $m$ , where  $1 \leq m \leq n$ . There are

$$\binom{n}{m} = \frac{n!}{m!(n-m)!}$$

strictly increasing sequences of row indexes. Each sequence produces  $k^m$  different petrostructural fabrics. The number of possible petrostructural fabrics after  $n$  metamorphic stages is then obtained by summing over  $m$ , where the unit on the left hand side accounts for the rock which started the process, the protolith.

$$1 + \sum_{m=1}^n \binom{n}{m} k^m = \sum_{m=0}^n \binom{n}{m} k^m$$

## S13.3 The evolution and architecture of rifts and rifted passive margins: observations and modelling

### KEYNOTE

#### How to form hyperextended continental margins

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Many passive continental margins are characterised by along-strike differences in margin width, onshore topography, fault patterns, and offshore sediment thickness. For example, it has been suggested that the mid-Norwegian margin may be hyper-extended, thus displaying highly thinned continental crust extending towards the oceanic domain over a wide region, whereas other continental domains of the margin are much narrower. In the past decade, numerical experiments of continental rifting have converged to a fair understanding of the role of crustal rheology and extension velocity in shaping passive margins. A relatively “strong” lower crust leads to fast lithospheric break-up and a short margin accompanied by high rift flank uplift. A “weak” lower crust at moderate extension rates delays break-up and thus leads to formation of a long, hyper-extended crust. However, unless along-strike differences in crustal strength are invoked, these experiments cannot explain along-strike differences in margin width.

We use 2D numerical experiments to show how hyper-extension may be further promoted by testing two examples of natural variations in the rift system. We first highlight the impact of collision-phase inheritance on rifted margin architecture. Elevated temperatures in the collisional crustal nappe stack weaken its crustal rheology, thus promoting hyper-extension. We then show that sedimentation may alter margin architecture for cases with an intermediate strength lower crust by shifting the style of break-up from fast break-up with a sharply tapered margin to prolonged rifting with the development of hyper-extended crust. Natural along-strike variations in collision-phase inheritance combined with

the interplay between crustal rheology and surface processes can therefore provide an explanation for variations in margin architecture observed in passive margins such as the Atlantic margin systems.

### KEYNOTE

#### Splitting continents: Lessons from Afar

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From 2005-2010, the Afar Triple Junction experienced an intense period of tectonic and magmatic activity. During this rifting episode, the Dabbahu-Manda-Hararo segment of the Nubia-Arabia plate boundary opened by up to 10 m in a sequence of 14 dyke intrusions. This activity provided the focus for an equally intense period of scientific investigation of the region. The Afar Consortium, a collaboration between scientists in Ethiopia, the UK, the US and France, carried out a series of integrated geophysical, geological, and geochemical studies in Afar, with the aim of understanding continental breakup and the processes that lead to the formation of new crust at spreading centres. In this presentation, I will show some of the key findings from this work. I will focus on the role of melt in the breakup of continents, tracking that melt from its generation in the mantle through to its intrusion in the crust, or eruption at the surface, via a complex magma plumbing system.

### ORAL

#### Results and regional context of outcrop samples and shallow cores on the outer continental margin of the Norwegian Sea.

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Presence of basaltic volcanic rocks severely hampers seismic imaging of the pre-Eocene strata in the western part of the Norwegian Sea. Therefore,

very little information is available regarding the sub-basalt strata. In order to obtain geological more information from this geological province, the Norwegian Petroleum Directorate (NPD) decided to carry out a rock sampling program in the area.

In 2013, the NPD in collaboration with the University of Bergen conducted seafloor sampling along the steep escarpment formed by the Jan Mayen Fracture Zone along the southern flanks of the Vøring Marginal High and the Vøring Spur. The sampling sites include the southern termination of the Gjallar Ridge. The operations was carried out by using a remotely operated underwater vehicle (ROV). The ROV was equipped with a hydraulic chain saw, making it possible to sample directly from the exposed outcrops. In the Vøring Marginal High, the sampling proved intrusives, in part dacitic, intercalated by mudstones of Late Cretaceous age. Mudstones of the same age in rock falls adjacent to alkaline basalts in the Vøring Spur escarpment indicate that parts of this spur may be of continental origin. The bare rock surfaces are ubiquitously covered by manganese crust.

In 2014, the NPD carried out a shallow drilling program in more than 2000 meters water depth on the Møre Marginal High. The objective was to acquire further knowledge about the geological evolution of this structural element and its delta like features in these outermost, deepwater parts of the Norwegian Sea. The cores showed massive Eocene hyaloclastites representing volcanic deposits in direct contact with water, which seems to make up large parts of the lava deltas that form the Møre and Vøring Escarpments.

The results points to a complicated continental break-up and early ocean spreading history of the Møre-Vøring Margin. It shows the need for more detailed understanding of the interaction between the seafloor spreading and the broad Jan Mayen Fracture Zone system. The individual timing of a set of separate, minor spreading segments within this fracture zone system seems to be of particular interest. In general, the results may also have implications for the understanding of the evolution of the geology at sub-volcanic levels in the Jan Mayen Micro-Continent.

ORAL

### **Coupling of mantle and flood basalt provinciality in continental rifts: example from Karoo-Ferrar LIP**

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The incipient rifting stage of continental breakup often involves emplacement of compositionally diverse flood basalts. The cause of the general geochemical lithosphere-affinity of flood basalts is highly relevant to understanding of rift zones and the composition and convection of Earth's mantle. Specifically, it is still unclear whether the geochemical lithosphere-affinity arises primarily from large-scale melting of heterogeneous continental lithospheric mantle or complex magmatic differentiation.

In the Jurassic Karoo-Ferrar flood basalt province, the occurrence of compositionally different magma types that range from mildly enriched (low-Ti) to strongly enriched (high-Ti) varieties has been commonly ascribed to strongly heterogeneous lithospheric mantle sources. Here I re-examine the roles of mantle source heterogeneity and differentiation in the Karoo-Ferrar province and show that the flood basalts can be readily divided into geochemically distinctive i) eastern and western sub-provinces and ii) high-pressure and low-pressure mantle melting environments using Nb-Zr-Y and REE systematics, respectively.

The magma types of the eastern (~Antarctic) sub-province are characterised by Nb-Zr-Y systematics typical of depleted mantle-sourced magmas, whereas those of the western (~African) sub-province show affinity to primitive or enriched mantle sources. Comparison of the least-contaminated rock types and geochemical modelling suggest that the Nb-Zr-Y dichotomy stems from a large-scale mantle heterogeneity beneath Gondwana, whereas the numerous magma types generally result from differentiation (cf. Luttinen et al., 2015). Given that 1) the geochemical province boundary coincides with the incipient Africa-Antarctica rift-zone, 2) the rift-zone flood basalts can be distinguished by depleted heavy REE suggestive of very high pressure melting, and 3) the rift-zone basalts record the oldest emplacement ages, it is conceivable that the

geochemical provinciality and onset of rifting and magmatism in the Karoo-Ferrar province, as well as the eventual breakup were controlled by a sub-Gondwanan mantle province boundary revealed by the Nb-Zr-Y characteristics.

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Luttinen, A.V., Heinonen, J.S., Kurhila, M., Jourdan, F., Mänttari, I., Vuori, S., and Huhma, H. 2015. Depleted mantle-sourced CFB magmatism in the Jurassic Africa-Antarctica rift: petrology and  $^{40}\text{Ar}/^{39}\text{Ar}$  and U/Pb chronology of the Vestfjella dyke swarm, Dronning Maud Land, Antarctica. *J. Petrol.* 56, 919-952.

ORAL

### Investigating feedbacks between surface processes and tectonics in rift settings using coupled geomorphological and thermo-mechanical models

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The Earth's landscape is a product of complex feedbacks between tectonics, driven by plate motion, and climate, which control the erosional processes. Interactions between erosion, tectonics and climate form, modify or destroy geomorphic features while the transfer of mass resulting from erosion and sedimentation affects isostasy and the mechanical behaviour of the lithosphere. Evolution of extensional basins and rifted continental margins creates significant topography, which in turn can change precipitation and erosion patterns. Transfer of sediments from the margins into the basin may change the stress pattern in the crust and thus affect the geometry of the rift.

Modelling the complexity of such a system requires an integrated approach looking at interactions between tectonics and surface processes on a range of spatial and temporal scales. We use high-resolution numerical experiments coupling a 2D upper-mantle-scale thermo-mechanical model with a plan-form 2D surface processes model (SPM) to investigate the factors controlling the style of deformation. The experiments consist in simple extension models involving lithosphere with variable thickness (normal-like lithosphere to thick cratonic-like lithosphere) and explore the effects of rheological and compositional variability of the layer components of the crust and the lithosphere. We

also explore different values of erosion efficiency together with different pattern of precipitation, including orographic effects.

The models provide a basis to discuss the type of interactions between erosion and tectonics in rift settings. Preliminary results show that if erosion does play a role, sediment load and deposition evolution plays a much bigger role on controlling the activity of fractures and rift geometry. We discuss the implications in our understanding of the coupling between mantle dynamics, lithosphere and atmosphere.

ORAL

### Long-term coupling and feedbacks between surface processes and tectonics during rifting

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Whereas significant efforts have been made to understand the relationship between mountain building and surfaces processes, limited research has been done on the relationship between surface processes and extensional tectonics. Here we present high-resolution 2-D coupled tectonic-surface processes modeling of extensional basin formation. The main aim is to find out how erosion and deposition affect the deformation in extensional systems. We test sensitivity of the rift mode to the combined effects of crustal rheology and varying surface process efficiency (erodibility, sea level). The results show that both erosion of rift flank areas and basin deposition enhance localization of crustal deformation. Frictional-plastic extensional shear zones accumulate more deformation during a longer period of time, and time of lithospheric rupture is delayed when fluvial erosion, transport and deposition are efficient. We show that removal of mass from rift flanks and sedimentary loading in the basin area are the main cause of the feedbacks providing a first order control on the style of extensional basin formation. Variation of strain localization in natural rift systems correlates with the observed behavior and suggests similar feedbacks as demonstrated by the forward numerical models.



ORAL

### Preferential development of extension-orthogonal basins in oblique continental rifts

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Deformation occurs on a wide range of scales in the Earth's lithosphere. On the largest scale, oblique deformation where slip vectors are not precisely orthogonal to plate boundaries is an inevitable consequence of relative plate motion on a spherical surface (McKenzie and Jackson, 1983). In tectonic environments where oblique extension dominates three-dimensional deformation inevitably develops and drives complex strain partitioning in the lithosphere. Understanding the preferred orientations and relative timing of the geologic structures formed during oblique rifting is critical to study passive margins development and remains an active research topic.

We use a high-resolution three-dimensional thermo-mechanical numerical model with a free-surface (May et al., 2015), to investigate the relative timing and distribution of geologic structures during oblique rift development in the continental lithosphere. The obliquity of the rift is prescribed in the models using a wide oblique heterogeneous weak zone allowing intra-rift shear zones to form freely.

We show that strain localisation and the evolution of the deformation pattern in oblique rifts promotes the development of complex transtensional systems in which extension-orthogonal shear zones play a critical role. Comparison with observations from natural oblique continental rift and passive margins confirms the importance of extension-orthogonal shears in accommodating pre-breakup extension.

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May, D., Brown, J., and Le Pourhiet, L., 2015, A scalable, matrix-free multigrid preconditioner for finite element discretizations of heterogeneous Stokes flow: *Computer Methods in Applied Mechanics and Engineering*, v. 290, p. 496-523.

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and fault movements within a deforming zone: *Earth and Planetary Science Letters*, v. 65, p. 182-202.

ORAL

### A dissected central volcano at Biggjarskor, Faroe Islands

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Prestfjall Fm fluviolacustrine sediments and Hvannhagi Fm tuffs and agglomerates are capped by Malinstindur Fm compound basaltic flows possibly erupted during the onset of breakup of the NE Atlantic. We report new observations bearing on faulting, uplift, erosion, topographic inversions and explosive volcanic activity occurring prior to the onset of eruption of Malinstindur Fm basalts, including the discovery of an intact dissected central volcano at Biggjarskor. The Biggjarskor volcano section is beautifully exposed in a ca 200 m vertical sea cliff and comprises a mixture of basaltic flows, agglomerates and ignimbrites crosscut by vent structures and a complex network of dikes and sills. Incised valleys cut through Hvannhagi and Prestfall Fm sediments on nearby Tindholmur island and are filled with megabreccias, lahar deposits and agglomerates likely coeval with eruption of Biggjarskor or other nearby volcanoes. Ongoing work is focussed on sequence stratigraphy of Prestfjall and Hvannhagi Fm strata and dating of Biggjarskor ignimbrites. Prestfjall and Hvannhagi Fm sediments have similar composition and mineralogy to sediments on Mars and mapping and analyses of the Biggjarskor and Tindholmur sections involve deployment and testing of science questions and payload instruments onboard Mars missions. Field deployment included remote

sensing (telephoto) and the mast camera (PanCam, HRC), close-up imager (CLUPI) and Raman spectrometer onboard ESA's ExoMars rover.

ORAL

### **Sedimentary rock record and rapakivi granite emplacement as components of rift basin evolution model**

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Emplacement of the rapakivi granites and associated mafic intrusions is the latest major crustal-scale event in the eastern part of the Fennoscandian Shield. Most realistic models of anorogenic bimodal magmatism involve crustal extension with subsequent downfaulting and development of intracratonic rift basins. The range of the rapakivi intrusion ages is rather well defined (1.65–1.53 Ga). In contrast, the knowledge regarding the basin setup, deposition and stratigraphy of the corresponding time span (c. 170 Ma) is poorly known. The presentation opens new insights both to unmetamorphic sedimentary cover pre-dating the rapakivi's and to the basin development directly (spatially and temporally) connected to the anorogenic magmatism.

Mesoproterozoic sedimentary sequences (arkose, siltstone, shale, conglomerate) are known in some ten localities within the shield area. All these occupy tectonic depressions or graben-like basins bordered by fractures or fault zones most of which are NW-SE oriented. Both the lithology (dominantly arkosic sandstones) and basin architecture of the typical examples (e.g. Satakunta, Lake Ladoga) are in accord with an overall intracratonic setting. Although the original extent of the basin system is hard to estimate reliably, the comparisons to the assumed scale of Mesoproterozoic basins of the Russian platform suggest that deposition may have been more widespread than the currently preserved deposits indicate.

A minimum age (1265 Ma) is well constrained for the Satakunta sandstone, and the results from the Lake Ladoga area indicate that sedimentation occurred here shortly after or concurrently with the emplacement of the 1560–1530 Ma Salmi rapakivi granite complex. In general, however, the depositional age of Mesoproterozoic sequences is still poorly constrained.

Special emphasis is put in re-interpretation of some classical localities (Suursaari, Taalikkala,

Eräjärvi) with quartz-arenitic sandstones. It is envisaged that these represent remnants of widespread cratonic deposits pre-dating the extension manifested by mantle derived mafic dykes and – finally – rapakivi's. The evidence supports rapakivi granite emplacement in very shallow crustal depths.

In summary, all the evidence collected during the last 15 years point to two major conclusions: (1) the first supracrustal rocks directly related to 'rapakivi stage' (mafic lavas) deposited on top of quartz-arenitic rocks representing cratonic platform cover on deeply eroded Svecofennian crystalline rocks and (2) all known Mesoproterozoic sedimentary sequences can be interpreted as deposits reflecting basin formation coeval to rapakivi emplacement. Nevertheless, it is possible that the preserved Mesoproterozoic strata represent repeated rifting, complex basin configuration and multiple depositional stages.

## S13.4 Imaging and modelling geological structures from microscopic to orogen scales

**KEYNOTE**

### Imaging rock deformation on multiple scales: advances in better understanding heterogeneous deformation

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Heterogeneous deformation is intrinsic to natural deformation. Using the orientation of principal strain axes inferred from fault-kinematic analysis, the heterogeneity of upper-crustal deformation is illustrated for the southern Central Andes, Argentina, and the Eastern Penokean Orogen, Canada. In both regions, the data sets amount to several thousand brittle faults. To better comprehend such large data sets with regard to the heterogeneity of deformation from the outcrop to the crustal scales, several methods imaging strain perturbations were applied. Scaled analogue experiments allowed an assessment of the influence of mechanical anomalies on the patterns of principal strain axes. For the central Andes, analysis of remote sensing data complemented the experiments and involved the development of an ArcGIS workflow quantifying geomorphic indices. For the Eastern Penokean Orogen, the principal strain axis pattern was visualized by a workflow that involved Python scripting and ArcGIS-based interpolation based on Ordinary Kriging. The application of various imaging techniques provided a number of fundamental results regarding the heterogeneity of deformation: (1) Strain perturbations caused by mechanical anomalies lead to kinematic partitioning of deforming upper crust that significantly influences patterns of principal strains. (2) The inversion of brittle shear faults adheres to local strain, not paleo-stress, and portrays the kinematics of prominent discontinuities. (3) Differently oriented strain axes may not unequivocally point to regional deformation caused by successive and distinct deformation regimes. (4) Brittle fault data should not be used as proxy for estimating directions of plate-scale motions.

**ORAL**

### Seismic investigations in the central Swedish Caledonides

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The Collisional Orogeny in the Scandinavian Caledonides (COSC) project aims to provide a deeper understanding of mountain belt dynamics with a focus on the central Scandinavian Caledonides. It involves two 2.5 km deep fully cored scientific boreholes and a wide range of related investigations in the county of Jämtland in western Sweden. Reflection seismic imaging of the sub-surface structure is an important component, both to allow identification of potential drill sites and planning of the drilling, and to provide a link between the detailed studies at the boreholes and the large scale understanding of the tectonic evolution in the region.

A series of reflection seismic profiles have been acquired along a composite c. 55 km long profile to image the upper crust in high resolution. Sub-horizontal reflections in the upper 1-2 km are underlain and interlayered with strong west-to northwest-dipping reflections, suggesting significant east-vergent thrusting of the Caledonian allochthons. Shallow drillholes further to the south-east and previously acquired seismic, magnetotelluric and magnetic data, constrain the basal orogenic detachment to continuous reflections at c. 1-1.5 km depth. The interpreted underlying basement is characterized by a pattern of strong sub-horizontal to northwest-dipping reflections of unknown origin. These may be related to compressional tectonics during the Caledonian or earlier orogeny, and/or part of an extensional system that was active during passive margin formation.

