Divergent plate boundaries – enigmatic ocean floor elemental flux in space and time

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FluxBEATS is a doctoral training network, funded by the Marie Skłodowska-Curie Actions, in which research and training aim at a holistic understanding of the global bio- and geochemical elemental fluxes at divergent plate boundaries. A total of ten doctoral researchers in seven European institutions study the magmatic, hydrothermal and biological processes from the mantle through the crust to the hydrosphere, and from the Archean to the present. FluxBEATS officially started in November 2024. The doctoral researchers were recruited in spring and summer 2025, meaning the network is still in its early phase of implementation.

FluxBEATS is designed to provide the doctoral researchers with a professional and personal training environment around the topics of environmental and analytical geosciences. This includes state-of-the-art field, analytical, modelling, and software techniques, and soft skills such as effective dissemination and outreach. The next generation of Earth Scientists trained in FluxBEATS will be leading experts in geological and biogeochemical analysis and modelling. This expertise is critical for understanding the processes which affect the sustainable exploration of mineral resources on the seafloor and on-land and the Critical Raw Materials Act required for the future energy transition, supporting the European Union's Green Deal initiative and commitment for a sustainable future.

Training and science in FluxBEATS

In FluxBEATS, the doctoral researchers not only obtain training in collaboration with academic and non-academic partners, but many will also have the opportunity to join a research expedition at sea. This will be a challenging yet rewarding learning experience with the unique opportunity of facing, not only the technical difficulties of marine work, but also a possibility to see the seafloor and obtain samples from regions that few humans have ever seen. Understanding the processes operating on the modern seafloor is essential for gaining insights to the processes which may have affected many of the rocks exposed in the Finnish bedrock. Better comprehension of changes in geodynamic processes and their geochemical signatures from the Archean to the present is crucial in determining the origin of life and the formation of many metal deposits.

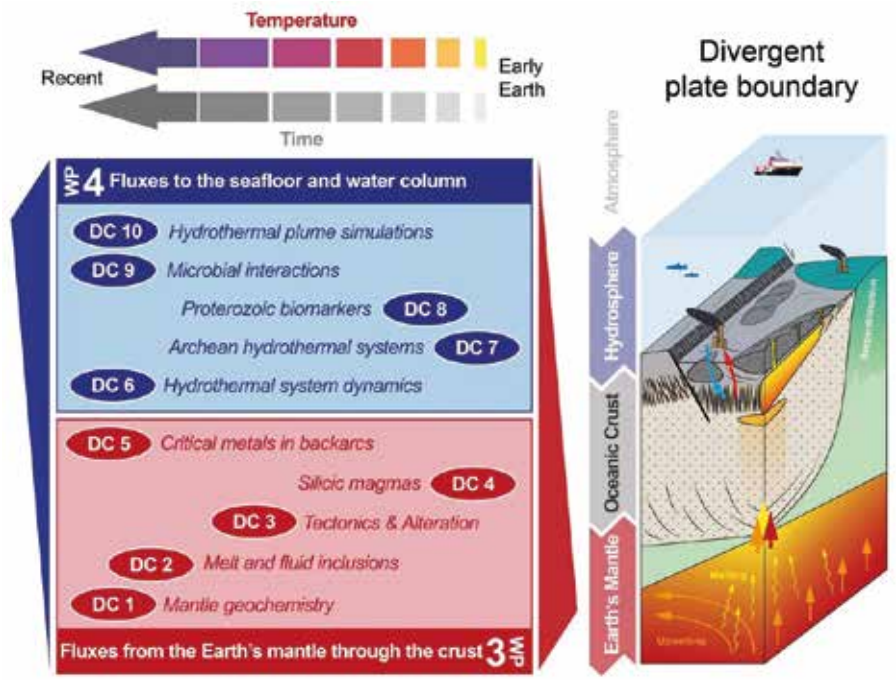

Figure 1. The scientific research in FluxBEATS is divided into two scientific work packages (WP). Work package 3 focuses on melting processes in the mantle beneath spreading ridges, as well as the evolution and chemical modification of magmas in the oceanic crust. Work package 4 focuses on the interplay between magmatic differentiation, degassing, fracturing of crustal rock units, seawater circulation, and crustal alteration, as well as consequences of these processes for the formation of massive sulfide deposits, hydrothermal plumes, and chemosynthetic ecosystems. DC indicates individual projects for doctoral research. Figure: Philipp Brandl (GEOMAR).

Kuva 1. FluxBEATS-verkoston tieteellinen tutkimus tehdään työpaketeissa (WP) 3 ja 4. Työpaketti 3 keskittyy keskiselänteiden alla tapahtuvaan vaipan sulamiseen sekä merellisessä kuoressa tapahtuvaan magmojen kehitykseen ja kemialliseen muuntumiseen. Työpaketti 4 keskittyy magmaattisen differentioitumisen, kaasunpoistumisen, kuoren kiviyksiköiden murtumisen, meriveden kierron ja kuoren muuttumisen vuorovaikutukseen sekä näiden prosessien vaikutukseen massiivisten sulfidiesiintymien, hydrotermisten pluumien ja kemosynteesiä hyödyntävien ekosysteemien muodostumisessa. Yksittäiset väitöskirjatutkijoiden projektit on merkitty DC:llä. Kuva: Philipp Brandl (GEOMAR).

