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Geophysical and geological modelling of the Sotkuma gneiss dome; Implications for the relationships of the Archean basement and the Paleoproterozoic cover in North Karelia, Eastern Finland

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Abstract

We studied the basement-cover relations in North Karelia, eastern Finland by modelling (1) regionally the thickness of the cover sequence and (2) the geometry of the Sotkuma dome (basement inlier). We utilized geological and aeromagnetic maps, together with the abundant structural data, in compilation of the cross-sections. The sections were adjusted by gravimetric modelling of the regional data and detailed profiles around the Sotkuma dome. A schematic 3D block-model visualizing regionally the depth and overall geometry of the basement-cover interface in North Karelia is presented.

Both the Archean basement complex and the Paleoproterozoic cover sequence display structures developed in response to collisional tectonic processes c. 1.92–1.82 Ga ago. Compared to the thickness of the Archean crust, the sedimentary cover sequence in North Karelia is rather thin; the modelling along the regional gravity profile indicates overall cover thicknesses around 4 to 6 km. Between the Sotkuma and Kontiolahti domes the cover rocks of the Höytiäinen Belt form an almost upright outlier between the basement blocks. Within the Outokumpu Area the basement-cover interface is interpreted as a very open synformal structure between the Sotkuma dome and the Maarianvaara basement inlier.

According to the detailed gravity profile modelling around the Sotkuma dome, the basement-cover interface dips steeply (in the north and west) or moderately (in the south) outwards. The eastern margin of the dome is modelled as a step-like structure of west dipping thrust slices of basement gneiss. The modelled geometry, the structural features and the pattern of mafic dykes within the dome, are interpreted with a multistage genesis: (1) repeated rifting and normal faulting (N-margin ~2.2 Ga; E-margin ~2.1 Ga) during the extensional basin formation stage, and (2) crustal shortening (~1.9 Ga) and associated thrusting.

In our modelling the Sotkuma basement window represents the northernmost part of a large ‘basement high’ block, spatially extending some 30 km south. Suitability of the term ‘dome’ – with genetic and geometric connotations – is questioned within the study area and usage of the neutral term ‘basement inlier’ is suggested instead.

Keywords: Basement inlier, basement-cover relationships, gravimetric modelling, gneiss dome, Sotkuma, North Karelia, Finland

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1. Introduction

The structural style of the Karelia foreland during the Svecofennian Orogeny has been discussed for as long as the research history exists in this field. The basement domes (inliers) have stimulated ideas of their origins and of the basement depth variation in different parts of the area.

The Sotkuma dome has been mapped in detail (e.g. Huhma, 1975 and references therein), but the 3D-structure and the origin of the inlier have remained unclear. A better understanding of the inlier geometry would substantially improve the overall structural reconstruction of the study area. The work herein contributes to several classical research issues in eastern Finland: (1) the nature and origin of the ‘mantled gneiss domes’ and other basement inliers, (2) the reason for the contrasting structural styles between the Outokumpu Area and the Höytiäinen Belt and, finally, (3) the overall style of the basement deformation within the collisional foreland.

The complex foreland deformation issue can be condensed into the following three main questions: Were cover and basement deforming together (thick-skinned model) or was cover detached from the basement (thin-skinned model)? How was the degree and the distribution of the granitoid basement ductility. What was the role of inherited basin stage structures and their reactivation during the crustal shortening. The study of the basement-cover relationships is a key to better understanding of the foreland deformation.

The impetus for the geophysical field work was to test the applicability of gravimetric method around the Sotkuma Dome where the density difference between the modelled units (basement granitoids vs. cover metasediments) is relatively low (60–110 kg/m^3). One reason for the regional geophysical interpretation was originally to prepare for the massive seismic experiment (FIRE 2001–2005; see Kukkonen & Lahtinen, 2006). Preliminary results of our work have been presented in two symposium abstracts (Kohonen & Elo, 1991, Kohonen et al., 2003).

We use the detailed gravimetric study around the Sotkuma basement inlier as a test bench for alternative geometries and structural models, and apply the regional gravity data in the modelling of the Paleoproterozoic sedimentary cover thickness in North Karelia. The main intention of our regional study is to depict the overall geometry and major structural features of the B–C interface; both along the exposed contact traceable in geological maps and at the unexposed Archean – Proterozoic boundary concealed by the sedimentary cover.

In the following, we first present a regional review and the modelling of the B–C interface on a regional scale. The results of the Sotkuma dome case study are interpreted and discussed within this regional framework. Finally, we compare the features of the Sotkuma dome to the other Archean inliers in North Karelia and discuss their origins.

2. Geological setting

The ancient margin of the Karelia Craton experienced a sequence of tectonic events referred to as Svecofennian Orogeny c. 1.92–1.82 Ga ago (e.g. Lahtinen et al., 2005). In the western parts of the Karelia Province both the Archean basement gneisses (~ 2.8–2.7 Ga) and the Paleoproterozoic cover rocks (~ 2.4–1.92 Ga) display structures developed in response to collisional tectonic processes. The stratigraphic nonconformity between the Archean basement and the Paleoproterozoic supracrustal sequence is the most fundamental geological boundary in eastern Finland and in what follows is termed as 'basement – cover interface' (B–C interface).

Elliptically shaped Archean gneiss domes are characteristic of the Karelia Province (e.g. Eskola, 1948; Brun, 1980; Brun et al., 1981; see Fig. 1). Within the study area two geological map features, Sotkuma and Kontiolahti domes (Fig. 2), are important elements in structural modelling of the B–C interface. Both domes are also visible as negative anomalies in a regional gravity (Bouguer anomaly) map (Fig. 3).