After the first COSC borehole was drilled in 2014, targeting the subduction-related Seve Nappe Complex, a major seismic survey was conducted in and around the borehole. This included a 3D reflection seismic experiment designed to image the structures around the borehole and allow extrapolation of results from borehole and core into the surrounding rock. The complex geology of the Lower Seve Nappe, with an abundance of mafic lenses within felsic rocks, produces a pattern of west dipping reflections of limited continuity. At c. 1.7 km depth, the COSC-1 core enters a major thrust zone

that extends to the bottom of the 2.5 km deep borehole. This thrust zone is imaged as a package of more continuous southeast-dipping reflections with an abrupt decrease in reflectivity at c. 2350 m depth, correlating with a change in lithology that could indicate a transition into underlying allochthons.

ORAL

### Polyphase mafic dykes in the Caledonides of Finnmark revealed by a new high-resolution aeromagnetic dataset

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New high-resolution aeromagnetic data from the Caledonides and Archaean-Palaeoproterozoic basement of Finnmark and North Troms derived from surveys conducted as part of NGU's MINN programme provide spectacular and confirmatory evidence for the continuation of diverse, Precambrian greenstone belts and granulite terranes beneath the relatively thin-skinned Caledonian nappes. In addition, the surveys highlight the extensive presence of blind metadolerite and unmetamorphosed dolerite dykes. Three ages of dykes are documented from isotopic dating studies – Ediacaran, Late Devonian and Early Carboniferous. The mafic dykes of Ediacaran age (c. 577 Ma) occur as swarms of metadolerite dykes in thrust-sheets in northwestern Varanger Peninsula, north of the Trollfjorden-Komagelva Fault Zone (TKFZ), and are clearly recognised as high-amplitude magnetic responses in our dataset. Such metadolerites also occur quite extensively in the Laksefjord and Kalak nappe complexes. In NW Varanger Peninsula, individual metadolerite dykes can be followed inland as linear positive magnetic anomalies over distances of 25 km or more.

In the case of the younger unmetamorphosed dolerite dykes, actual dyke outcrop is very limited. The few Late Devonian dykes (c. 370 Ma) occur mostly in eastern Varanger Peninsula. The new aeromagnetic data show, however, that up to 20 such dolerite dykes can be followed inland in the subsurface based on their linear positive magnetic anomaly signatures. The c. NNE-SSW-trending, blind dykes clearly transect structures of both Timanian and Caledonian age. South of the TKFZ, two well studied dykes are clearly identifiable by their

long, linear, magnetic signatures both onland and offshore beneath Varangerfjorden. Perhaps the most spectacular manifestations of blind dolerite dykes are seen as linear positive magnetic anomalies coinciding with Early Carboniferous (Viséan; c. 337 Ma) dolerite dykes exposed on Magerøya and western Digermul Peninsula. These prominent linear anomalies can be traced along many of the NW-SE to WNW-ESE-trending faults that have disrupted the Caledonian nappes. These particular dykes and faults are interpreted as relating to a period of major rifting and extension that occurred in the SW Barents Sea and onshore areas of Finnmark in Carboniferous time.

ORAL

### Trialing the anisotropy of magnetic susceptibility (AMS) to determine the West Spitsbergen Fold-and-Thrust Belt Palaeostress pattern

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This contribution investigates the extent to which the anisotropy of magnetic susceptibility (AMS) method can aid the definition of the tectonic palaeostress pattern responsible for the formation of the West Spitsbergen Fold-and-Thrust Belt. The magnetic properties, including: hysteresis loops and the magnetic susceptibility variations at high temperatures, of 31 oriented Lower Triassic rock samples from 4 sites (159 specimens) were analyzed. The main purpose was to identify the ferro- and paramagnetic minerals and assess of the extent to which they have influenced the magnetic susceptibility. Magnetite and pyrrhotite are main ferromagnetic minerals present in most sites and the magnetic susceptibility is controlled mainly by paramagnetic minerals. Only in one site, COND1, were ferromagnetic minerals more dominant. In two sites a normal magnetic fabric of sedimentary origin was detected which was associated with a relatively good clustering of the maximum AMS axes, caused by the tectonic strain. The orientation of the magnetic lineation, which indicates that of the

maximum tectonic strain, approximates the regional structural NNW-SSE trend of the WSFTB. These results appear to support a pure orthogonal compression model for the formation of the WSFTB. The remaining two sites had mixed and inverted fabrics, the latter probably arising from the presence iron-bearing carbonates in the samples.

## ORAL

### The Scandian folds on the Paleozoic sedimentary cover of Estonia

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The Scandian orogenic event from Cambrian to Silurian is studied in Estonia. Folding of the sedimentary rocks usually occur in the sequences, where harder rocks alternate with softer layers. Several folds and faults have been documented in the oil shale deposit, in underground mines and surface quarries. The density of pure oil shale is 1450–1680 kg/m<sup>3</sup>, but in limestone layers with some kerogen the densities vary between 2160–2410 kg/m<sup>3</sup>. The oil shale layers with limestone nodules have densities between limestone and oil shale. One anticlinal fold is studied in the Cambrian bedrock in the Tallinn city near the SE shore of the Kopli Bay. The axial plane of the fold and related faults indicate the orientation of regional pressure. In this anticline axial plane the orientation is to NE 65°, inclined to SE at angle 82°. It means that pressure came from NW 335° and the lower layers moved faster than the upper layers. Three subhorizontal drag folds up to 30–40 cm long were found in the aleorolite layers, which proves horizontal movement of the layers.

Numerous folds, faults and karst zones are documented in the Estonian oil shale deposit. Recent studies in the Põhja-Kiviõli near surface quarry gave new data about folds and folding in the oil shale. In the centre of the quarry the first Sonda deformed zone with width about 205 m was observed, containing 10 uplifted anti-clines with synclines between. As a rule the synclines do not have fault zones and the anticlines have a karst clay with thickness of 0.5–5.0 m. Their upper parts are turned 160° SE, the pressure at folding being from NW. Some hydrothermal minerals like calcite, dolomite, marcasite, pyrite, galenite were found in one of the anti-cline. It proved the age of the Scandian event

here. The main observation is that most synclines are very wide and do not have faults, but all anticlines have faults with karst clay fillings. Typically the synclines lie on the Middle Ordovician hard limestones and the anticlines formed in soft seam on the oil shale.

In 2008–2014 the first folds in the Silurian Llandovery series of the central Estonia were found. In the quarries of Otsaare, Koigi and Sopimetsa dipping of the carbonates is often up to 6–10°. The typical inclination of undeformed bedrock of Cambrian, Ordovician and Silurian is 3 m per one km or 0.1–0.2°. The folds may be single with a width of 25–30 m or open wide folds, some hundred meters long on the quarries walls, where the flat anti-clines and synclines alternate. The axial plane orientations are near NE 60° and may be with open faults with karst clay fillings.

All studied structures have very similar pressure orientation and moving direction, the main pressure being from NW to SE, the axial planes of the folds turning to NE 50–65°. The uplifted Precambrian basement on the Valmiera–Mõniste–Lokno zone belongs most likely also to the Scandian event.

The last Middle and Upper Devonian epochs of Estonian geology and tectonics began after the Late Silurian and Lower Devonian break in sedimentation.

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## KEYNOTE

### Rock mechanics characteristics of fault zones and their effect for designing underground facilities

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Understanding the nature of the host rock, especially the structural geology features, is one of the keys to the successful design and construction of all underground facilities located in rock masses. The most important features are the faults because these are major discontinuities in the rock mass continuum — affecting the local rock stresses, providing high permeability paths for water flow, and potentially adversely affecting the rock mass stability. Accordingly, it is essential to understand the formation, geometry and mechanical properties of the faults, especially for major construction projects.

This paper gives overview how the fault zones are considered in the design of the underground

projects. The design aspects mainly involve the characterisation and properties of the zones for stability analyses and support and grouting design. Special attention has here laid on the properties the brittle deformation zones at the Olkiluoto nuclear repository site in western Finland which play critical roles in the strength and hydrology of the host rock mass. In Olkiluoto a procedure was implemented for incorporating information on deformation zones obtained through boreholes into quantitative engineering design. Ductile and brittle deformation zones are classified based on their characteristics in drillhole cores as brittle joint clusters, brittle fault zones, or semi-brittle fault zones, with an awareness of the geologic processes that caused the zones to develop as they did.

Finally, the paper describes how the mechanical properties of the fault zones can be calculated or estimated by one of the several methods, each of which has advantages and disadvantages.

ORAL

### Seismic images providing glimpse into the deep geology of Pyhäsalmi mining district in Finland

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Seismic reflection method is one of the few methods capable in imaging geological interfaces of the subsurface to the depth of several kilometers with high resolution. Method relies on sharp changes of density or seismic velocity between different geological formations. Physical rock properties provide important background knowledge about feasibility of imaging certain rock contacts. In Pyhäsalmi-Mullikkoräme volcanic hosted massive sulfide district in Finland geophysical drill hole logging results indicate that contact of interest, interface between felsic and mafic volcanic rocks, can be seismically imaged (Heinonen et al., 2012). Fourteen high resolution seismic reflection profiles acquired in the Pyhäsalmi-Mullikkoräme mining district reveal the subsurface continuation of the reflective volcanic strata underneath seismically transparent intrusive granites. The 3D-modeling of the

seismic reflections revealed a major reverse fault dividing Pyhäsalmi and Mullikkoräme volcanic units to blocks with varying deformation style. Fault and difference of deformation style is also evident in the crustal scale seismic profile acquired close by the mining camp.

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ORAL

### Detail scale *in situ* fracture modelling of excavation damage zone

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Posiva Oy is responsible of implementing the final disposal programme for spent nuclear fuel of its owners TVO and Fortum Power & Heat. Within the geological concept of final disposal, knowledge of the properties and limitations of surrounding rock are on high importance for long term safety analysis. For example excavation damage zone (EDZ) studies in ONKALO research tunnel are part of this long term safety analysis

As a part of these EDZ studies, a detail scale *in situ* fracture model has been created. A specific area from ONKALO has selected for EDZ Study Area and from this area, totally four ca. 1m<sup>2</sup> rock blocks were wire sawed and lifted from tunnel floor. These rock blocks were sliced ca. 10 cm rock slices and these rock surfaces were covered with penetrant, photographed and measured with tacheometer. With this data, rock slice photographs were transferred to 3D form with Geovia Surpac software.

From each rock slice, visible fractures were digitized and characterized in four categories: 1) Excavation induced fractures, 2) Natural fractures 3) Natural fractures opened by excavation and 4) Horizontal, possibly stress induced, fracture. After digitizing, fracture strings were started to combine between the rock slices to create fracture planes of the area. The result was an exact fracture pattern model of the wire sawed area.

The key results of this study was the actual *in situ* fracture model and also recognize the areas

were located most of the excavation induced fractures. Based on the model, most of the EDZ fractures locate close to round ends. It was also possible to detect that EDZ fractures themselves don't form a continuous planes in the tunnel floor but they do connect to natural fracture network.

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ORAL

### Deformation phases delineated by AMS in high-grade migmatites, Olkiluoto, SW Finland

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The present study was carried out to get additional information of ductile structures and deformation phases at the site for the long-term disposal of high nuclear waste in Olkiluoto, SW Finland. Detailed structural geological mapping and sampling to study anisotropy of magnetic susceptibility (AMS) was conducted at selected outcrops in Olkiluoto. The AMS has proven to be a useful tool for further examinations on mineral fabrics in high-grade migmatite terrains and our study focuses of coupling AMS fabric to the different ductile deformational phases recognized in the earlier site studies at Olkiluoto.

Three different deformation phases have been determined during earlier structural studies, but only limited lineation data was possible to acquire. The results obtained from our AMS study shows discernible linear data, which can be connected to the previously collected structural information. Each individual deformation phase exhibit a difference in the structural pattern for the mineral fabric indicated by a more oblate or prolate deformational ellipsoid. The AMS data also shows both  $\alpha$ -lineation and  $\beta$ -lineation which verifies the importance of a detailed structural understanding of the

study site prior to when an AMS study is carried out in a polyphasically deformed high-grade migmatite environment.

ORAL

### The tectono-metamorphic evolution of basement rocks as revealed by combining optical, 3D neutron diffraction and x-rays synchrotron microstructural analyses

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Microstructures are fundamental keys to the interpretation of geological processes at various scales and times. In this contribution we will discuss quantitative approaches to microstructural analysis to investigate active processes, their physical conditions and geodynamic environment in basement rocks from the Alps.

Two main parts constituting the rock fabric are investigated by mean of quantitative 3D techniques: shape preferred orientation (SPO) and lattice preferred orientation (LPO).

- The SPO is quantified by means of **image analysis at 2D or 3D** combining orthogonal thin sections or by **X-ray synchrotron microtomography** allowing 3D investigation over a relatively small sample.

- The LPO quantification is performed by **neutron diffraction texture analysis** allowing a complete statistical coverage of large volumes of the order of 1 cm<sup>3</sup>.

We will discuss the investigation of natural cases from the Alps and their effect on the reconstruction of the tectono-metamorphic evolution of these lower and middle crust rocks during alpine subduction and collision.

## ORAL

**Characterizing ore textures by combining synchrotron-based X-ray 3-D nanotomography and LA-ICP-MS analyses: Insights from the Suurikuusikko orogenic gold deposit, Finland**

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High resolution X-ray micro- and nanotomography (CT) are emerging, non-destructive analytical tools for visualizing ore textures at micro- and nanoscale, and providing a holistic 3-D approach of ore-forming processes. In this study, we analysed in-situ microscale textures in 3-D using centimetre-scale drill core samples from the Suurikuusikko orogenic gold deposit, northern Finland. For the 3-D nanotomography, individual arsenopyrite (APY) crystals were separated and scanned, followed by 2-D imaging and micro-analytical procedures. The micro-CT scans of drill cores were carried out with a lab-based custom-built Phoenix X-ray Nanotom 180 NF scanner at the University of Helsinki, with an effective pixel size of 31µm. Nanotomography scans of individual sulphide grains were performed on beamline ID16B at the European Synchrotron Radiation Facility, France, with the voxel size of reconstructions from 50 nm to 150 nm. Field emission scanning electron microscopy (FE-SEM) and laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) imaging and analyses were performed at the Geological Survey of Finland, Espoo.

Microtomography revealed the size, shape, spatial distribution and geometrical orientation of sulphide minerals in the oriented drill cores, which are rather difficult to discern from 2-D optical or SEM imaging technologies. The synchrotron-based nanotomography illustrated 3-D distribution of micron to nano-scale gold particles, mostly associated with rutile (primary) or along microfractures (secondary) inside APY. The same set of APY crystals were then analysed using LA-ICP-MS, which show correlations in the concentrations of Au and associated elements, and an especially strong antithetic

relationship with Sb. The latter results further indicate gold occurs lattice-bound in each APY crystal and also in association with nano-scale Sb-Ni-Co bearing mineral inclusions, beyond the detection limits of synchrotron-based X-ray nanotomography.

This work was partly supported by the Academy of Finland project No. 281670 to F. Molnár.

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## POSTER

**Prediction of Zones of Weakness – from ground to tunnel**

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In the Helsinki Capital area interpretation of the zones of weakness in bedrock was carried out by GTK in early 2000. Later 2006 – 2007 the 13.5 km long and max 60 m in depth railway tunnel was excavated from Vuosaari to Kerava, in the same area. Geological (GTK) and engineering geological (Pöyry Finland Oy) mapping was performed in the tunnel. The interpretation and mapping results were compared in order to develop interpretation methods.

The bedrock in the area consists of strongly migmatized Paleoproterozoic supracrustal and plutonic rocks. The bedrock is peneplaned and Quaternary sediments cover approximately 70 % of it. The interpretation of the zones of weakness was based mainly on topographic and aeromagnetic data and outcrop mapping. Out of the 40 interpreted zones of weakness in the tunnel area 32 were found in the tunnel. In addition 22 new zones were observed. These zones remained undiscovered in the topographic and aeromagnetic data even afterwards. All interpretations that had been confirmed by an outcrop fault observation turned out correct in the tunnel.

The interpreted zones of weakness had been divided into three classes based on the length of the zone, data on fault rocks in the area and previous geotechnical information from old tunnels. The three classes increased in width and low-quality rock characteristics, like fracturing and weathering. The mapping results showed that variations within two smaller classes did not regularly depend on the



length or fault type. Only the largest zone, about 15 km long, was clearly broader and of poorer rock quality than the others. In assessing the quality of the zones of weakness only by the length, two classes would be sufficient.

Weathering in the zones of weakness occurred as expected. When several zones of weakness coexisted the weathering was more intense and occurred also between the zones. Sites with only single zones of weakness were insignificantly weathered.

The influence of the zones of weakness was discovered also on filled joints. The clay mineral or other in-cohesive material filled joints, wider than 5 mm, existed only at the sites of several zones of weakness, to say four or more zones in kilometers length.

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**POSTER**

**Use of terrestrial laser scan data in detailed geological structure mapping: a case study from Vekara, SW-Finland**

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In the ongoing research project dense network of terrestrial laser scanning (TLS) point clouds has been acquired on a small, perfectly exposed skerry SW of the Vekara island in SW Finland. This study aims at extraction of structural surfaces from TLS point clouds to retrieve the attitudes and networks of geological structures such as beddings and fractures. To test the applicability of the method for the relatively flat topography of the study area, the results will be correlated with transit compass measurements conducted on specific structural planes (Assali et al., 2014, Kwong et al., 2007 and Fishera et al., 2014), and localized by RTK-GPS. Future work will focus at (semi)automated extraction of structural data from TLS points clouds. Future work will further utilize high-resolution aerial photography in recognizing the networks of brittle structures and their relationships with the ductile structures.

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**POSTER**

**Characterization and 3D -modelling of the brittle structures in Westmetro tunnels**

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The tunnels of the western part of the Helsinki region subway network (“Länsimetro”) locate within the Svecofennian domain of the crystalline Paleoproterozoic bedrock. The metro tunnels are total 21 km in length. The pilot area for the detail models is situated in the Hannusjärvi area in Espoo.

Geological Survey of Finland has done detailed field work and analysis of the structures from the pilot area which gives good basic knowledge for this study. They have interpreted geophysical and geological data during 2000-2008. Pajunen ed. (2008) has attributed the structures to specific deformational events.

The main aim of this study is to construct detailed 3D-models over the networks of brittle structures and to identify the kinematic indicators of the structures and the factors controlling the fluid flow through the fracture networks. This helps the underground construction planning.

The first part of the study is to map and characterize the brittle structures of the pilot area, from the tunnels. The mapping results will subsequently be correlated with ground surface LiDAR data and existing structural interpretations (Pajunen ed. 2008), and tentative structural 3D-models will be constructed. The initial models will be refined by drill hole, geophysical, and groundwater well data from the study area, available through collaboration with the subway constructor.

We have now collected all the drill hole data to an Access –database and created a 3D visualization from the weakness zones in the drill holes. We have also created a database from the outcrop mapping data covering the whole study area.