The objectives of the network are distributed in two scientific work packages from the mantle to the crust, and from the crust to the hydrosphere (Fig. 1). They are designed to develop an integrated chemical budget of the oceanic crust characterizing the geochemical flux at divergent plate boundaries from the Earth's mantle through the crust to the ocean. Melting, melt evolution, and fluid-related metal enrichment processes along active divergent plate boundaries are quantified and compared to processes operating in the Proterozoic and Archean. Both work packages explore metal enrichment through time using geological, analytical, geostatistical, and semi-automated machine learning algorithms. The sources, composition, and magnitude of chemical fluxes in hydrothermal systems and their interaction with the microbial biosphere from the Archean to the present day will be characterized. A validation of elemental flux into the ocean and the distribution and speciation of metals utilizing geochemistry, computational fluid dynamics,

Figure 2. On-site participants of the FluxBEATS summer school at Þingvellir, a stunning rift valley located between the North American and Eurasian tectonic plates. Persons standing from left to right are the doctoral researchers Jakob Rahner (Polito, Italy), Francesco Magnani (GTK, Finland), Ana Clara Legora Woitech Hecksher (University of Bergen, Norway), Yadav Krishna (GEOMAR, Germany), Lisa Pirko Heinz (GEOMAR), Jaime Cataldo Bacho (University of Helsinki, UH, Finland), Linus Hüne (UH) and Martina Spinella (University of Münster, Germany) (back row). In the front row Christoph Beier (UH), Elina Lehtonen (UH), Sylvia Sander (GEOMAR), Felix Genske (University of Münster), Joonas Virtasalo (GTK) and Philipp Brandl (GEOMAR) represent the supervisors of the network. Photo: Christoph Beier.

Kuva 2. Paikan päällä FluxBEATS-kesäkouluun osallistuneita Þingvellirissä, upeassa hautavajoamassa Pohjois-Amerikan ja Euraasian tektonisten laattojen rajalla. Seisovat henkilöt vasemmalta oikealle ovat väitöskirjatutkijat Jakob Rahner (Polito, Italia), Francesco Magnani (GTK), Ana Clara Legora Woitech Hecksher (Bergenin yliopisto, Norja), Yadav Krishna (GEOMAR, Saksa), Lisa Pirko Heinz (GEOMAR), Jaime Cataldo Bacho (Helsingin yliopisto, HY), Linus Hüne (HY) ja Martina Spinella (Münsterin yliopisto, Saksa). Eturivissä Christoph Beier (HY), Elina Lehtonen (HY), Sylvia Sander (GEOMAR), Felix Genske (Münsterin yliopisto), Joonas Virtasalo (GTK) ja Philipp Brandl (GEOMAR) edustavat verkoston ohjaajia. Kuva: Christoph Beier.

and thermodynamic computations of fluid speciation and mineral solubility further expand the scientific portfolio.

Developing scientific and soft skills

The training in FluxBEATS is centered around two essential components: secondments which the doctoral candidates will be doing in other European academic and non-academic institutions and three regular summer schools during which the doctoral candidates, supervisors and partners of the network meet for scientific and soft-skills training. The secondments are organized around each individual research project, but are also planned so that doctoral candidates with a project centered around analytical geochemistry are being exposed to modelling techniques and *vice versa*.

The summer schools are each designed around a unique scientific scheme. The first FluxBEATS summer school was held from September 9 to 16, 2025, in Iceland (Fig. 2 and cover photo). The geological themes of the summer school targeted the processes at modern divergent plate boundaries, i.e. the processes during melting, hydrothermal alteration and formation of the crust. The compositional and structural heterogeneity of the modern oceanic crust reveals how complicated the interpretation of Proterozoic and Archean bedrock geology could be, but also allows to determine the temporal variability of the processes involved. The program of the first summer school included field excursions (Fig. 3), invited lectures addressing the

Figure 3. During the summer school in Iceland, the participants explored young volcanic processes and the dynamics of divergent plate margins. One of the field sites, Háifoss, includes a geological sequence of lavas, tuffs and sediments dating back to the upper Pliocene. Photo: Christoph Beier.

Kuva 3. Islannin kesäkouluun osallistuneet tutkivat nuoria vulkaanisia prosesseja ja toisistaan erkaantuvien laattojen rajan dynamiikkaa. Yksi kenttäkohteista, Háifoss, koostuu yläplioseenin aikana muodostuneista laavoista, tuffeista ja sedimenteistä. Kuva: Christoph Beier.