The second part of the study is to create the kinematic indicators to study the fluid flow in the

structures. This is carried out after the fracture network model is completed and the fractures are properly characterized.

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## S13.5 Impact cratering as a geological process

ORAL

### Postimpact crater sedimentation in marine-target impact structures.

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Marine impact craters represent the most common impacts on Earth. In this presentation a general succession of the postimpact subaqueous filling history will be outlined.

The general depositional developments and most likely fill succession in marine impact craters will be explored in the light of new information from the Ritland and the Chesapeake Bay impact structures (Dypvik and Kalleeson, 2010; Azad et al., 2015; Dypvik et al., in prep.).

A first depositional stage (late syn- to early postimpact) is dominated by poorly sorted rock avalanche, scree and slump deposits. In most marine postimpact successions these deposits are overlain by sediments of mass flow deposition as debris flows. These are further commonly topped by fluid flow and suspension current deposits. The internal relations and dimensions of these formations are controlled by e.g. crater size, target lithology, and water depth (Azad et al., 2015).

The minor (2.5 km diameter crater) Ritland impact occurred in shallow shelf conditions with a crystalline target rock. Avalanche, scree and mass flow deposits dominate the postimpact succession (Azad et al., 2015).

In the much wider Chesapeake Bay impact structure (about 90 km in diameter) the bolide also impacted into shallow water, but into a thick sequence of sedimentary formations. This resulted in a weak rim development, with crater sedimentation dominated by multiple events of large scale debris flows.

Due to plate tectonics and surface processes on the Earth, only parts of ancient crater fill successions can be expected to have survived; only in rare cases will the complete package be found. Knowledge of postimpact succession stratigraphy in addition to classic impact characteristics may help in recognizing new craters and understanding their postimpact history.

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ORAL

### The Lockne – Målingen doublet impacts, the result of a binary asteroid from the 470 Ma Main Asteroid Belt Event

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Approximately 470 million years ago one of the largest cosmic catastrophes occurred in our solar system since the accretion of the planets. A 200-km large asteroid was disrupted by a collision in the Main Asteroid Belt (MAB), which spawned fragments into Earth crossing orbits. This had tremendous consequences for the meteorite production and cratering rate during several millions of years following the event. The 7.5-km wide Lockne crater, central Sweden, is known to be a member of this family. The 600 m large Lockne asteroid was a binary and had a companion in space by a smaller 150 m satellite. The recent discovery of the nearby, 0.7-km diameter, synchronous Målingen crater suggests it to form a doublet impact structure together with the larger Lockne crater, and as we will show here, most likely by a binary, ‘rubble pile’ asteroid. Despite observational evidence that about 16% of the Near Earth Asteroids (NEA’s) are binary, only a handful of the approximately 188 known craters on Earth have been suggested as potential doublets. The stratigraphic and geographic relationship with Lockne suggests the Lockne and Målingen craters to be the first described doublet impact structure by a binary asteroid into a marine-target setting. In addition, the precise dating of the Lockne-Målingen impact in relation to the MAB breakup event provides a hands-on reference for studies of the formation of binaries from asteroid breakup events.

ORAL

### Comparing methods to estimate the decay rate of fracturing away from impact centers

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Four methods can be used to estimate the fracturing rate away from the impact center: (i) mapping shock induced fracture densities with remote sensing tools, geophysical methods, or by in-situ field measurements (Gurov&Gurova 1983; Pesonen 2011, Henkel 1992); (ii) modeling damage and deformation in the impact structures and surrounding target rocks using numerical codes (Collins et al. 2004); (iii) interpreting gravity anomalies of the impact and fractured target layers in terms of porosities (Henkel et al. 2010); or (iv) studying porosities of impact and target rocks vertically down (deep cores) or horizontally away (sampling of exposed rocks) (Pesonen 2011). All methods have serious flaws and their comparison is difficult. Here we present a study of 18 impact structures on Earth from which we have shocked samples as a function of radial distance. The rocks were split into 5 types in order of decreasing shock: melts, suevites, breccias, fractured and unfractured target rocks. The petrophysical properties measured in a laboratory were: density, porosity, susceptibility, NRM and the Q-value. The data reveal distinct trends: 1. Porosity decreases from suevites to breccias to melts to fractured target rock up to unfractured target. By analogy, the density increases in same order, 2. The case for susceptibility is more complex: the fractured rocks reveal declined susceptibilities which is the main cause for the magnetic “haloes” surrounding many impact structures. 3. The NRM is also very variable: the suevites and melts have the highest NRM’s and Q-values. The main result of this work is that porosities and fracture densities decay away from the center with much faster rate than the fracturing in the numerical models or in gravity data. We discuss the possible causes of these discrepancies in terms of defining the radial distance, assessing shock degree to various samples, and how to account for the various ages and erosion levels.

ORAL

### Impact cratering model of the Chelyabinsk meteoroid formation

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Chondrite Chelyabinsk is unique meteorite due to its fall, structure and influence on people and science. It is ordinary chondrite LL5 S4 W0, however, it contains few different lithologies [Galimov 2014; Badyukov 2015; Grokhovsky 2014; Righter 2015].

As it is known, light and dark lithologies are of identical LL5 composition [Galimov 2014; Kohout, 2014]. Probably, all lithologies have same initial matter.

After the study of Chelyabinsk fragments it was found:

- All mentioned lithologies were present in large samples;
- Large brecciated samples contained roundish light lithology parts;
- Individual large light lithology samples had slickensides;
- Dark lithology was the result of shock darkening, it contained melted metal and troilite impact veins;
- Dark lithology could be found in the form of individual samples, as dykes and as main mass encapsulating light lithology parts in large samples;
- Large parts of dark lithology were adjoined with melted parts.

All three different lithologies are results of Chelyabinsk parent body complicate shock history. We suppose that Chelyabinsk breccia formation mechanism was similar to the impact cratering. The structure of main Chelyabinsk fragment looks like suevite structure from impact craters [Stoffler 2013].

This work was supported in part by RFBR #15-35-21 164 and Geophysics laboratory, Department of Physics, University of Helsinki.

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ORAL

### Post-Impact Modification of Craters on Titan by Aeolian and Fluvial Processes : Lessons from Earth Analogs

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While impact craters on icy worlds present novel challenges in that the impactor population and the target lithology/rheology is rather different from the terrestrial planets, Titan's craters as observed by the Cassini mission (and especially its radar mapper) have the additional difficulties that the craters are generally heavily modified. Not only are the craters generally shallower than their Ganymede counterparts, but there is direct evidence of aeolian infilling and fluvial modification. Submarine craters may also have formed on Titan. Examination of terrestrial analogs such as Roter Kamm (aeolian/pluvial modification), Lawn Hill (submarine) and Waqf as Suwaan (moderate fluvial) are helping with the interpretation of these structures.

ORAL

### ASPECT CubeSat mission to a binary asteroid

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The ASPECT mission aims to study the composition of the Didymos asteroid and the effects of

space weathering and shock metamorphism in order to gain understanding of the formation and evolution of the Solar System.

The joint ESA/NASA AIDA (Asteroid Impact & Deflection Assessment) mission to binary asteroid Didymos includes an impact experiment to demonstrate kinetic deflection of potentially hazardous asteroid. The mission will also include two CubeSat miniaturized satellites, released in asteroid vicinity by AIM (Asteroid Impact Mission) spacecraft (ESA AIDA mission component). This arrangement opens up a possibility for secondary scientific experiments. Whereas Didymos is a space-weathered asteroid, the impactor is expected to produce a crater and excavate fresh material. Spectral comparison of the mature surface to the freshly exposed material will allow to directly determine space weathering effects. It will be also possible to study spectral shock effects within the impact crater.

ASPECT is a 3U CubeSat (size of 3 units Fig. 1) equipped with a spectral imager with 500–2500 nm wavelength range and spatial resolution better than 10 m.

ASPECT will also demonstrate the capabilities of a CubeSat and a miniature spectral imager for the first time in deep-space environment. This work is done under SysNova: R&D Studies Competition for Innovation contract with ESA.

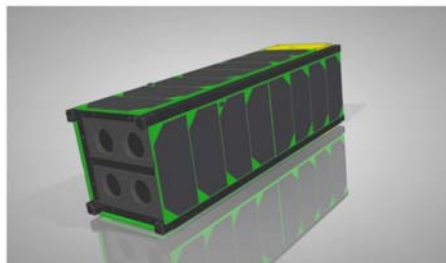


Figure 2: Proposed ASPECT CubeSat

## POSTER

**Deep subcrater shock effects in large terrestrial impact structures**A.A. GARDE<sup>1\*</sup>, N. KEULEN<sup>1</sup> AND T. JØRGART<sup>2</sup><sup>1</sup>GEUS, Øster Voldgade 10, 1350 København K, DENMARK

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Mid- to deep-crustal effects of asteroid impact on Earth can effectively only be studied in its two largest impact structures: the poorly exposed, 2.02 Ga Vredefort structure in South Africa eroded to ~10 km below the impacted surface, and the well-exposed, 3 Ga Maniitsoq structure in SW Greenland, exhumed by as much as 20–25 km.

Bulk shock melting at surface and, with decreasing shock wave intensity, formation of quenched single-mineral melts, diaplectic mineral glass, shock lamellae, etc., are well-known shock-related, near-surface phenomena. But what happens under large structures where the shock wave is not attenuated already in the upper crust?

Re-formation of shock-melted K-feldspar as an interstitial crystalline network rather than a glass was first reported from pelitic granulites close to the centre of the Vredefort structure, whereas adjacent shock-melted biotite recrystallised as mixtures of several new, anhydrous phases. A new study at Maniitsoq (Keulen et al. 2015) shows that shock-melting of K-feldspar was very widespread (d ~ 80 km). K-feldspar melts invaded into impact-induced fractures in adjacent plagioclase where a new ternary alkali feldspar melt was formed, resulting in rocks with three alkali feldspars and complex melt- and exsolution textures. Shock-melted biotite at Maniitsoq was re-formed as biotite without volatile loss.

At Vredefort, low-grade hydrothermal alteration without concomitant melting is known from both country rocks and pseudotachylytes, whereas no phenomena ascribed to seismic shaking have so far been reported. At Maniitsoq, the shock mineral melting was accompanied by impact-induced seismic shaking, transforming its inner part into a 35 by 50 km large, mechanically homogenised domain. Subsequent impact-induced mantle melting resulted in a 75 km long, curvilinear belt of norite intrusions, and deep-crustal hydrothermal alteration led to pervasive recrystallisation and formation of granitic melts.

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<http://dx.doi.org/10.1016/j.tecto.2015.07.028>

## POSTER

**Söderfjärden impact crater, new results and new drilling plan**S. HIETALA<sup>1\*</sup>, L. J. PESONEN<sup>2</sup>, M. ANDERSÉN<sup>3</sup>, AND P. EDÉN<sup>4</sup><sup>1</sup>Geological Survey of Finland, PO Box 1237, 70211 Kuopio, FINLAND (\*correspondence: satu.hietala@gtk.fi)<sup>2</sup>Physics Dept., University of Helsinki, 00014 Helsinki, FINLAND<sup>3</sup>Meteorita Söderfjärden Visitor Centre, Marenintie 294, 65410 Sundom, FINLAND<sup>4</sup>Geological Survey of Finland, PO Box 97, 67101 Kakkola, FINLAND

Söderfjärden is one of the best preserved Early Paleozoic impact structures on Earth. As seen from the air, there is a distinct circular field surrounded by a crater rim of hills. The diameter of the crater is 6.5 km and the depth over 300 m. The target rock consists of Svecofennian rocks, such as the Vaasa granite dated at 1875 Ma (Suikkanen et al. 2014). Geological research has been conducted at Söderfjärden since 1970's. Seven drill holes have been drilled into the crater, the deepest reaching down to 347 m. The age of the crater was earlier estimated at ~525 Ma, based on microfossils in the Cambrian sediments (Tynni 1982, Utela, pers. comm.). New <sup>40</sup>Ar/<sup>39</sup>Ar dating results for a melt vein from boulder, suggests a Neoproterozoic age of ~640 Ma (Schmieder et al. 2014).

So far only few impactites have been found. The previous drillings have yielded polymict allochthonous breccias, which contain planar deformation features, feather lamellae and planar fractures in quartz grains. (Öhman&Preeden 2013) No melt or suevites had been found until 2013 when new findings from the south-east side show distinct evidence of impact origin. Moreover, magnetic and gravity data indicate that a small buried impact melt body may occur near the center (Abels et al. 2002).

Our new research plan calls for a new drilling coupled with seismic surveys crossing the central uplift and possible the melt body. The drilling may also shed new light on life evolution during the Cambrian, on the various Pleistocene glacial deposits and related to the development of the Baltic

Sea, and many other geological, environmental and anthropogenic interferences, which affected soils and waters in Söderfjärden during historic times. The new drilling plan includes also modeling of the heat energy that emerged from the collision, and an attempt to obtain absolute (using shocked zircons) radiometric dating of the impact event and the original crater dimensions. Sampling of the entire sediment sequence can provide very valuable research information, including estimates of the post-glacial sulphur-rich sediments and potential chemical variations in stratigraphy within them. Such knowledge is valuable in the evaluation of the environmental risks that might arise from land-use in areas with acid sulphate soils in Ostrobothnia.

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**POSTER**
**Reflection seismics of the Dobele impact crater, Latvia**

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The Dobele crater is a valuable object for impact crater researchers as the complex crater is entirely in sedimentary rocks, the target is horizontally layered and it is relatively well preserved. Unfortunately, this structure is not well known as there is only a limited number of publications describing it (e.g. Masaitis, 1999). We conducted reflection seismics at Dobele aiming at detailisation of its size, location and inner structure.

Altogether about 19 km of high-resolution reflection seismic profiles were acquired along Dobele – Tervete highway and local gravel roads. Seismic waves were generated using earth tamper (vertical stack typically 300-500 hits) and recorded by 72 geophones that were spaced every 10 m. The deepest reflections came from the top of crystalline basement at about 1.5 km depth.

Seismic sections suggest that the centre of the Dobele crater is located at 23°17.4' E, 56°34.2' N that is a couple km eastward of commonly reported location. Position of the centre of crater can be estimated from the shape of central uplift and annular moat. The rim of crater is not visible on the seismic sections. Reflections from the crater floor

rise towards the rim area where subhorizontal layered strata continue. Some profiles suggest that the rim has already been eroded prior formation of Late Paleozoic sediments, but it certainly has been also eroded by Scandinavian Ice Sheets.

According to drilling and seismic data, the allochthonous breccias occur at about 300 – 350 m depth in the annular moat that surrounds central uplift. Seismic sections also suggest no significant rise of Silurian carbonate rocks under the central uplift, but overlaying Lower Devonian siliciclastic rocks have gained thickness, probably due to increased porosity and fracturing. The reflection from the base of clayey dolomite of the Middle Devonian Narva Stage rises toward the centre from about 600 m depth in surroundings to couple hundred meter depth and these rocks have been found to outcrop in shallow drillings (50 to 100 m depth).

The central uplift is relatively large in diameter. It appears to be more than two km across at the foothill level. Pattern of reflections allow speculating that the central uplift has collapsed.

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**POSTER**
**Shock-darkening in ordinary chondrites: impact modelling**

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LL ordinary chondrites of the Chelyabinsk meteorites show characteristics of shock-darkening in the retrieved samples (Kohout *et al.*, 2014) associated with partial melting of iron metal and sulphides. Our aim is to come up with a model to map the pressure-temperature (p-T) conditions under which Fe-Ni metals and iron sulphide begin to melt, leaving olivine grains in a solid state. To do so we use the iSALE-2D shock physics code (Wünnemann *et al.*, 2006). Fig. 1 shows theoretical peak pressures, post-shock temperatures and melt distribution after a 5 km/s impact shock-wave, through a

sample made of forsterite and iron grains, from the top. These observations rely on strength models as well as chosen equations of state.

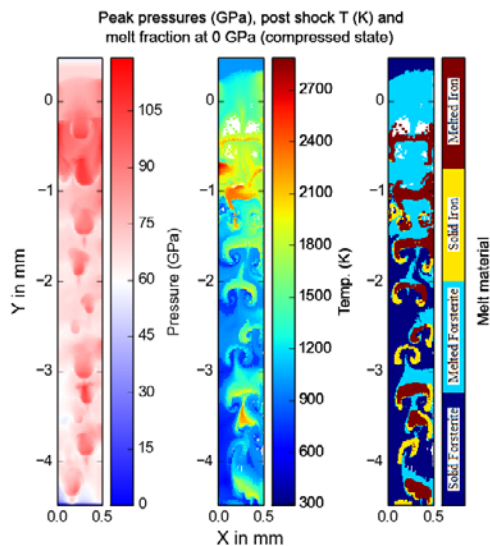


Figure 3: Section of a mesoscale simulation after a 5 km/s impact shock-wave on a sample made of forsterite with iron inclusions. Peak-shock pressures, post shock temperature and resulting melt fraction are shown.

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#### POSTER

### Reflectance spectra of meteorites and asteroids – new results and applications?

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Reflectance spectroscopy is a useful tool to search links between meteorites and their parent

asteroids. The variations of the spectra within a class, group or petrographic type can reflect surface conditions due to terrestrial or space weathering as well as due to metallic content or shock history of the bodies. We present a novel database of meteorite reflectance spectra (“MetRefl”) based on literature and on our own measurements. So far the database consists of 105 spectra representing most chondrite and achondrite classes and groups. The spectra have been parametrized into bandwidths, depths and band areas. The database is coupled with other data such as finds and falls to allow terrestrial weathering effect to be studied, petrophysical properties, and various “alteration” indices. To study the effect of a body’s shape (e.g., sphere, ellipsoid, “binary”, “potato”, etc.), size, surface roughness (smooth, knobby, rubble pile) and metallic content on its spectra, we measured different Bjurböle (L/LL4 chondrite) pieces from our collections. The most striking effect is the distinct flattening of the spectra with increasing darkening due to increased metallic content. Here the new meteorite reflectance database is presented with examples of its applications.

#### POSTER

### Geological overview of the Ritland impact structure

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The early/middle Cambrian impact at Ritland, SW Norway, excavated a simple crater, 2.7 km in diameter. The target was basement rocks with a cover of c 20 m thick clay in a shallow sea. There are excellent exposures of the crater walls and the infilling sediments, the rim and ejecta. Fieldwork, laboratory and modelling studies were conducted by the University in Oslo 2009-2012 with support from the Norwegian Research Council (e.g. References 1 to 3) Three zones of ejecta were identified with increasing distance from the crater rim. Zone 1 (to about 900 m) consists of a continuous sheet of brecciated but coherent basement gneiss, 20-30 m thick. Zone 2 (to 1200-1500 m) contains gneiss megablocks. In Zone 3 (up to 5 km) ejecta forms a 1 to 5 m thick layer of ejected gneiss fragments contained in a shale matrix. The ejecta bed rests on a sequence boundary between a silty shale



and an organic rich shale. Distribution of ejecta is asymmetric, indicating an impact direction at relatively low angle from the north. The oldest sediments infilling the crater overlie a thin bed of melt rocks. They are interpreted as avalanches and debris flows, which are succeeded by debris flows and density flows. The section is followed by shales deposited in a quiet marine environment after the sea re-entered the crater.

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#### POSTER

### Inverted Structure of Suevites at Bosumtwi Crater: Implications to Mixing of Outer Suevites

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The Bosumtwi impact crater in Ghana is one of the best-preserved large impact structures (Koeberl *et al.* 2007). Impactite lithologies at Bosumtwi include outer suevite deposits. The Bosumtwi suevite is found as either displaced blocks measuring up to several meters or as patches of suevitic material found N and SW of the crater (Boamah & Koeberl 2006).

In this contribution we study mineral and chemical composition of a suevite bed exposed at Sarpung Nkwanta, located north of the inner crater rim. The motivation of the study was to characterize the variation of the suevite composition in a 4.5 m thick section with emphasis on devitrification and alteration mineralogy.

Mineralogical analyses reveal gradual changes in lower part of the suevite deposit from a kaolinite-rich composition characteristic to clastic breccia below the suevite bed to a glass-rich suevite material largely devitrified to spinel-plagioclase and secondary cristobalite-smectite mineral phases. Kaoli-

nite phase is detritic, originating from the weathering crust of the target-rock and its content decreases upwards in the outcrop section. In contrast, the content of plagioclase, spinel and impact glass alteration products – smectite and cristobalite – increases. Similar trends occur in major oxide composition, which show decrease in Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub>, and corresponding increase in SiO<sub>2</sub> and CaO.

Compositional trends at the lower boundary of the suevite bed imply to a contact zone that in our opinion refers to mixing of underlying clastic breccia and overlying suevite deposits due to the horizontal movement of the suevite complex during its formation.

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#### POSTER

### On the Scaling of Small Impact Craters on the Moon

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Small projectiles derived from beyond the orbit of Mars interact dynamically with celestial bodies, so that they occasionally encounter the terrestrial planets of the inner Solar System. On Earth and in recent times, the vast majority of these small meteoroids burn up during their passage through the atmosphere. However, a smaller number of larger objects occasionally disrupt in the atmosphere causing blast wave damage (e.g., the Chelyabinsk meteor). For higher energies, these objects can reach the Earth's surface, leading to the formation of an impact crater structure (e.g., Barringer crater). A vital component of impact hazard assessment is the accurate estimation of the rate at which objects of different sizes collide with the investigated target object. The Moon is nearly the only object for which we can measure crater frequencies in a directly time-calibrated frame, thus, it is the ideal “witness plate” for constraining the flux of impactors in near-Earth space. The inactive, unprotected lunar surface is an excellent recorder of collisions with objects at all

sizes. Meter-sized objects create craters tens of meters in size that are occasionally detected in orbital images.

Previous approaches on calibrating the lunar impact flux history of small bodies has encountered several challenges, for examples: (1) the crater size–frequency distributions (CSFDs) on same aged units show apparently both different densities and slopes (e.g., craters on melt pools vs. ejecta blankets), (2) it is still controversial on whether or not most of the small crater population on the Moon is dominated by secondaries, and (3) large uncertainties exist in linking the size of the final crater with both seismic energy detected by in situ Apollo missions and impact illumination detected by Earth-based telescope. One of the critical threshold in solving the problem is that the scaling of small impact cratering ( $D < 1$  km) is not well known. The shape of CSFDs for young lunar surfaces (rayed craters) show variation due to e.g., target properties, secondary cratering and saturation, and undermines the determination of ages of geologically young features by crater counting. We will present preliminary results from our observation of numerical simulations.

## S13.6 Interactions between climate, erosion and tectonics

ORAL

### A field perspective on the role of creep processes for development of high altitude low relief surfaces

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The characteristic high altitude low relief surfaces (HALRs) of Southern Norway have a disputed origin. Current modelling experiments contradict the traditional 'paleic' interpretation of these surfaces, and point to recent development in a periglacial environment [1]. If this interpretation is correct, it provides an example of large-scale periglacial bedrock landscape development and further underlines the importance of cryo-conditioning for long term landscape development [2]. The periglacial 'buzzsaw' involves two aspects: sediment production by frost weathering, and sediment transport by periglacial mass wasting, i.e. solifluction. We assess the results from numerical landscape models by spatial and temporal upscaling from current periglacial solifluction landforms and process rates.

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ORAL

### Glacial striations from the Varangerian glaciation in South Norway

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Neoproterozoic glacial deposits ('tillites') referred to the Varangerian or Marinoan glaciations (Ediacaran or Cryogenian age) are in Scandinavia well known from South Norway, central western Sweden and northern Norway. In Finnmark, northern Norway, glacial striae on a quartzitic basement beneath the Smalfjord Formation at Bigganjargga were documented already by Reusch (1891). ESE-WNW oriented glacial striae also occur on polished granitic basement beneath the Moelv Fm diamictite east of Storsjøen in South Norway (Nystuen & Lamminen 2011). Glacial striations of basement rocks in Scandinavia have elsewhere been ascribed to Pleistocene glaciation.

Remapping of the Sub-Cambrian Penplain (SCP) in Hardangervidda, South Norway, has confirmed the striking topographic regularity of this surface (Rekstad 1903). The surface is locally involved in Caledonian deformation and is faulted and warped in places (Jarsve et al., 2014). A plethora of sediments of contrasting origin have been preserved in primary (erosional) and secondary (tectonic) pockets on top of crystalline basement rocks. The SCP is characterized by a mm-thick coating of Fe(OH), MnO(?) and locally Pb-minerals (Gabrielsen et al. 2015). Careful inspection in localities where the SCP is particularly well preserved reveals a set of W-erly directed striae of glacial origin. The striae are associated with chatter marks also indicating westerly transport, which is oblique to the Weichselian glacial transportation in the area (south to south south-east). Compared to Pleistocene glacial structures, striae and chatter marks are slightly rounded/weathered and covered by the Fe(OH)/MnO-mineralized coating. In one locality (Holværsvatn, eastern Hardangervidda) glacial striae are broken by a system of NE-SW-striking (N215-225E, down-to-the SE) mineralized microfaults. Postglacial mineralized fractures cutting glacial striae are not known from South Norway.

The observed glacial striae are therefore supposed to be of similar age as the striae beneath

the Moelv Fm at Storsjøen. This correlation indicates a widespread Neoproterozoic ice sheet of Baltica, likely corresponding to the 635 Ma Marinoan glaciation. The striations of the basement also put the age of the SCP back in time as a Sub-Ediacaran Peneplain.

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ORAL

### Tectonic controls of the eolian deposits in Chinese Loess Plateau — A preliminary hypothesis

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Previous studies show that the thick eolian dust deposits in the Chinese Loess Plateau (CLP) started to accumulate since the early Miocene or even late Oligocene and they are considered to provide the best terrestrial record of the onset of the Asian interior aridification and the evolution history of the Asian Monsoon. However, large variability in the basal ages of eolian deposits makes the eolian dust depositional history and the controlling dynamics controversial. We present that on the tectonic controls of the eolian dust deposition in the CLP by

connecting the two main uplift events of the Tibetan Plateau and the regional tectonic events with the eolian dust accumulation history. The regional tectonic events in the Ordos block (the basement of the CLP) during the late Cenozoic era are less recognized controlling mechanisms for the eolian dust accumulation by sculpturing the surface landscape. The stable tectonic environment of the Ordos block since the late Miocene might have been the main controlling factor enabling the wide deposition of eolian Red Clay after the ~8 Ma. Here we hypothesize that especially with the large-scale monsoon system and central Asian arid land existence since at least the early Miocene, the accumulation and preservation of eolian deposits within the CLP during the Miocene are actually directly controlled by the regional tectonic environment not as much by climatic factors.

ORAL

### Variations in the Provenance of the Late Neogene Red Clay in Northern China

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In northern China, late Neogene wind-blown sediments are comprised of two units: the Quaternary loess and the underlying late Miocene-Pliocene Red Clay deposits. Knowledge on the provenance of these sediments is fundamental in reconstructing wind patterns and the aridification history of Asian interior during the late Miocene and Pliocene. Notable progress has been made in understanding the origin and deposition of Quaternary loess. However the underlying Mio-Pliocene Red Clay sequence is lithologically more diverse system and no consensus has been reached on its provenance.

In this study, a combination of end member modelling on the bulk grain size distributions and U-Pb dating of single grain detrital zircons, together with the newly developed dust trajectory modelling, allows us to investigate the spatial-temporal variation in the provenance of Red Clay at the three

Red Clay sequences in the Chinese Loess Plateau (CLP). Our results show that while the majority of the detritus of the Red Clay in the CLP was mainly derived from the northern Tibetan Plateau, Red Clay in the northern CLP shows signatures of increased sources from the Central Asian Orogeny Belt. This spatial pattern is supported by the results from the backtrace trajectory modelling of the dominant dust transport pathways in the CLP for the late Miocene. It is also noted that around 3.6 Ma, Red Clay from the northern CLP shows increased contribution from the western China, possibly indicating an intensified aridity of NTP and Taklimakan desert due to the uplift of Tibetan Plateau in the late Pliocene. The Red Clay deposits in the two sites of southern CLP show analogous provenance but divergent end member grain size components, highlighting the significance of local pedogenic processes in altering the sediment composition.

ORAL

### Dust trajectory changes over the Loess Plateau due to regional mountain uplift

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Eolian deposits over the Loess Plateau, which can be traced back to more than 20 million years ago, are important archive for the past environmental changes in the Asian continent. Understanding the sources and transportation of these eolian deposits provides valuable information on the evolution of the Asian monsoon system and the aridification of its interior.

The Asian mountain uplift, in particular the Tibetan uplift since the Cenozoic, is widely known to have exerted a profound impact on the Asian environment. But how it left footprints in the dust deposits over the Loess Plateau remains highly speculative. In this study, we employ the trajectory model (LAGRANTO) driven by the output from our regional model COSMO-CLM experiments with different Asian orography to explore how the growth of different regional mountains in Asia affects the potential dust transport pathways to the Loess Plateau.

We select several localities over the Loess Plateau with well-preserved Red Clay and Loess sequence to perform backtrajectory calculation. The results are compared with the proxy records retrieved from these localities to see whether the changes in the dust transport pathways due to different mountain uplift may offer an explanation to the variation observed in the proxy records.

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POSTER

### First magnetostratigraphic time frame for the fossiliferous late Eocene – early Oligocene sequence at Ulantatal, Inner Mongolia, China

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Since the discovery of the mammalian fossils from the Ulantatal region, Inner Mongolia, in 1970, several expeditions have collected fossils from the low-relief exposures in this area. Although the area has produced a significant collection of vertebrate faunas, the stratigraphy, ages and depositional environments have remained poorly known or nearly non-existing. This study presents preliminary results of the stratigraphical investigations from the Ulantatal area and provides age estimations for the fossil-bearing horizons.

Our field investigations in Ulantatal have yielded over 5500 specimens including insectivores, lagomorphs, rodents, artiodactyles, perissodactyls, carnivores etc. The sequence produces fossils along much of the section with richest fossil occurrences in the lower half of the sequence. Lithologically, the sequence shows a rather uniform pattern characterized by interbedded reddish to yellowish brown claystones and siltstones with minor fine-grained sandstones.

Paleomagnetic samples were collected from several local sections 20–25 m thick and analyzed

using alternating field demagnetization. Samples yielded characteristic remanent magnetization carried by magnetite. Our magnetic section suggests a correlation in the magnetozones C15n through C9n with an age range of about 35–27 Ma and places the lowermost fossil site in Ulantatal to the latest Eocene.

This correlation places for the first time a precise temporal control on the Oligocene stratigraphy of the Ulantatal area and provides a unique area to investigate in detail the physical and biotic changes during a period of major global paleoenvironmental changes at the Eocene – Oligocene transition.

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**POSTER**

**Noble gas geochronology: new tools for constraining the landscape evolution of Scandinavia**

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Deep-weathered crystalline basement is relatively common in Scandinavia. Offshore blanketing by Mesozoic sedimentary sequences provides minimum ages for these potential reservoir rocks. Onshore, the occasional occurrence of kaolinite suggests formation in a warmer, Cenozoic or older climate. On-shore western Norway, saprolites appear to be preserved mainly in fracture systems. Therefore, constraining saprolite formation and landscape evolution goes hand in hand with constraining the brittle deformation history of the crystalline basement.

Chemical weathering and faulting lead to the break-down and transformation of rock-forming minerals into various clays, including illite, whose neoformation can be precisely dated using the K-Ar system. However, altered rock typically hosts a range of metastable K-bearing minerals such as feldspar and amphibole, the relative concentrations of which decrease towards smaller grainsizes (<0.4 and <0.1  $\mu\text{m}$ ).

At NGU, clay-bearing samples are disaggregated using freeze-thaw cycles in a cryostatic bath, then suspended in de-ionized water. Illite is subsequently isolated from other K-bearing phases using continuous flow centrifugation, and particle

sizes down to 0.014  $\mu\text{m}$  are monitored with LPS-PIDS. Dry clay size fractions are degassed in a specially engineered ultra-high vacuum system, and argon isotopic concentrations are quantitatively determined using a new IsotopX NGX multicollector noble gas mass spectrometer using isotope dilution. Accurate determinations of the concentrations of K and other cations are made using ICP-OES, and clay mineralogy is quantitatively determined using XRD.

The IsotopX NGX noble gas mass spectrometer was commissioned in November 2015 to complement the existing <sup>40</sup>Ar/<sup>39</sup>Ar facility at NGU. The high mass resolution of the NGX (>600) permits accurate determinations of stable cosmogenic nuclides <sup>3</sup>He, <sup>21</sup>Ne and <sup>38</sup>Ar, and future applications may include dating of paleosurfaces, fault scarps and landslides. Unlike cosmogenic radionuclide <sup>10</sup>Be, the scope of cosmogenic noble gases extends well beyond the Quaternary.

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**POSTER**

**A fluvial facies in the Mesoproterozoic Dala sandstone. Preliminary results from the Moberget quarry, west-central Sweden.**

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The Mesoproterozoic Dala sandstone is an approximately 1300 m thick clastic unit of red continental deposits ranging from conglomerates to shale (Ripa et al. 2012). In Norway this unit is referred to Trysil sandstone. Despite its wide distribution in Sweden (>6000 km<sup>2</sup>), there are few vertical outcrops restricting the possibility to describe and interpret existing depositional environments. The lack of fossils disables correlation throughout the sequence.

The Dala sandstone has previously been interpreted as a primarily aeolian deposit with ephemeral lakes (e.g. Pulvertaft 1985). Evidence is based on a combination of large cross-bedded sand-dunes and periodically wet interdune areas illustrated by ripples, and desiccation cracks. A wave-dominated delta facies has been interpreted from Fulufjället (Ripa et al. 2012) and a supposedly fluvial facies from Fjätafallen was mentioned by Pulvertaft (1985), however, it was not described in detail. The

study presented herein provides the best evidence, so far, that the Dala sandstone partially was deposited in a fluvial environment.

The Stora Moberget quarry, close to the Norwegian border represents a 9 m fluvial sequence with sediments ranging from gravel to mudstone. The following facies have been observed; (1) high to low angle trough cross bedding interpreted as channel fills, 3D dunes, scour fills and antidunes; (2) planar crossbeds interpreted as 2D dunes; (3) horizontal lamination interpreted as planar beds; (4) flaser, lenticular and wavy lamination and desiccation cracks interpreted as being deposited in over-bank areas, abandoned channels or as waning flood deposits. These facies can be grouped into a fluvial facies association and the most suitable depositional environment is a braided river environment.

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## S13.7 Supercontinents through time

ORAL

### The inner core nucleation of the Earth and its paleogeographic implications

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For the age of the onset of the Earth's inner core, widely varying estimates have been presented, due to varying quality of data and poor knowledge of geothermal parameters. The advent of new paleointensity data, however, allows a robust investigation on the topic.

To determine the behaviour of the Earth's dipole moment during the Precambrian, our study applies 320 entries from the PINT paleointensity database, with newly assigned  $Q_{PI}$  data reliability values. Based on the availability of data, we have divided paleointensity values into timeslots of 3500-2400 Ma, 2400-1400 Ma and 1300-500 Ma. The mean dipole moment obtained from the early and middle intervals is smaller, and statistically distinct from that of the late interval, thus implying an abrupt increase of field intensity in late Mesoproterozoic when the chemical convection began to dominate the dynamo process which was previously run by vigorous thermal convection. However, the field of 1300-500 Ma appears rather similar to that of the last 300 Ma, indicating that the chemical dynamo process still continues.

Our analysis suggests that the Earth's inner core was formed at 1500-1000 Ma coincide with the time when the Nuna supercontinent disintegrated. In addition, the global paleomagnetic record of 1500-1200 Ma was characterized by an anomalously large proportion of low inclinations potentially associated with the presence of zonal multipolar geomagnetic fields between periods in which the Geocentric Axial Dipole (GAD) model appears valid. Therefore, a readjustment of paleogeographic models may be

necessary in this period, which is likely to be associated with the shift of the long term geomagnetic field from a stable to a less stable state as observed in the paleosecular variation data.

ORAL

### Unknown details of Palaeoproterozoic evolution of the Karelian Craton: new U-Pb and geochemical data for mafic dykes

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New U-Pb (ID TIMS, baddeleyite, SIMS, zircon), geochemical and Sr-Nd isotopic data for the mafic dyke swarms in the Karelian Craton (Russia) have been obtained. These data give an additional information to the mafic igneous events sequence described in [1] and [2].

The U-Pb data for ca. 2.45 Ga mafic dykes demonstrate that a wide range of both low-Ti and high-Ti rocks were formed during ca. 10-15 M.y. period, and probably indicate a similarity between Palaeoproterozoic and Phanerozoic plume events. New data for ca. 2.4-2.1 Ga period reveal existence of several pulses of mafic magmatism related to fragmentation of the Neoproterozoic continental crust followed by continental breakup at ca. 2.13 Ga. Data for the 2.1-1.95 Ga period indicate a wide spread of the ca. 1.98 Ga mafic sills and dykes in the central part of the Craton, and previously unknown ca. 1.956 Ga mafic sills in the Onega structure.