Figure 4. The summer school also had a workshop related to data management delivered remotely by Hela Mehrtens and Doris Maicher from the GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany. The workshop included a Lego-based metadata exercise, in which participants systematically built a submarine vehicle, demonstrated the significance of accurate metadata description. Photo: Elina Lehtonen.

Kuva 4. Kesäkouluun sisältyi etäyhteyksin toteutettu työpaja, joka käsitteli tiedonhallintaa ja jonka pitivät Hela Mehrtens ja Doris Maicher GEOMAR Helmholtz -merentutkimuskeskuksesta Kielistä, Saksasta. Työpajaan kuuluneessa Lego-pohjaisessa metatietotehtävässä osallistujat rakensivat järjestelmällisesti vedenalaisen kulkuneuvon, mikä havainnollisti tarkan metatiedon kuvaamiseen merkitystä. Kuva: Elina Lehtonen.

geological and hydrothermal evolution of Iceland, and workshops covering essential topics such as PhD life, data management (Fig. 4), project planning, and scientific writing and presenting.

The second summer school in 2026 at GEOMAR Helmholtz Centre for Ocean Research Kiel will focus on marine geological research and the interpretation of shipboard geological data. A profound lack of knowledge

from the deep seafloor, – only about 10–15 % of the seafloor are mapped to a resolution of less than 100 m – requires that ocean floor research is increased particularly in the light of an increasing threat of deep-sea ecosystems by commercial demands and climate change. The final summer school in Finland, in 2027, will be centered around the evolution of the Proterozoic and Archean bedrock, and will be analogous and expanding the knowledge gained during the summer school in Iceland and during the entirety of the project.

The mobility of both the doctoral candidates and supervisors expands the scientific and training portfolio of the doctoral candidates and provides an opportunity to be exposed to different working and living cultures. The training also involves increasing knowledge of state-of-the-art analytical techniques which are central to modern geosciences research.

The project is a challenging yet unique opportunity for cross-disciplinary research in that it involves a broad spectrum of analytical and training opportunities for both the doctoral candidates but also a rewarding learning process for the supervisors.

FluxBEATS is coordinated by the University of Helsinki. The additional beneficiaries of the doctoral network are Geological Survey of Finland, the University of Bergen (Norway), GEOMAR Helmholtz Centre for Ocean Research Kiel (Germany), University of Münster (Germany), Politecnico di Torino (Italy), and Université Claude Bernard Lyon 1 (France), along with academic and non-academic partners throughout Europe.

More information about the network can be found on the network's website: https://www.fluxbeats.eu/

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Tiivistelmä

Erkanevat laattarajat – arvoituksellisia merenpohjan alkuaineiden virtauksia tilassa ja ajassa

FluxBEATS on Marie Skłodowska-Curie Actions DN -ohjelman tohtorikoulutusverkosto, jonka tutkimus ja koulutus tähtää globaalien biogeokemiallisten alkuainevirtojen kokonaisvaltaiseen ymmärtämiseen toisistaan erkanevien laattojen rajoilla niin nykyajassa kuin geologisessa historiassa. Verkostossa on mukana kymmenen väitöskirjatutkijaa seitsemästä eurooppalaisesta instituutiosta. FluxBEATS-verkoston toiminta alkoi virallisesti marraskuussa 2024, mutta väitöskirjatutkijoiden rekrytointi tapahtui keväällä ja kesällä 2025. Verkosto on siis vielä toimintansa alkuvaiheessa.

Verkoston tavoitteita toteutetaan kahdessa tieteellisessä työpaketissa (kuva 1), jotka käsittelevät prosesseja maapallon vaipasta kuoreen ja kuoresta vesikehään. Verkoston koulutus sisältää esimerkiksi kolme kesäkoulua. Ensimmäinen kesäkoulu järjestettiin syyskuussa 2025 Islannissa (kuvat 2, 3, 4 ja kansikuva), ja sen teemana oli prosessit moderneilla erkanevilla laattarajoilla. Ensi vuonna Saksassa GEOMAR – Helmholtz Center for Ocean Research Kiel -keskuksessa järjestettävä kesäkoulu keskittyy merigeologiseen tutkimukseen. Vuonna 2027 Suomessa järjestettävä viimeinen kesäkoulu käsittelee proterotsooista ja arkeeista kallioperää.

FluxBEATS-hanketta koordinoi Helsingin yliopisto. Muut verkostoon kuuluvat edunsaajat ovat Geologian tutkimuskeskus, Bergenin yliopisto (Norja), GEOMAR – Helmholtz Center for Ocean Research Kiel -keskus (Saksa), Münsterin yliopisto (Saksa), Politecnico di Torino (Italia) ja Claude Bernard Lyon 1 -yliopisto (Ranska). Verkoston toimintaan osallistuu myös muita eurooppalaisia akateemisia ja akatemian ulkopuolisia yhteistyökumppaneita.