The recognized magmatic events, "recorded" in the Neoproterozoic Karelian craton, give insights into mantle melting processes during divergent stage of an Early Precambrian supercontinental cycle since final assemblage of Kenorland to the beginning of Columbia (Nuna) amalgamation.

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ORAL

### Paleomagnetism of the Keuruu dyke swarm with implications for Nuna supercontinent

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We present a new paleomagnetic pole and isotope ages for the late Paleoproterozoic (Svecofenian) diabase dykes from Keuruu, Central Finland. The paleomagnetic results reveal a dual-polarity remanent magnetization with asymmetry, i.e. the mean directions are not antiparallel at 95% confidence level, and do not pass the reversal test (McFadden & McElhinny 1990). This is explained mainly by an unremoved secondary component contaminating both normal (N) and reversed (R) vectors. An R polarity dyke shows a U-Pb age of 1870±9 Ma, and zircons from an N polarity dyke show a Pb-Pb age of 1868±7 Ma. The primary nature of magnetisation in R polarity dykes is supported by a positive baked contact test (Buchan, 2013). As the N polarity dykes and the unbaked host rocks is of similar age (Huhma, 1986), and show similar paleomagnetic directions, we illustrate the baking by means of remanent magnetisation intensity decay behaviour. By combining the dual polarity means, we obtained a new key pole for Baltica at  $Plat = 45.4^\circ N$ ,  $Plon = 230.9^\circ E$ ,  $A95 = 5.5^\circ$ . Our data positions Baltica at low latitudes ( $19^\circ$ ), and aligns with Laurentia in a way that would easily proceed into the 1.8-1.2 Ga NENA (North Europe–North America) configuration (e.g. Salminen et al., 2014) of the Nuna supercontinent.

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ORAL

### Profile sampling of the host rock of rapakivi batholiths – A novel way to map Precambrian polarity reversals

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Recent analyses of the inclination distribution, paleosecular variation and intensity of the Precambrian magnetic field, although showing long term trends, (Veikkolainen et al., 2014a, b; Biggin et al. 2015), indicates that the field resembles much of the present field and is more dipole like than previously thought. However, the reversal rate is clearly much lower during the Precambrian than during the Phanerozoic&Paleozoic eras. One reason for this is that the Precambrian rate estimates are based on magnetostratigraphic sequences of a few sedimentary units only, since there are no ocean floor anomaly data and the APWP's have age gaps which hampers them to be used for reversal rate estimation. Here we present a novel idea to improve the reversal rate determination during Precambrian. Our study is motivated by the observation that we found several reversals in a contact aureole of the Åland rapakivi massif (ca. 1580 Ma), presumably recording successive reversals during the propagation of the heating/cooling fronts away from the contact.

Our new technique combines paleomagnetic measurements and thermal modelling of the heat effect of rapakivi batholite on the host rock, notably along a profile crossing the contact, the heated and partially heated zones up to the unheated host rock at distant areas. We use 2D cartesian and axisymmetric cylindrical models of the heat conduction equation to calculate the maximum temperatures reached at successive points along the profile. These and the cooling rates are used to estimate the remanence blocking temperatures with the relaxation theory of Pullaiah et al. (1975). The model applies the heat conduction code by Jöeleht et al. (2005), which takes into account the latent heat, water circulation, erosional level, as well as the batholite's dimensions (width, depth). Preliminary modelling results from the profile of Åland rapakivi batholite to granodioritic host rock are presented in terms of observed paleomagnetic reversals.

ORAL

### From Nuna to Rodinia: Stenian-Tonian paleogeography

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Stenian – Tonian (~1200-850 Ma) times are generally associated with a significant part of supercontinental cycle: breakup of Nuna followed by assembly of Rodinia. The global paleogeography of this time interval is poorly understood because of a deficit of reliable geochronological, paleomagnetic and other datasets. Consequently there is a variety of opinions about paleogeographic locations of many Precambrian cratons and about their kinematics. Differences in lengths and shapes of late Mesoproterozoic Apparent Polar Wander Paths of several continents suggests that a large supercontinent did not exist between ~1300 and 1000 Ma. Almost every new well-dated paleomagnetic pole, or re-dated old paleopole, or discovered LIP event causes significant reconsideration of existing paleogeographic models. Many interesting results have been reported in last few years from Baltica, India, Siberia, North China, Australia, Congo-São Francisco and other building blocks of Nuna and Rodinia. Recent testings of some paleogeographic reconstructions and re-interpretation of orogenic histories (e.g. Grenville and Sveconorwegian) also require revisiting of Late Mesoproterozoic – Early Neoproterozoic paleogeography. This study summarises these new data and new ideas. Proposed updated positions of some continents are now better justified. Most changes are associated with North China and Congo-São Francisco cratons. Kinematics of the transitional period between the breakup of Nuna and the assembly of Rodinia is now better understood and better constrained, but some aspects are still controversial.

ORAL

### Did the Grenville – Sveconorwegian belt go north?

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The Grenville and Sveconorwegian orogenic belts in SE Laurentia and SW Baltica, respectively, together with the Susnas belt in SW Amazonia, formed during the late Mesoproterozoic to early Neoproterozoic assembly of the supercontinent Rodinia. In the ‘Samba’ model of Johansson (2009, 2014), Baltica and Amazonia, together with West Africa, formed a coherent unit already prior to this collision, which rotated clockwise relative to Laurentia before colliding with its present-day southeast margin, thereby creating a wedge-shaped combined Grenville – Sveconorwegian – Susnas orogenic belt.

According to this model, the Grenville – Sveconorwegian belt would close northwards in an area between SW Scandinavia and eastern Labrador, that may also involve the northern British Isles. However, Lorentz et al. (2012) and Gee et al. (2015) have proposed a northerly branch of the Grenville – Sveconorwegian orogen extending between Scandinavia and eastern Greenland into the High Arctic, paralleling the future Caledonian orogen, based on the presence of detrital zircons with Grenvillian and older Mesoproterozoic ages in many Neoproterozoic sedimentary sequences in these areas, as well as granites of late Grenville age (900 – 1000 Ma) within the Caledonides of the Arctic areas.

However, a northerly branch of the Grenville – Sveconorwegian belt between Scandinavia and Greenland, also including older Labradorian-Pinwarian or Gothian-Telemarkian rock units, would require an ocean with active margins separating Laurentia and Baltica throughout the Mesoproterozoic, thereby destroying the generally accepted NENA (Northern Europe – North America; Gower et al. 1990) connection, and necessitating a drastic revision of the configuration of the Columbia (Nuna) supercontinent. Alternatively, if this ocean only existed for a shorter period prior to the Grenville – Sveconorwegian orogeny, one would either see a purely Grenvillian (900 – 1200 Ma) detrital zircon signature in the Neoproterozoic sequences, or a Grenville signature mixed with Archean and Paleoproterozoic zircons, but not the

dominantly Mesoproterozoic (900 – 1800 Ma) signatures actually seen.

Instead, a wedge-shaped geometry of the Grenville – Sveconorwegian belt is preferred, with an ocean opening between Greenland and Baltica in the late Mesoproterozoic due to the clockwise rotation of Baltica, followed by geographically and geodynamically separate early Neoproterozoic subduction-related magmatism along the part of the outer margin of Rodinia bordering that ocean, as proposed by Cawood et al. (2010), and transport of sediments from the eroding Grenville – Sveconorwegian mountain belt across the cratonic foreland into this ocean or into local rift-related basins.

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ORAL

### Exploring the hidden Rodinia: crustal xenoliths of Vestfjella, Dronning Maud Land, Antarctica

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Lamproite-hosted crustal xenoliths from Vestfjella, Dronning Maud Land, Antarctica, provide unique insights into the Mesoproterozoic crustal evolution of a poorly exposed region at the former juncture of Antarctica, southern Africa, and the Falkland plateau. The lithologically diverse suite of xenoliths is dominated by high-grade metamorphic rock types (Romu et al., 2008). On the basis of mineralogy and geochemistry, the metagabbroids and metapelites represent granulite-facies samples from lower to middle crustal levels (6-19 kbar), whereas the metagranitoids were probably derived from the upper crust. Thermobarometric studies record consistently high temperatures of 650-1100 °C for metagabbroids, 800 °C for metapelites, and 750-800 °C for metagranitoids. Our U-Pb (SHRIMP,

SIMS) zircon ages indicate emplacement of syn- to post-orogenic silicic magmas in a rapid succession at ca. 1.0–1.1 Ga during Rodinia assembly. The oldest ages of ca. 1.3 Ga from zircon cores likely correspond to formation of juvenile crust in a volcanic arc setting. Sm-Nd isotopic data on the metagabbroids are compatible with generation of mafic magmas during this period. A heterogeneous zircon population from a quartz-diorite yielded ca. 0.5-1.3 Ga concordant ages. We interpret these ages as crystallisation ages of xenocrystic detrital grains originally derived from diverse magmatic rock types associated with Rodinia breakup and amalgamation of Pangea. Importantly, Hf isotopic data on zircons representing different xenolith types invariably indicate ca. 1.3–1.4 Ga juvenile sources which suggests that crust formation during the 1.0–1.1 Ga orogeny and subsequent magmatic events in the Vestfjella sector of Rodinia was insignificant.

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ORAL

### Paleogeographic evolution of the late Neoproterozoic and early Phanerozoic with new paleomagnetic constraints from West African Craton

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The paleogeographic evolution of the late Neoproterozoic and early Phanerozoic is dominated by the dispersion of Rodinia and the assembly of Gondwana. The timing of these two episodes is still highly debated, partly due to discordant paleomagnetic data which imply rapid polar wander between 600 and 550Ma in several continents. In order to better constrain the paleogeography for this epoch, we bring new paleomagnetic data on volcanic series

from the West African Craton (WAC), which is a key block to understand the evolution of these two supercontinents. We conducted a paleomagnetic study on pyroclastic and lava flows dated by SHRIMP U-Pb method on zircon from the groups of Ouarzazate (upper Ediacaran) and Taroudannt (lower Cambrian) in the Anti-Atlas (Morocco). Three components of magnetization were thermally isolated, mainly carried by minerals of the titanohematite family, magnetite contributing sometimes to the magnetization. The group A, of shallow inclination and south-east declination is mainly observed in the Ouarzazate group. This direction is interpreted as a Permo-Carboniferous remagnetization. The B and C components are observed at two distinct stratigraphic levels: the former at the base of the Ouarzazate group (572-570Ma) and the latter at intermediate and top levels of the Ouarzazate group and in the Taroudannt group (565-530Ma). Both consist of dual-polarity directions supported by positive fold tests and may represent the characteristic magnetizations. The calculated poles are separated by around 100° which imply rapid polar wander between 615 and 565Ma in the apparent polar wander path (APWP) of WAC similar to what is observed in data from other continents. We will discuss this global feature and address the existence of True Polar Wander episodes or perturbations of the Earth magnetic field during the Ediacaran. The tectonic implications will be examined as well.

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**POSTER**
**Geomagnetic Field at the Mesoproterozoic - Geocentric Axial Dipole?**

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New Mesoproterozoic paleomagnetic data have been produced for Baltica from Subjotnian mafic dyke swarms in Finland (e.g. Salminen et al., 2014; 2015). The data are of high quality, with well-defined U-Pb ages, showing two polarities of remanence. These data all show a fairly large asymmetry: i.e. the mean directions are not antiparallel at 95% confidence level and do not pass the reversal test (McFadden & McElhinny 1990). The

following explanations for the asymmetry are discussed: (1) contamination of the dipole field by a permanent non-dipole field (e.g. Veikkolainen et al., 2014a,b); (2) an unremoved secondary component; (3) age difference between dykes showing reversed (R) and normal (N) polarity coupled with continental drift (Swanson-Hysell et al., 2014); (4) relative crustal tilting between R- and N-polarity "dominated" blocks (Halls & Shaw 1988).

(1) Inclination and reversal asymmetry analyses of global Precambrian data indicate that the Geocentric Axial Model of the geomagnetic field is valid during the Precambrian. (2) Secondary component vector addition to a probable, antiparallel primary component give rise to N and R components similar to the observed N and R components. Furthermore, the N-polarity data have a wider dispersion of inclinations than R-polarity. Additional support for component mixing comes from the secondary component distribution, which is streaked in part toward the N-polarity direction. (3) A small but significant age difference between N and R magnetized dykes could explain the asymmetry, but the actual age span for the Subjotnian dykes for Baltica awaits further precise datings. (4) Majority of the dips of the R- and N-polarity dykes are vertical to subvertical and and so do not support the different tilting of the blocks.

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**POSTER**
**Testing the core of the Proterozoic Supercontinent Nuna**

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To understand processes occurring from the planetary interior to the surface environment, a robust paleogeography of tectonic plates is important. The development of models of pre-Rodanian

Paleo-Mesoproterozoic Nuna supercontinent has been slow (Evans 2013), but recently new high quality paleomagnetic and U-Pb data from mafic dykes have been produced allowing new Nuna reconstructions. To reconstruct complete Nuna and to study its life cycle it is vital to reconstruct its core.

There is a general agreement that a tectonic core of the Nuna includes geologically and paleomagnetically viable connection between Northern Europe and North America (NENA), where Baltica is in “upside-down” position relative to Laurentia (e.g. Gower et al. 1990). However, contradicting reconstructions have been proposed (e.g. Halls et al. 2011). Here we show that recent data for Baltica supports the NENA connection.

Other Nuna core continents include Australia and Siberia (e.g. Evans 2013). Commonly Australia is shown in geologically and paleomagnetically valid proto-SWEAT juxtaposition with western Laurentia allowing later standard Rodinia models. Siberia has been reconstructed either in tight fit with NENA (e.g. Wu et al. 2005) or ca. 1500 km away from it (Pisarevsky et al. 2008). Based on coeval 1.5 Ga magmatism on Siberia and Congo/São Francisco (C/SF) a direct link between them has been proposed (e.g. Ernst et al. 2013). We test with new 1.5 Ga paleomagnetic data for C/SF its proposed connection with Siberia and NENA. Finally we will show our tentative Nuna reconstruction including also Amazonia, West Africa, Kalahari, India, North China and South China.

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## S13.8 Volcanology

### KEYNOTE

#### The role of volatiles in the formation of basaltic to kimberlitic maar-diatreme volcanoes, and its wider implications

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Maar-diatreme volcanoes are one of the most common volcanic landforms on Earth and the associated magmas span in composition from rhyolites via basalts, to the alkaline series (nephelinites, melilitites, kamafugites) and kimberlites. Traditionally, maar-diatreme volcanism has been attributed to interactions with a relatively shallow external water source (i.e., phreatomagmatism) producing fine-grained juvenile deposits mixed with a high degree of country rock. In recent years, new research has showed that there are significant differences between basaltic maar-diatreme volcanoes and those of the alkaline series (as well as the kimberlites). This difference can be related to the volatile content of the magmas involved. Generally, low polymerization in the melt structure allows for more CO<sub>2</sub> to be dissolved under pressure. For example, melilititic magmas can hold up to 18 wt.% CO<sub>2</sub> dissolved at 2 GPa pressure (Brooker et al., 2001). These magmas also rise (decompress) rapidly upon ascent (8–36 ms<sup>-1</sup>; Mattsson, 2012), which leads to violent exsolution of volatiles and fracturing/incorporation of country rock during ascent. Thus, although basalts and the alkaline magma series produces similar landforms on the surface of the Earth, the mechanisms behind are fundamentally different. This early exsolution of CO<sub>2</sub> at depth during decompression, and incorporation of mantle material, may also explain why some kimberlites are diamondiferous whereas others are not. However, the near vent deposits of most kimberlitic maar-diatreme volcanoes are poorly preserved and altered. Therefore, more focused studies of the better-preserved alkaline magma series (e.g., melilitites) may provide important information on the emplacement mechanisms of kimberlites.

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### ORAL

#### Episodic propagation of the 2014 Bárðarbunga-Holuhraun dyke intrusion, Iceland

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Volcanic eruptions in rift zones are frequently preceded by lateral migration of a melt-filled dyke, accompanied by abundant seismicity. The 2014 Bárðarbunga-Holuhraun dyke in the northern rift zone of Iceland propagated 46 km laterally, at 5–7 km depth b.s.l. over 13 days prior to erupting. More than 30,000 earthquakes (local magnitudes 1–4) were recorded by a local network of 76 seismic stations. Earthquakes migrated south-eastwards out of the caldera of the Bárðarbunga volcano, starting 16 August 2014, before turning north-eastwards. A 4-hour eruption at Holuhraun began 29 August, followed by the main eruption on 31 August. It continued until 27 February 2015, erupting 1.6 km<sup>3</sup> of lava across 84.1 km<sup>2</sup>.

An advancing earthquake swarm marks the leading edge of a propagating dyke. New segments opened by rapid advance of the dyke tip at 0.4–2.0 km/h, separated by stalled periods up to 81 hours. Seismicity was confined to the front of the propagating dyke, suggesting aseismic flow of magma once a pathway has formed and remains open.

Constructed fault plane solutions exhibit focal mechanisms with one nodal plane sub-parallel to the dyke trend, interpreted as the fault plane. The dominant left-lateral polarity can be explained by obliquity of the normal to the fault planes with respect to the regional extension direction of 106°. There is a surprising lack of normal faulting, even though this is an extensional rift setting.

The observations of strike-slip faulting at the dyke tip do not agree with theoretical models postulating failure ahead of the dyke at angles of 30–60° with the propagation direction. Presumably this is because the dyke is re-using existing dyke-parallel fabric in a tensile environment with high fluid pressures, rather than breaking intact homogeneous rock.

ORAL

### Volcano-tectonic interplay at the Askja volcanic system, Iceland: Finite element modeling constrained by geodetic measurements

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The Askja volcanic system, Iceland is located at the divergent plate boundary, the Northern Volcanic Zone, between the North American and Eurasian plates. A 1.2 km radial levelling line allows for investigation of subsidence or uplift of the caldera, by differencing the end points. Since 1984 the differences have decreased exponentially from -12.6 mm to 5.4 mm in 2015. Several processes are at work at Askja, 1) full plate spreading with 18.4±1.5 mm/yr; 2) a general uplift mostly attributed to glacial isostatic adjustment (GIA) of ~ 9-12 mm/yr; and 3) contraction and magma migration from two magma chambers. The maximum subsidence observed between 2008 and 2013 in the centre of the caldera at the station MASK (Mid Askja) is 11.9±0.1 mm/yr. Correcting this for the GIA uplift, the subsidence is ~24 mm/yr caused by volcano-tectonic deformation processes of Askja. To investigate the volcano-tectonic interplay of deformation processes in the Askja region, we construct a 3D finite element model of the volcanic system, including volcano deformation sources (two magma chambers) and plate spreading.

ORAL

### <sup>40</sup>Ar/<sup>39</sup>Ar dating basaltic melt segregations in Reykjanes Peninsula, SW Iceland

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The Reykjanes Peninsula in southwest Iceland is a subaerial part of Mid-Atlantic Ridge. Its surface geology is dominated by móberg ridges and pāhoehoe lavas erupted during the Brunhes normal polarity chron. Ages of the postglacial extrusives (age < 13 ka) are reasonably well-constrained. However, despite their regional importance, the chronology of the interglacial lavas (13–781 ka) is effectively unknown. These basaltic lavas have remained undated as they are too old for radiocarbon dating and their depleted character with low K-content makes them challenging for K–Ar, <sup>40</sup>Ar/<sup>39</sup>Ar and U–Pb geochronometers.

In order to circumvent the problem of low-K, we sampled incompatible element-enriched basaltic melt segregation from the interglacial lavas for dating by <sup>40</sup>Ar/<sup>39</sup>Ar method. Basaltic melt segregations are cylindrical or sheetlike vesicular formations present in the lava core of pāhoehoe flow lobes. They are formed by closed system fractional crystallization of the host lava and preferentially preserved during the period between flow stagnation and solidification. These melt segregations are enriched in K, and other incompatible elements, by a factor of 1.6–4.

Basaltic melt segregations and their host lavas were sampled from four locations on the Reykjanes peninsula. Geochemical work indicates that the potassium in the samples is primarily located in interstitial glass and in the outer most rind of feldspar. At the time of writing, interpretation of the <sup>40</sup>Ar/<sup>39</sup>Ar age data is ongoing, but initial results reveal low radiogenic Ar values, and sub-atmospheric initial <sup>40</sup>Ar/<sup>36</sup>Ar ratios. One sample produced a conclusive plateau age: a segregation from the town of Garðabær with a preliminary age of 327±51 ka (1σ). Despite the K-enrichment in segregations, ages cannot be determined for the other samples, possibly

because of their young age (< 100 ka?). However, one positive result gives us hope that sampling melt segregations for dating young pāhoehoe lavas can be advantageous.

## ORAL

### Multi-disciplinary approaches to studying volcanic plumbing systems – a Nordic case study

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Magma transport and storage in volcanically active regions involves a multitude of complexly interacting physical and chemical processes. The study of magma channels and reservoirs, so-called volcanic plumbing systems, is therefore intrinsically multidisciplinary, commonly involving e.g. igneous petrology, volcano seismology and geodesy, and volcano-tectonics. Unfortunately, research efforts traditionally remain within disciplinary boundaries, which has thus far hindered a more holistic understanding of processes in active volcanoes.

In order to overcome these traditional boundaries and facilitate multi-disciplinary research, it is essential to be aware of the capabilities and limitations of individual approaches. Here we give an overview of the most common methods in volcanic plumbing system research and discuss how these can be combined to complement each other, using the 2014-2015 Holuhraun eruption on Iceland as an example. We also highlight the potential for closer Nordic collaboration in the future.

The recent fissure eruption was well monitored with geodetic and geophysical methods that indicated shallow magma storage beneath, and lateral magma transport from, the neighbouring Bárðarbunga volcano (Riel et al., 2015; Sigmundsson et al., 2015). We investigated the link between Bardarbunga and Holuhraun through mineral textures, thermobarometry, and major-, trace element-, and oxygen isotope geochemistry of the Holuhraun lavas. Combined with existing geophysical data, our results support a model of initial vertical magma ascent within the Bárðarbunga plumbing system followed by lateral transport of aggregated magma batches to the Holuhraun eruption site.

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## POSTER

### Explosive volcanism in Iceland between 8000 and 60.000 years as expressed by tephra layer frequency in marine sediments.

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Volcanism is a major force in shaping the Earth Environment. Understanding volcanic processes is therefore an important goal, which can benefit significantly from a thorough knowledge of past behavior of volcanoes and the course of volcanic events.

In the project presented here the aim is to unravel the activity of volcanic systems in Iceland between 8000-60.000 years as expressed by tephra layers in five cores from high-resolution marine sediments on the shelf and slope fans north and northeast of Iceland. The cores used in the study are; core MD99 2271, MD99 2272, MD99 2275 collected in 1999 and cores IS-4C and IS-1C collected in 2012.

Here we present preliminary results from three cores MD99 2271, MD99 2272 and MD99-2275. In core MD99-2271 roughly 60 tephra layers, spanning the Holocene and Late Glacial, have been identified and traced to a source volcanic system. In core MD99-2275 about 60 tephra layers from early Holocene and Late Glacial have been identified and chemically analyzed. However further high-resolution studies between 8000-15.000 years remain to be carried out. Over 200 potential tephra layers have been identified in core MD99 2272, which spans approx. 60.000 years. Thereof are 20 layers that have been analyzed for geochemistry. Remaining layers await further investigation i.e. acquiring chemical composition, source volcano and



confirming pristineness. Investigation of cores IS-1C and -4C is in progress.

## POSTER

### Tephra in the effusive Bárðarbunga 2014-2015 eruption, Iceland.

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On the 29<sup>th</sup> of August 2014 an effusive fissure eruption began north of Vatnajökull glacier, Iceland. The activity paused on the 30<sup>th</sup> of August and then continued for the next six months, ending on the 27<sup>th</sup> of February 2015. Chemical composition of erupted products was homogeneous and confirms a source in the Bárðarbunga volcanic system.

Tephra was produced throughout the eruption, although the tephra fall was not substantial. It was most significant in proximity of the eruption vents. However, tephra was detected as far as 40 km from vents and direct tephra fall was observed in up to 14 km distance. At these distances peles' hairs, a tephra type that is fine and light enough to be transported tens of km, was observed. Closer to the eruption vents the longest measured peles' hair was 22 cm. At 20 km distance from source, the longest measured peles' hair was 8 cm. On the 17<sup>th</sup> of September 2014 a tumble-weed like transport of peles' hairs was observed. This is related to more vigorous gas flow (i.e. due to narrowing of conduit) forming longer peles' hairs than previously, that curled up and formed bundles that saltated over the sand during post depositional transport. These bundles were readily stopped in water ponds and were well preserved within the ponds in the vicinity of the eruption site.

Other types of tephra grains produced during the eruption were fine peles' tears (<0.5 cm), achneliths and golden pumice, up to 10 cm. Close to the vents some scoria was observed. All these grain types are formed in a gas charged high velocity fire fountains, as can be expected during a Hawaiian to Strombolian eruption. Vesicularity and density were measured and ranged from 82-93%, with an average of 89.5% and density ranges from 0.19-0.52 g/cm<sup>3</sup> with an average of 0.29 g/cm<sup>3</sup>.

## POSTER

### Origin of the Lake Natron Footprint tuff, northern Tanzania

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Here we present the results of a multidisciplinary study in order to constrain the provenance and the age of the Footprint tuff at Lake Natron in northern Tanzania. We combine geochemistry, mineral chemistry and sedimentology with geophysics in order to ensure a correct interpretation of the environment that has a significant anthropological interest as it preserves multiple tracks of people (Homonids) and animals (Bovids) of disputed age.

Based on the geochemical, mineralogical and magnetic data we collected from this site, we can deduce that the nephelinitic footprint-bearing horizon was deposited during one big eruption originating from the Oldoinyo Lengai volcano. The footprint-bearing horizon has been slightly reworked by water (ephemeral streams and/or fluctuations in the lake level) as indicated by the Anisotropy of Magnetic Susceptibility in the volcanoclastic sediments. The material that comprises the upper horizon, which covers the footprints, was deposited as windblown sediments from the Lake Natron – Engaruka Monogenetic Volcanic Field (i.e., melilititic in composition). Based on the petrology/mineral chemistry in combination with field observations and a compilation of climatological data from the region we further conclude that the age of the Footprint tuff is most likely less than 11 ka old.

## S15.1 Applied 3D and 4D modelling in geosciences

### KEYNOTE

#### The significance of recognizing the structural setting within the context of geological 3D-modelling

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Defining a correct reference orientation or a set of reference structures is nearly always essential for a successful structural geological investigation. In 3D-modelling the requirements are one step higher as the attitude of the reference, or the 3D-network of the reference structures must be known. Selection of the reference or references may be quite straightforward in areas characterized by good exposure and limited tectonic overprint. In contrast, the crystalline Precambrian domains are characteristically structurally complex and poorly-outcropping.

For these reasons, understanding the structural setting of the area of interest, further developed into an evolutionary model or a set of justified hypotheses, and finally into structural references will be required at an early stage of a 3D-modelling project.

This presentation provides a set of examples where understanding the regional-scale structural evolution has proven valuable in understanding the locally developed structural geometries. The cases from the Skellefte District, Sweden, illustrate the role of both the arrangement of early-orogenic faults and the subsequent transpressional overprint in contributing to the present-day attitudes and shapes of the ore deposits. A case from the Peräpohja Belt, Finland, shows how the basement structures controlled the deposition and deformation of the overlying strata. Finally, recognition of the termination of the strike-slip Somero fault in SW Finland is used to understand the topography of the bedrock surface and how it affected glacial erosional and depositional processes.

### ORAL

#### 2D and 3D Resistivity Models From Magnetotelluric Measurements North East of Kiruna, Sweden

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In the frame of Barents mapping project the Geological Survey of Sweden (SGU) carried out magnetotelluric (MT) measurements at two areas in northern Norrbotten during summer of 2014. The survey objective was to model the variation of electrical resistivity of the upper crustal structures. The upper crust around Kiruna is largely composed of various supracrustal units dominated by metabasalts, felsic metavolcanic and clastic metasedimentary rocks. These rocks rest on an Archean metagranitoid complex. All of these units have been intruded by plutonic rocks, and to variable degrees are folded, sheared and metamorphosed, during the Svecofennian orogeny.

The collected MT signals cover a wide frequency band from  $10^{-2}$  to 300 Hz. 2D and 3D modeling of the collected data imaged the variation of electrical resistivity down to a depth of about 30 km. The resistivity models resolved three distinct highly resistive structures that most probably represent crystalline rocks such as granitic and gabbroic intrusions and volcanic units. The resistive features at some places reach a depth of about 20 km. The resistivity models also show low resistivity zones at various depths and locations almost in the entire study area. An extremely low resistivity feature is resolved about 10 km west of Vittangi village with known graphite mineralization. The low resistivity feature deeps towards the WSW.

The 2D resistivity model along the profile in the second area shows a highly conductive feature ( $\sim 1$  ohmm) that reaches depths greater than 5 km. The anomaly can be caused by either the graphite layer within the metasedimentary rocks crossed by the profile or highly conductive zones of sulfide mineralizations reported in the other parts of the area. SGU has recently funded airborne VTEM (Versatile time domain electromagnetic) measurements. The VTEM data close to this zone have detected

elongated very low resistivity anomalies. The resistivity model from 1D inversion of the VTEM data along part of a flight line close to the MT line shows considerable correlation with the 2D MT resistivity model.

ORAL

### 3D-Norge: a new project to build a nationwide 3d bedrock map of Norway

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3D Norge is a new project at NGU which will create a full 3D model of the bedrock geology in Norway, with 3D line shapefiles and mesh surfaces. Several reasons exist for making a 3D bedrock model of onshore Norway. Firstly, from a mineral resource viewpoint, the state of surface mapping of resources has perhaps reached a stage where the discovery of new deposits is increasingly more unlikely without utilising a 3rd dimension. Secondly, in the last 5 years there has been a marked increase in the interest and investment in mineral resources, both from government funding to the NGU and from the minerals industry. Thirdly, Norway doesn't have one.

The 3D modelling package *3D MOVE* was chosen for its user friendliness and ability to model complex structures. We use a 10m x 10m DEM created by the national mapping authority in Norway. A 1:2M bedrock surface was used as a geological basis. and then used to create a simplified 8-fold tectonostratigraphy, which would form the basic units for the creation of 3D shapefiles and mesh surfaces in 3DMOVE. Geologist-constructed geological profiles, both 50K and 250K, are the basis for the 3D modelling. 110 250K and 549 50K profiles have been imported and georeferenced in the model. Additional structural data is supplied from a recently compiled structural database of the whole of Norway, containing over 26000 points. Regional scale seismic profiles are also included in the model.

This project is an initiative of the Mineral Resources Division at the Geological Survey of Norway and several key Norwegian mineral deposits will be integrated seamlessly into the 3D model. These deposits have been modelled in 3D previously in *TARGET* for ArcGis. It will then be possible to

zoom from a national scale into these individual deposits, with their detailed geology, boreholes and ore volumes. The Geomatics division at the Geological Survey of Norway will facilitate the systematisation and standardisation of the 3D data which will be inputted into the model and has begun to assess the possibilities for a web-based user interface. We plan to create a web-based service, accessed through the NGU website, where the user can call up the 3D model anywhere in the field on their phone and visualise themselves within the model. This project is seen as a method development project, to understand and develop the workflows and databases to allow the creation of the 3D model, organisation of the different data types and databases and a web-based interface. Towards the end of the project we will assess the connection to other areas of geology in Norway and at NGU, for example landslides and onshore-offshore relationships and how this model can be extended to make more complex models for mineral deposits and specific places of interest in sub-areas.

ORAL

### Porosity, Permeability, Thermal Properties of clastic rocks. A case study in Stenlille Structure, Denmark

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The focus of this study is to understand the properties of clastic rocks (Fjerritslev Fm- Gassum Fm) in Stenlille area in order to know if the reservoir is a suitable model for a deep Heat Storage site. The Stenlille Structure is a gas storage facility for Danish natural gas. It became clear in the 1980s that the Stenlille facility could also function as a seasonal heat storage (Laier T., 2012) in shallow layers. Rise of temperature due to the injection of hot water (90°C) influences the properties of reservoir such as Porosity, Permeability, Heat Capacity and Thermal Conductivity.

Properties of rocks are investigated by different methodologies:

- The Porosity is calculated from standard well log interpretation starting from Density and Resistivity log.
- The Permeability is based on Kozeny equation (Kozeny J., 1927) and on core data.

- Thermal Properties (Thermal Conductivity, Heat Capacity) are calculated according well log interpretation and empirical relationship with porosity (Fuchs S., 2014).
- With the aim of Petrel2015 we will be able to calculate volumes of the Sandstones bodies ( Gassum Fm) Shales ( Fjerritslev Fm) and also estimate the distribution of the properties described above in order to recognize patterns between them.

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ORAL

### Regional-scale 3D temperature distribution beneath the northern North Sea and adjacent areas of the continent according to lithosphere-scale 3D thermal modelling

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To understand the regional thermal pattern beneath the northern North Sea and adjacent areas of the Norwegian mainland, a 3D conductive thermal modelling has been performed in the framework of the Crustal Onshore-Offshore Project (COOP project). The lithosphere-scale 3D model has been used as a realistic approximation of the geometries of the sedimentary infill as well as of the underlying crystalline crust and lithospheric mantle during the 3D thermal modelling. Construction of the 3D model has been done by use of recently published/released structural data. Configuration of the 3D structural model has been validated by a 3D density modelling which has been carried out by use of the software IGMAS+ (the Interactive Gravity and Magnetic Application System). Based on the 3D density modeling, the crystalline crust of the study area consists of several layers. The obtained Moho is strongly uplifted beneath the Central and Viking grabens, whereas the lithosphere-asthenosphere boundary is relatively shallow beneath the western part of the model area.

The 3D thermal modelling has been made by using commercial software package COMSOL Multiphysics. For the upper boundary, time-dependent temperature at the Earth's surface and sea bottom has been used. This has been done by considering palaeoclimatic changes during the last 228,000 years. The lithosphere-asthenosphere boundary has been chosen as a lower thermal boundary which corresponds to the 1300 °C isotherm. Results of thermal modelling within the upper part of the 3D model indicate that the mainland is generally colder than the basin areas. This regional trend of temperature is mostly related to the low thermal conductivity of sediments which increases heat storage within the areas covered by thick sedimentary cover. The sediments-related thermal effect is especially pronounced within the Central and Viking grabens, the East Shetland and Norwegian-Danish basins where the sedimentary cover is thickest. Furthermore, the effect of increased radiogenic heat production within the upper crust is prominent beneath the Horda Platform, where the highest geothermal gradient is modelled within the upper part of the 3D model.

ORAL

### 3D petrographic imaging and diagenetic modelling of reservoir formations

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The Utsira High (Norwegian North Sea) has been a petroleum exploration target since late 1960s. It is a large basement high (about 200x50 km) located 190 km west of Stavanger, flanked by the Viking Graben to the West and Stord Basin to the East.

The southern part of the Utsira High complex ("Haugaland High") gained new interest when Lundin Norway in 2007 discovered commercial hydrocarbons in deposits of Permo-Triassic and Early Cretaceous age.

A detailed mineralogical and sedimentological study of these rocks is carried out. These include

sedimentological core logging and petrographical analyses e.g. optical mineralogy, XRD (bulk & clay) and SEM.

The present study focuses on the application of high-resolution 3D micro-CT scans in order to provide new insights into the diagenetic processes which has taken place in the reservoir rocks. In particular, the heterogeneous cores samples (e.g. conglomerate) exhibit a range of mineral phases (particularly quartz, feldspar, ferromagnetic minerals, clays) and have significant primary and secondary porosity often filled in by authigenic clays. The non-destructive high-resolution 3D micro-CT technique may improve our knowledge of the evolution of inter-connectivity of primary and secondary porosity through time ("4D diagenesis").

The development of CT methods has improved significantly during the last years, enabling us to get detailed petrographical information across scales; from nanometer to centimeter scale. The determination of different mineralogical phases in the grey scale CT images still remains a challenge due to similarities in material composition and density, i.e. different minerals with similar density appears as the same grey tone. To get additional mineral information additional imaging techniques are required, e.g. SEM-EDS analysis. Polished surfaces of the micro-core samples previously imaged by CT, are subsequently scanned by SEM-EDS producing a quantified representation of the mineralogy. The 2D mineral map can then be registered to the corresponding slice of the CT scan. This approach allows us to get more accurate quantification of mineral and diagenetic phases in the 3D CT data. By combining these methods a diagenetic 3D reconstruction model can be made making it possible to quantify the porosity evolution through time. The project goal is consequently better prediction of reservoir characterization through time.

ORAL

### Talsinkifix – new challenges for engineering geologists

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The capital areas of Helsinki in Finland and Tallinn in Estonia have grown enormously during the last 20 years. About 5 million inhabitants live in the daily working area of the cities. Today 30,000 people commute weekly or monthly from Estonia to Finland. Eight million passengers crossed Gulf of Finland year 2014. The idea of a tunnel between Tallinn and Helsinki was presented in early 1990's known today as Helsinki–Tallinn fixed link, "Talsinkifix". Prefeasibility studies and the assessment of socio-economic impacts show that the planning of a tunnel should be continued. The tunnel will connect the two cities with trains operating with maximum speed 250 km/h to achieve 30 minutes travel time. The tunnel will be an extension of the future Rail Baltic line railway offering north–south connections among European Union Member States. Construction could start 2025–2030 and would take eight to ten years. The tunnelling and bedrock construction share of the costs is estimated to 3,6 - 4,1 billion €. The total cost estimate is 9 – 13 billion €.

The tunnel area is located at the border of the East European Platform and the Fennoscandian Shield. The investigations of bedrock construction conditions of the area in Gulf of Finland will present great challenges for geologists. Most important in undersea tunnelling is the elevation of bedrock surface and location of major bedrock fracture zones. Tunnelling will be challenging especially in the vicinity of Tallinn in the about 1.2 billion years younger sedimentary rocks. In buried valleys the Quaternary sediment thickness may reach up to 150 m with high groundwater pressures. The blue clay stratum is a good environment for tunnelling because of low water conductivity. The Ediacaran water saturated silt and sandstones, reaching up to 60 m in thickness, are an important source of water supply for the Tallinn city and thereby one of the main challenges.

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Ikävalko, Ossi; Vähäaho, Ilkka; Suuroja, Sten 2013. Soil and bedrock conditions to be expected in Tallinn – Helsinki tunnel construction. In: *Strait Crossings 2013 : proceedings / Tor Erik Frydenlund, Kaare Flaate, Håvard Østlid*

## POSTER

### Kersilö database and its applications within the ice divide zone of Finnish Lapland

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The remains of sediments originating prior the last glaciation are abundant within the ice divide zone of Finnish Lapland. Rautuvaara in Kolari and Sokli in Savukoski are well studied key sites for Weichselian stratigraphy, but Sodankylä area in between is less well known in this respect. However, it can be suggested, that the area might bring some additional information, especially related to the history of fluvial sedimentation, because the flat-lying plateau is occupied by large rivers and their floodplains even today.

The main target of the study was to gather and organize all existing sediment data of Kersilö area (20 x 18 km) as a database. Kersilö database includes over 2700 observations. Database consists of targeting till geochemistry, overburden thickness, Auger-drillings, percussion drillings, test sites from GSF, peat investigations, groundwater wells and national drill core archive data. The database is part of a more detailed GIS based infra model, where additional 2200 drillings were used to model the bedrock surface. The infra model will include 3D model of surficial deposits and solid bedrock within a detailed 3 x 3.5 km model area.

The surficial deposits in Kersilö area consist of at least 3–4 till beds interlayered by sorted sediments. The average thickness of surficial deposits is 5 m and 8 m in detailed model area near Kärvasniemi. The thickest sediment layers in Pahalaaksonmaa reach over 40 m. Bedrock topography varies 190–148 m a.s.l in detailed model area and 229–142 m a.s.l. in whole area. The mean altitude of whole area is 190 m. The mean altitude of the bedrock of the detailed area is relatively lower being 178 m a.s.l. The thickest sediment deposits as in Kärvasniemi and Pahalaaksonmaa lie on the depressions of the bedrock. Some of the fractures of bedrock are

visible in the bedrock model. The bedrock model indicates sedimentation basin of Kärvasniemi area might be connected to depression of west corner of Viiankiaapa mire and to Pahalaaksonmaa. 3D model will give a basis for developing a hydrostratigraphical model to explain the ground water – surface water interactions in the area.

## POSTER

### High-performance geoscientific computing in multi-scale mineral potential studies

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A central task in mine site evaluation and 3D mineral potential studies is to collect data on multiple spatial scales and then use inverse methods to infer the location and extent of commercially interesting mineral deposits. Datasets comprise, for example, geophysical data measured from the air, the surface or along drill holes, geological data from geological cross sections, maps, drill core logs and geochemical data. Directly observed geological information is often sparse (e.g. drillholes) and subsurface geology has to be inferred through inversion of measured geophysical data. In order to be able to handle the huge data sets coming from mine sites and mineral potential field mapping areas in an organized manner, a good workflow is needed. 3D models and all geoscientific data should be included in the same 3D grid, also called CEM ('Common Earth Model').

The increasing amounts of data has led to the need to use of high performance computing techniques in geosciences, with parallel computing and the use of modern accelerator technologies like graphical processing units GPUs to speed up calculations. In project Gecco, financed by the Academy of Finland during 2015-2019, we aim to advance the CEM concept in mineral exploration by utilizing high performance computing in geomodelling of heterogeneous areas where limitations of computing power have previously prevented the use of detailed CEM grids with e.g. unconstrained meshes

and the use of all available information simultaneously. This project combines expertise in high performance computing and geomodelling, and aims to develop tools for faster geological modelling in an effective computing environment. The two test areas Mullikkoräme near Pyhäsalmi Zn mine and Vuonos from Outokumpu mining area, Finland, will be used.

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**POSTER**
**3D brittle and lithological models of Olkiluoto**

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In Finland, Posiva Oy is preparing for the final disposal of spent nuclear fuel waste deep in the crystalline bedrock. As a result of extensive site selection programme and preliminary and detailed site investigations, Posiva proposed Olkiluoto as the site of the final disposal facility. In December 2000, the Government made a decision in principle in favour of the project, and in May 2001, the Parliament ratified the Government's policy decision. From that on, the investigations have been focused solely on Olkiluoto.

The geological and geophysical studies at Olkiluoto have been continued over 20 years. In addition to extensive geological mappings, a wide range of geophysical methods, including airborne, ground and drillhole surveys in 57 deep drillholes have been applied. As a part of the investigations, an underground rock characterisation facility, the ONKALO, was constructed at Olkiluoto over the period from 2004 to 2012.

The geological and geophysical investigations have resulted in 3D geological model of the Olkiluoto site. The geological model consists of four sub-models: the lithological model, the ductile deformation model, the brittle deformation model and the alteration model. This paper introduces two sub-models, the lithological and brittle model of the site. The lithological model presents the general lithological properties of definite rock volumes or units

that can be defined on the basis the migmatite structures, textures and modal compositions. The model is aimed to describe the spatial distribution of genetically related bedrock units, which have sufficiently constant properties. The brittle deformation model describes the products of multiple phases of brittle deformation, fault zones and other fractures. The model shows the localities and orientations of specific brittle fault structures and is aimed to illustrate all significant fractures created by long-lasting evolution of brittle deformation.

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**POSTER**
**Geological 3D modeling of clastic rocks. A case study in Stenlille Structure, Denmark.**

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The focus of this study is to build a geological 3D model of clastic rocks (Fjerritslev Fm.- Gassum Fm.) in Stenlille area (Denmark) in order to obtain a frame for further investigations (for example Petrophysical modeling).

The entire model is built with the aid of Petrel E&P Software Platform 2015 (Schlumberger).

Our data package includes: Well log data (GR, Resistivity, Density, Acoustic); Seismic lines; Well correlations.

Combining well log data and seismic lines, we define the geometry of the reservoir and also the surrounding area. Well correlations are used to define the top of each layer, we are interested to model.

Starting from well tops we build 12 surfaces that reflect the stratigraphy of reservoir: S1, SH1, S2, SH2 (Fjerritslev Fm.) and S3, S4, S5, S6, SH3, S7, S8, SH4 (Gassum Fm.).

All these surfaces are deformed by the underlying salt structure.

We will describe different cross-sections of the structure from the marginal to central part of the reservoir.

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**POSTER**

**Map database of superficial deposits and glacial geomorphological landforms in Finland — methodology and classifications**

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A Quaternary deposits and glacial geomorphological landforms map database has been defined by the Geological Survey of Finland (GTK). The definition combines various Quaternary geological map databases (1:20/50 000, 1:100 000 and 1:200 000) and other geological data, especially aggregate, engineering geological and aquifer investigation data with topographical map database and orthophoto information, but especially LiDAR based DEM information of the National Land Survey of Finland.

The multi-year project aims to produce 'the best mapping data for each location' with a cost-effective processing approach. The various themes combine both the main geological unit information with the new, landsystems-based glaciodynamical themes. The mapping process emphasizes interpretation of the various data sets to an integrated, holistic thematic combination with minimal fieldwork.

Previously, the Quaternary mapping information to the scale of 200k was the best available for the whole country and only included sediment material (texture) type. New map themes will additionally include the classification of glaciogenic deposit and landform types and will differentiate between glacialfluvial deposits and littoral deposits typically forming the same polygon in 200k maps. Various moraine landforms will also be described. The glaciodynamic themes included into the database are: Mega scale glacial lineations (MSGL) (drumlins, megaflutings etc.) and various types of other moraines referred to much slower ice flow velocities or terminus features (ribbed moraines, hummocky moraines, De Geer moraines and end moraines). During the course of the project, new glacial features cf. reflecting variations in ice flow velocities

will be mapped using LiDAR-DEM data. The new map database will be a significant contribution for the mineral exploration studies and land use management in Finland.



## S15.2 LIDAR in geology

### KEYNOTE

#### Distribution and annual-origin of De Geer moraines in Sweden with insights from LiDAR

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De Geer moraines (DGMs) were first identified in Sweden by Gerard De Geer in 1889. Using airborne Light Detection and Ranging (LiDAR) data, we have mapped DGMs over the entire country, and we show that they occur predominantly in two distinct areas: in south-central Sweden north of the Middle Swedish end-moraine zone and in northeast Sweden. DGM formation occurs predominantly where the local relief is low, the ice-margin retreat rate was high and the sedimentation rate low. Formation of DGMs occurred over short time spans of a few hundred years – between 11 500 and 11 000 cal years BP for the southern group and from 10 700 and 9900 cal years BP for the DGMs in the north. DGMs have been suggested to be made by a number of processes at subaquatic ice margins, including pushing during winter readvance, squeezing into subglacial crevasses, deformation during calving events and deposition as subaquatic fans. Therefore, we recognize DGMs to be equifinal landforms, made by several related mechanisms. However, we observe that the most common occurrence of DGMs in Sweden are as regularly spaced even ridges below the highest shoreline whose spacing closely corresponds to independently determined ice-margin retreat rates. We therefore suggest that where regular evenly spaced DGMs occur, their spacing likely represents the local ice-margin retreat rate, and that the majority of these ridges were made annually by winter advances.

### ORAL

#### Occurrence of De Geer moraines in Finland based on LiDAR DEM

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LiDAR digital elevation models (DEMs) from Finland were investigated to map and discriminate features of De Geer moraines, more scattered end moraines, and larger end moraines features. We showed that LiDARs are able to record small moraine ridges very sensitively and accurately with regards to their length, width, height, orientation and interdistances. De Geer moraines were found to be typically 50-300 m long, 10-20 m wide, 0.5-2 m high, with considerable inter- and intrasite variability. Comparisons of the measured variables of De Geer moraines with their deposition environment suggest that their dimensions are less dependent on the depositional environment compared to ridge morphological features and interdistances.

The results indicate that the occurrence and distribution De Geer moraines and scattered end moraine ridges in Finland are more widespread than previously suggested. This is probably attributed to the ease of detecting and mapping these features with high-resolution DEMs, indicating the efficiency of LiDAR applications in geological and geomorphological studies.

The variable appearance and distribution of moraine ridges in Finland indicate that no single model is likely to be appropriate for the genesis of De Geer moraines at all localities and for all types of ridges. De Geer moraine interdistances are suggested to be due to a combination of the rapidity of ice margin recession, proglacial water depth and terrain topography. The correlation between the varved clay-based rate of deglaciation and interdistances of distinct and regularly-spaced De Geer moraines indicates that the rate of deglaciation is probably involved in the ridge-forming process, but more thorough comparisons are needed to understand the extent to which De Geer interdistances represent an annual rate of ice-margin decay and the rapidity of regional deglaciation.

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ORAL

### The aeolian dunes of Bonåsheden, central Sweden: a geomorphological, geophysical and geochronological case study

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Despite its possible use as a palaeoenvironmental archive aeolian sediment in Sweden has been a low priority for the scientific community. The aeolian deposits have often been mapped, not least by the Swedish Geological Survey (SGU); however more detailed investigations, especially concerning their palaeoenvironment and geochronology, are uncommon.

Bonåsheden is the largest continuous dune field in Sweden, covers an area of ca 15.5 km<sup>2</sup> and is situated just north of the town of Mora, Dalarna, Sweden. The aim of this study was to describe the geomorphology of the dunes at Bonåsheden, interpret the local palaeoenvironment as well as determine the chronology of the sand drift events. The dunes were mapped using GIS softwares and LiDAR data. Remote sensing, ground penetrating radar and observations in the field showed that the majority of the dunes were transverse dunes, with some parabolic shaped dunes as well. This suggests that the majority of the dunes formed in an environment devoid of vegetation with an abundance of sediment available for sand drift. Most dunes displayed an orientation advocating formation of the dunes by north-westerly winds. At least two different generations of dunes, based on size and orientation, were identified through remote sensing, however only age determination of the larger generation of dunes is available at the present. Results from luminescence dating suggest ages of dune formation close to the deglaciation with a few minor subsequent events, mainly partial reactivation of the surface of the dunes.

ORAL

### Structural geology of the Naamivitikko and Riikonkumpu postglacial fault scarps in Finnish Lapland

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The recent availability of high-resolution LiDAR-based digital elevation models provides an outstanding possibility to discover and investigate postglacial fault scarps crosscutting glacial sediments and landforms (Palmu et al. 2015). In addition to establishing their geometrical characteristics, there is also apparent need to document the structural geological properties in more detail in order to gain understanding on the mechanisms and slip evolution of postglacial faults, which may further have implications e.g. for seismic hazard assessment for nuclear waste repositories.

The Riikonkumpu postglacial fault (PGF) scarp in Kittilä and Naamivitikko PGF in Kolari, northern Finland, were investigated with airborne LiDAR DEM, GPR, and lithostratigraphical studies of trenches excavated during the falls 2014 and 2015. The maximum height of the Riikonkumpu fault is 1.5-2 m and its SW-NE trending geometry can be traced about 15 km, whereas the Naamivitikko scarp is at least 6 m high but the scarp can only be traced for a length of 2-3 km.

Observations of the structures in the Quaternary sediments and bedrock can be used to assess the orientation of the actual fault planes but also the slip evolution of the faults, which in the case of the Naamivitikko PGF may indicate multiple slip events, in contrast to what is typically postulated for the PGFs. This paper describes results of these investigations.

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Palmu, J.-P. Ojala, A.E.K., Ruskeeniemi, T., Sutinen, R. and Mattila, J., 2015. LiDAR DEM detection and classification of postglacial faults and seismically-induced landforms in Finland: a paleoseismic database. GFF, DOI: 10.1080/11035897.2015.1068370

## ORAL

### Pattern recognition of mass-flow deposits from airborne LIDAR

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Mass-flow deposits, potential construction aggregates, exhibit as fields of ridges varying in elongation and in surface stoniness and boulder clusterings (Sutinen et al., 2009a). Mass-flow morphologies are linked to conduit infill sedimentation. The sedimentation presumably was initiated by the subglacial earthquake event(s) associated with lithospheric plate stresses and glacial isostatic adjustment (GIA). Mass-flow sediments are moderately sorted diamictons with a fine-fraction content less than 12% hence making them potential aggregates for construction purposes.

We aimed to develop a semi-automated pattern recognition approach to map mass-flow deposits as potential new aggregate materials using high-resolution airborne laser scanning (ALS) data. The study was conducted in the Kemijärvi mass-flow field, northern Finland, which has regional significance for aggregate production.

In the first stage, all hummocky features with a convex topographic form were delineated from the ALS derived DEM and its tilt derivative with an Object-Based Image Analysis algorithm developed in eCognition software. Then field recognition was conducted to provide validation and calibration data for classification of the delineated hummocky landforms into mass-flow deposits and other landforms based on their surface stoniness. The presence of stones was detected from the last-return point cloud ALS data by producing a surface triangulation with a limited spatial angle on every point. The signal was then amplified by a neighborhood voting and cumulated to grid points for classifying each mass-flow polygon. The approach was successful and presents the first attempt to semi-automatically map aggregate deposits from ALS data in Finland.

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## ORAL

### Timing of paleoseismicity in western Finnish Lapland

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High-resolution LiDAR-based digital elevation models provide an efficient tool to detect post-glacial fault (PGF) scarps and paleolandslides beneath forest canopies (Sutinen et al., 2014; Palmu et al., 2015). The spatial distribution of these features tend to be coincidental hence suggesting that dating of landslide-buried organic materials will provide evidence on the frequency of the past earthquakes.

We percussion drilled through the paleolandslide accumulations to find buried organic materials in 2012 and 2014, and were able to reveal several samples for the <sup>14</sup>C datings. In Kittilä, the Taalovuoma buried organic sediments yielded 5050 yrs calBP. In Kolari, Lehtolaki site provided data on three different paleoslide events with following ages: 1275, 1585, 5860, 10185 yrs calBP. In addition, three basal peat samples yielded 9220, 9480 and 9510 yrs calBP from peat bogs developed on the foot wall of the Ruokojärvi postglacial fault, just next to the fault scarp in Kolari.

Our previous finding of landslide-buried woody remnants of birch yielded 9730 yrs calBP in Kittilä (Sutinen 2005). We therefore propose that earthquakes around 9500-10200 yrs calBP, 5000-5900 and 1200-1600 yrs calBP occurred in western Finnish Lapland. Historical earthquakes ( $M < 4$ ) are spatially coincidental with PGFs, yet our results suggest that the frequency of major earthquakes ( $M \sim 7$ ) may be of the order of 4000 years within the Fennoscandian plate.

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## ORAL

### LiDAR-based interpretation of deglacial dynamics in SW Finland

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The aim of the research was to develop a proper working procedure for LiDAR data interpretation over large deglaciated areas and to promote the understanding of ice stream dynamics and related ice-marginal behavior of the Scandinavian Ice Sheet, especially in SW Finland. The detailed dynamic behavior of the ice streams is still poorly understood, but now the ALS-based high-resolution LiDAR (Light Detection And Ranging) data will facilitate the mapping of glacial landsystems (a holistic approach of terrain evaluation). It enables more accurate and uniform landform analysis over wide areas than with traditional geomorphological techniques and other methods of remote sensing. Like all remote sensing methods, LiDAR interpretations are also dependent on ground control, but the needed field work is much more focused and minimal.

The study area exhibits the withdrawal of the Scandinavian ice sheet from the II and III Salpausselkä ice-marginal complexes in SW Finland, recording the end of the relatively cold Younger Dryas period. A detailed picture of deglaciation and related ice-marginal depositional patterns, ice flow indicators, and hydrological changes depicted by esker patterns has been established for the deglacial Loimaa and Vanajavesi sublobes on the eastern part of the Baltic Sea ice stream. New landform features or assemblages supplemented with field observations have been mapped for the area.

The overall results support the usefulness of glacial landsystem approach even for deglacial environments with varying maturity of landsystem development. Moreover, the results explain the complex behaviour and ice flow patterns at the NE end of the III Salpausselkä affected by the deglacial activity of the Vanajavesi sublobe or ice flow cor-

ridor that best describes the landsystem development within the area. Fast deglacial changes in ice flow and landform patterns were affected by subtle changes in bed topography, proglacial water depths as well as changes in hydrological regime of the ice. We also suggest the presence of large subglacial lake and related outburst route within Urjala-Toijala area.

## POSTER

### LiDAR-based geomorphological mapping and Quaternary stratigraphy in the Sodankylä region, northern Finland

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The high resolution of LiDAR-derived Digital Elevation Models (DEMs) has improved the mapping process by clarifying interpretation of densely forested areas and allowing the identification of fine-scale land surface features not originally distinguished in the aerial photos and in the field. Such geomorphologies include low-relief features on top of moraine hills. The Geological Survey of Finland (GTK) carried out geomorphological mapping in 2013-2014 in the Sodankylä region of northern Finland. The mapping process was supported by the Quaternary stratigraphical and geochronological works.

Geomorphological mapping was based on an aerial LiDAR analysis supported by field observations, ground penetrating radar measurements and test pit surveys in a glaciogenic environment. The mapping area covered about 370 km<sup>2</sup>, with the LiDAR data having a pixel size of 2 m x 2 m and vertical resolution 0.3 m. The geomorphology of the area consists of large till-covered hills, ground moraine plains, glaciofluvial sand and gravel deposits composed of esker systems and related delta and outwash formations of the Weichselian cold stages, followed by pro-glacial glaciolacustric and post-glacial lacustric and fluvial sand/silt deposits. Large areas in low land areas are covered by Holocene mires.

The study proved that the benefit of LiDAR data compared with traditional interpretation methods was in more detailed identification of surface deposits particularly in densely forested areas. This is an advantage, for example, in the case of till-covered

stratified sand and gravel deposits, and in shallow till areas where the LiDAR interpretation provides more precise edging of the morphologies. As an example, based on the LiDAR mapping it was possible to distinguish several till-covered delta and sandur deposits which based on OSL dating date back to the Early Weichselian stadial (74-89 ka).

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**POSTER**
**Characterization of Riikonkumpu fault scarp in Kittilä**

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The recent availability of high-resolution LiDAR-based digital elevation models provides an outstanding possibility to discover and map postglacial fault scarps that crosscut glacial sediments and landforms (Palmu et al. 2015). In addition to establishing their geographical distribution, direction, and height in DEM surfaces, there is also apparent need to document their stratigraphic geometries in more detail in order to understand and estimate their possible implications for seismic hazards.

The Riikonkumpu postglacial fault (PGF) scarp in Kittilä, northern Finland, was investigated with airborne LiDAR DEM, GPR, and lithostratigraphical studies of a 80 m long and 5 m deep trench excavated during the fall 2015 fieldwork. The maximum height of the PGF is 1.5-2 m and its SW-NE trending geometry can be traced about 15 km. The Riikonkumpu PGF is parallel to the Isovaara PGF (Sutinen et al., 2014) located ca. 10 km SW of the Riikonkumpu site.

The trench through glacial sediments was orientated perpendicular to the LiDAR-detected fault line and excavated to reach the surface of intensively weathered metaphyllitic bedrock. Quaternary sediments and bedrock features on the vertical sections the trench were logged and photographed to create 3D imaginary of the sedimentological details. This information was used to study and interpret the lithostratigraphical and structural features of the fault rupture in Quaternary deposits and the bedrock

underneath. This paper describes results of these investigations.

**References:**

Palmu, J.-P. Ojala, A.E.K., Ruskeeniemi, T., Sutinen, R. and Mattila, J., 2015. LiDAR DEM detection and classification of postglacial faults and seismically-induced landforms in Finland: a paleoseismic database. GFF, DOI: 10.1080/11035897.2015.1068370

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**POSTER**
**Appearance of PGFs in Finland – case Lauhavuori**

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Northern Fennoscandia has experienced late- and postglacial fault (PGF) activity and high-magnitude seismicity attributable to lithospheric plate stresses and glacio-isostatic rebound. During the last decades, PGFs have been found and described in northern Fennoscandia, the first fault scarps being discovered in western Finnish Lapland in the 1960s. LiDAR-based digital elevation models (DEMs) have recently provided a new and accurate remote sensing mapping methodology for systematic screening and detection of geological and geomorphological features. It allows the rapid and low-cost mapping of late- or postglacial faults and, for instance, mapping of landslides from areas where they have not previously been recognized (Palmu et al., 2015).

In Fennoscandia, most PGFs have been found in Finnish Lapland and Norrbotten in Sweden. Recently, new potential PGF systems were discovered in Lauhavuori, western Finland (Palmu et al., 2015), and in Bollnäs, central Sweden (Mikko et al., 2015), both representing the southernmost locations of PGFs in Fennoscandia.

This paper describes the preliminary findings of the proposed Lauhavuori PGF. The general geological and geomorphological description of the PGF features in this locality is given. The geomorphological features extracted from the LiDAR DEM include

the ramp height of the fault and shoreline displacement features, used in the preliminary age determination of the proposed PGF.

#### References:

- Palmu, J.-P., Ojala, A.E.K., Ruskeeniemi, T., Sutinen, R. and Mattila, J., 2015. LiDAR DEM detection and classification of post-glacial faults and seismically-induced landforms in Finland: a paleoseismic database. GFF, DOI: 10.1080/11035897.2015.1068370
- Mikko, H., Smith, C.A., Lund, B., Ask, M.V.S. and Munier, R., 2015. LiDAR-derived inventory of post-glacial fault scarps in Sweden. GFF, DOI: 10.1080/11035897.2015.1036360

#### POSTER

### Distribution of the fine-grained sediments in Helsinki metropolitan area, Finland

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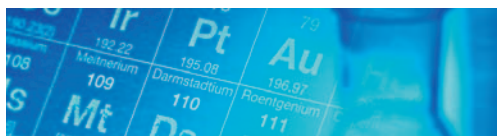
Urban growth leads to construction of buildings and infra in challenging areas with superficial deposits such as fine-grained sediments in the coastal area of Finland. The Helsinki metropolitan area has undergone many fresh water and marine stages after the last deglaciation and these stages of Baltic Sea basin have transported and accumulated fine silt and clay material. Geological and geotechnical properties and structure of these fine-grained sediments depend on the sedimentation environments, source material, and erosion and re-deposition during isolation.

A combined model of the appearance of the fine-grained sediments in the metropolitan area was made. The model is based on Quaternary maps of metropolitan cities Helsinki, Espoo, Vantaa and GTK, and thickness of the soft sediment layers from geotechnical investigations where available. The model was combined with high-resolution LiDAR DEMs for classification and visualization.

Based on the model, the fine-grained deposits were categorized into different classes according to their geological-geomorphological and geotechnical properties as well as location in the metropolitan area.



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## S15.3 Arctic research

### KEYNOTE

#### Monitoring of the Greenland ice sheet

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The Programme for Monitoring of the Greenland Ice Sheet was initiated in 2007 and sets out to monitor various aspects of the mass balance of the entire ice sheet. The chief component in PROMICE is the automatic weather station network, which targets the ablation area, a region which is difficult to reach and hard on instrumentation. Station transects provide the means to calculate the regional surface mass balance components. Yet combining PROMICE and GC-Net weather station data with MODIS surface albedo allows for a Greenland-wide observation-based estimate of surface melt. PROMICE weather station observations are also used to calibrate regional climate model output, improving surface mass balance calculations. To obtain the total mass balance from the ice sheet, the dynamic mass loss from ice berg calving is determined from airborne ice thickness measurements and satellite-based surface velocities.

Various related activities target mass balance processes in more detail. Firm coring campaigns discovered the existence of thick ice layers in firm in southwest Greenland, favoring runoff over percolation. Thermistor string measurements confirm that after big melt years refreezing does not occur below thick ice layers, but slush forms at the surface. The resulting surface darkening enhances melt through the melt-albedo feedback. We determine/validate the quantity of meltwater running off regionally by river discharge measurements.

### ORAL

#### Groundwater flow and solute transport modelling in coupled permafrost-hydrogeological systems

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There is a need for improved mechanistic understanding and quantification of permafrost and active layer change and its interactions with changes in subsurface water flow and solute transport. This is not only important for understanding dissolved carbon transport in the context of climate change, but also for understanding effects of anthropogenic pollution induced by increased arctic activity (Elberling et al., 2010; Jessen et al., 2014).

In this contribution subsurface solute transport in a degrading permafrost system is studied using a physically-based numerical model of coupled cryotic and hydrogeological flows combined with a particle tracking method (Frampton and Destouni, 2015). Changes in subsurface water flows and solute transport travel times are analysed for different modelled geological configurations during a 100-year warming period. For all simulated cases, the minimum and mean travel times increase nonlinearly with warming irrespective of geological configuration and heterogeneity structure. These travel time changes depend on combined warming effects of increase in pathway length due to deepening of the active layer, reduced transport velocities due to a shift from horizontal saturated groundwater flow near the surface to vertical water percolation deeper into the subsurface, and pathway length increase and temporary immobilization caused by cryosuction-induced seasonal freeze cycles.

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- Jessen, S., Holmslykke, H.D., Rasmussen, K., Richardt, N., Holm, P.E., 2014. Hydrology and pore water chemistry in a permafrost wetland, Ilulissat, Greenland. *Water Resour. Res.* 50, 4760–4774. doi:10.1002/2013WR014376

## ORAL

**Electromagnetic study of deep permafrost in Central West Greenland**

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A series of electromagnetic (EM) soundings were made in Western Greenland to test the applicability of the method for studies of deep permafrost in crystalline bedrock terrain. The study area consists of different geological and hydrological settings from the foreland and the ice margin areas onto the ice sheet. The analysis of the geophysical data is supported by the chemical and temperature data collected by the Greenland Analogue Project (GAP) from boreholes penetrating the ca. 350 m thick permafrost.

We applied a ground-based wide-band frequency-domain electromagnetic sounding system called SAMPO. A transmitter loop is used to generate a magnetic primary field at 82 discrete frequencies between 2 Hz and 20 kHz. For qualitative interpretation, the measured vertical-to-radial electromagnetic field component ratios are transformed into curves of apparent resistivity as a function of depth. For modelling the data we used 1D layered earth inversion.

The modeling provided a consistent cryogenic structure both for subglacial (4 layers) and proglacial areas (3 layers). The presence of deep permafrost could be confirmed, although the actual base of the permafrost was not detected due to too small electrical conductivity contrast. The weak conductor found at 550-750 m depth is located too deep to be the base of the permafrost, and the most likely explanation is saline groundwater.

**References:**

Ruskeeniemi, T., Engström, J., Lehtimäki, J., Vanhala, H., Korhonen, K., Lehtinen, A., Claesson Liljedahl, L., Pettersson, R. & Näslund, J.-O. Subglacial permafrost evidencing late-Holocene re-advance of the Greenland Ice Sheet over frozen ground at Kangerlussuaq, West Greenland (in prep.)

## ORAL

**Geological description of the DH-GAP04 borehole, Kangerlussuaq, Central West Greenland**

J. ENGSTRÖM<sup>1\*</sup>, K.-E. KLINT<sup>2</sup>, T. RUSKEENIEMI<sup>1</sup>, L. CLAESSION LILJEDAHL<sup>3</sup>, J.-O. NÄSLUND<sup>3</sup>, AND A. LEHTINEN<sup>4</sup>

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The *Greenland Analogue Project* (GAP) was initiated to understand the effects of glaciations on the thermal and hydrological behavior of crystalline rock during long-term disposal of nuclear waste for hundreds of thousands of years. To investigate the behavior of the crystalline rock within these circumstances a research borehole (DH-GAP04) was drilled to almost 650 m vertical depth, penetrating the permafrost and exposing the hydrology below the permafrost depth.

This study focuses on the geological observations made from the research borehole and its surroundings, which form the framework for the local hydrogeology. The borehole is drilled in a structural geologically complex location since it intersects a large shallowly plunging fold. The upper part of the borehole is located in the western part of the fold limb with parasitic folding while the borehole ends in the eastern fold limb. The fracturing and faulting within the borehole is also differing a lot both in terms of density and orientation. Moreover, the geology around the borehole is showing similar appearance with two larger lineaments exhibiting same orientations as the fracturing and faulting in the borehole. The final structural interpretation was of profound importance in understanding the hydrological variability observed in the research borehole.



## ORAL

### Hydrogeological and hydrogeochemical bedrock conditions under an ice sheet, Kangerlussuaq, Central West Greenland

J.-O. SELROOS<sup>1\*</sup>, S. FOLLIN<sup>2</sup>, A. LEHTINEN<sup>3</sup>, L. CLAESSION LILJEDAHL<sup>1</sup>, N. MARCOS<sup>4</sup>, J.-O. NÄSLUND<sup>1</sup>, P. PITKÄNEN<sup>3</sup>, I. PUIGDOMENECH<sup>1</sup> AND T. RUSKEENIEMI<sup>5</sup>

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The *Greenland Analogue Project* (GAP) aims at increasing the scientific understanding of glaciation and permafrost effects on hydrogeological and hydrogeochemical characteristics of fractured, crystalline bedrock within the context of geological disposal of nuclear waste. A borehole, reaching to almost 650 m vertical depth, was drilled in under the ice sheet margin, penetrating the full depth of permafrost in front of and under the ice sheet. The borehole was equipped with pressure monitoring and water sampling devices.

The present study focuses on hydraulic responses in the bedrock due to changing seasonal conditions on top of the ice sheet, and the chemical composition of the groundwater. Specifically, we investigate the pressure responses in the bedrock due to supra-glacial melt events with linked sub-glacial pressure changes, and confirm hydraulic connections through the supra-glacial/sub-glacial/subsurface system. However, local geologic-structural conditions imply differences in response in different borehole sections. The water chemistry confirms penetration of glacial meltwaters to great depths. Intrusion of oxygenated waters to corresponding depths is, however, not observed.

## POSTER

### Active rock glaciers at sea level in Finnmark, Northern Norway?

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Rock glaciers occur in continuous permafrost zones, and their current activity state therefore indicates occurrence of either present or former widespread permafrost. Today, active rock glaciers in Norway are found in the mountain permafrost zone, in both Southern and Northern Norway.

Recently, a series of seemingly active rock glaciers have been observed at sea level in Nordkinnhalvøya, Finnmark county, Northernmost Norway. These rock glaciers creep from talus slopes onto flat terrain; in this case raised post-glacial beach lines. This is a well-known landform configuration for rock glaciers terminating at sea-level in various other places, but always as part of the Arctic permafrost zone (e.g. Svalbard; Prins Karls Forland, Kapp Linné etc.). If these landforms are in fact active and creeping, this indicates that the very northernmost part of Norway should be considered as part of the Arctic permafrost zone rather than the mountain permafrost zone of Scandinavia.

A recently updated permafrost model of the Nordic countries (CryoGRID1; Gislås et al., *in prep*) simulates permafrost at similar elevations elsewhere in Finnmark, but mainly in connection to mires. Permafrost in mires, as palsas, is considered azonal. However, unlike palsas, the presence of active rock glaciers can not be considered azonal permafrost phenomena.

With permafrost thaw occurring wide-spread in the Arctic, this area could serve as a time-space substitute of high-Arctic landscapes like Svalbard in a changing climate. Further, this area serves as a perfect link between mountain permafrost processes in Scandinavia at large and Arctic permafrost affecting Svalbard.

#### References:

Gislås, K., Westermann, S., Schuler, T.V., Melvold, K. and Etzelmüller, B., *in prep*. Sub-grid variation of snow in a regional permafrost model. Submitted to The Cryosphere.

## S15.4 Nordic collaboration

ORAL

### NordVulk: Nordic Collaboration in Volcanology and Related Fields

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Nordic collaboration within volcanology and related fields has been facilitated through the Nordic Volcanological Center (NordVulk) through the past 43 years. NordVulk was first established in 1974, with full financial support from the Nordic Council of Ministers, and had the task to enhance Nordic research and educational collaboration in dynamic geology, focusing on volcanology and plate tectonics.

NordVulk has throughout its history been an asset to the Nordic countries, contributing to world-class research education and results published in the highest ranking scientific journals. The NordVulk fellowships for young researchers have provided young Nordic geoscientists with an opportunity to participate in studies of active processes, using Iceland's unique geology as a natural laboratory. The spectacular dynamic landscape in Iceland serves as an important factor in igniting interest and fascination in the minds of young researchers.

Today NordVulk promotes formalized university collaboration within its research themes together with the University of Iceland, by connecting geoscientists in all the Nordic countries in joint research projects, with special emphasis on joint/-double Ph.D. degrees to its Nordic students.

POSTER

### IGCP – International Geoscience Program – funding international networking in research

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The International Geoscience Program (IGCP) was initiated in 1972 and is a joint program between UNESCO and IUGS (International Union of Geological Sciences). Its prime recognition is the funding to international collaboration and networking in different geoscientific disciplines. This funding has since 1972 created and sustained global research networks through approximately 600 projects. Originally, focus was on global geological correlation and related research themes, but since 2011 the areas of interest have widened and include the following themes: Earth Resources - Sustaining our Society, Global Change - Evidence from the geological record, Geohazards - Mitigating the risks, Hydrogeology - Geoscience of the water cycle, and Geodynamic - Control our environment.

The international collaboration of IGCP-projects has been very important in the ongoing process of research leading to new knowledge about earth history, development and the large global geological contexts.

In Sweden, the national IGCP committee is organized under the Swedish National commission of UNESCO and the Geological Survey of Sweden (SGU) has been asked to lead its work. Project proposals have to go through the national committee before being submitted to the IGCP scientific board in Paris. The Swedish committee is also engaged in outreach activities and is co-organizing a workshop on geotourism and geoparks together with the Geological Survey of Sweden.

In connection with IGCP projects, geoheritage sites of national, regional and international importance have been described. These sites are important in understanding earth history and to show the relevance of geology to society. Geoheritage sites

are commonly used as study objects during field-trips with students at all levels. They are also appreciated by tourists and local people, being the backbone of geotourism in the area. By promoting such sites and their protection through outreach activities, IGCP also contributes to increase the general knowledge of earth science in society.





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