The original concept of 'mantled gneiss domes' by Eskola (1948) has dominated the naming convention of the basement inliers within the Karelia Province, although the idea of diapiric uplift origin for the 'domes' has been questioned and several alternative models for basement inlier origin have been presented (e.g. Gaal et al., 1975; Park, 1981; Polyanskii & Efremov, 1989; Ward, 1988; Kohonen, 1995). We follow the established regional terminology (e.g. Sotkuma Dome, Kontiolahti Dome) but use the term 'dome' purely in a descriptive sense – simply meaning an Archean basement window surrounded by rocks of the younger cover sequence.

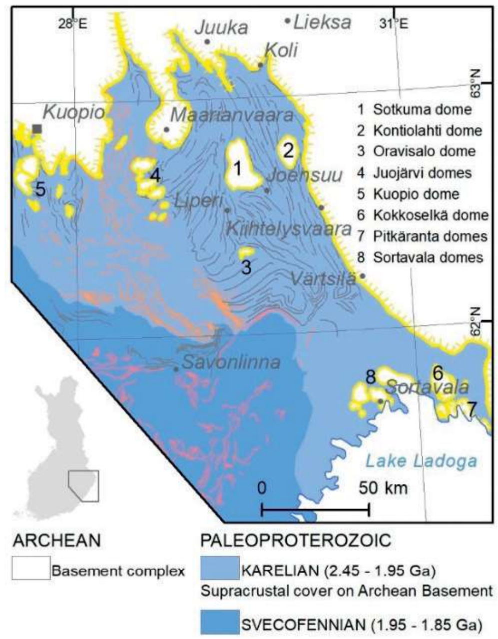
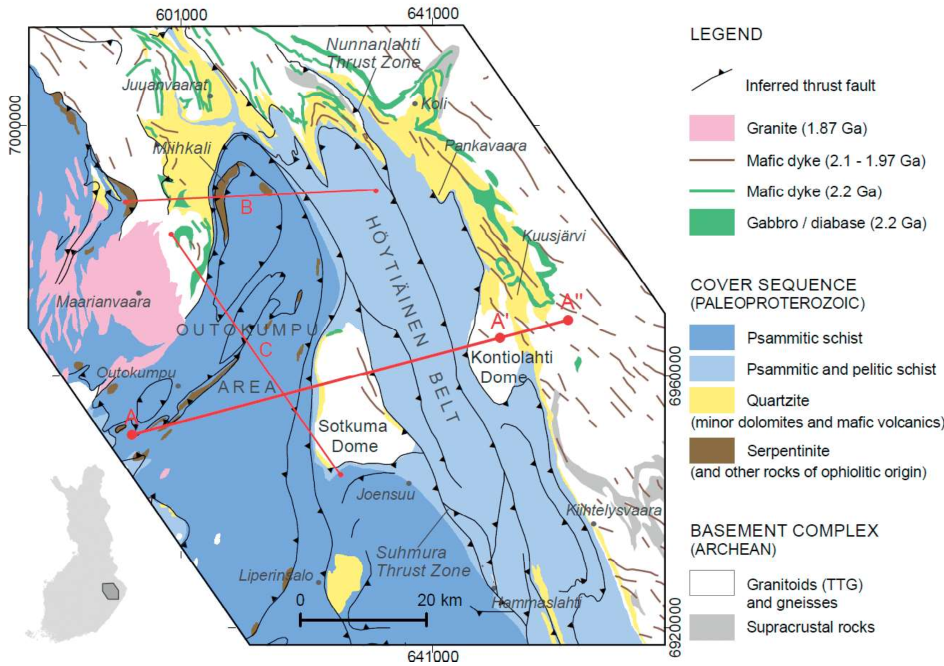


Figure 1. Generalized geological map and distribution of the basement domes in eastern Finland and north Ladoga region (Russia). The nonconformity between the Archean basement complex and the Paleoproterozoic cover is highlighted in yellow. The overall trends of the foliation (blue) and migmatite structures (orange, red) are indicated (lacking in Russian part of the map). Location is shown in the index map (lower left).

The study area is located in North Karelia (eastern Finland), and corresponds to the Höytiäinen Belt and Outokumpu Area (see Fig. 2) in the regional terminology proposed by Nironen et al. (2002). These two structural domains have been recognized since the classic regional work by Väyrynen (1939). The Sotkuma dome is located at the boundary of those Paleoproterozoic domains.

Within the Höytiäinen Belt the autochthonous (or parautochthonous) cover schists are squeezed and buttressed against the eastern basement block to form rather upright, tightly folded synformal outlier of the cover (e.g. Kohonen, 1995). The cover schists of the Outokumpu Area are understood to represent a system of allochthonous thrust sheets (Outokumpu nappe complex) transported tectonically from the west to their present location (e.g. Koistinen, 1981; Sorjonen-Ward, 2006). In

Figure 2. Simplified geological map of the study area. The location of the regional profile (the Bouguer anomaly interpretation A–A' and the geological section A–A'') is indicated (see Figs. 3, 4 and 5). The locations of the reference sections (B) by Lahti et al. (2016) and (C) by Heinonen et al. (2016) are also shown. The map extent (the NW and SE corners) corresponds to that of Fig. 3. Geographic location is indicated in the small index map of Finland (lower left).



this paper, we focus on the Sotkuma dome and on the overall geometry of the B–C interface within the study area. A comprehensive regional overview of the Karelian supracrustal rocks can be found in Laajoki (2005).

Väyrynen (1939) was the first to apply 'Alpine ideas' with thrust tectonics (Wegmann, 1928) to regional mapping in North Karelia, proposing a major thrust zone between the Höytiäinen Belt and the Outokumpu Area. Ward (1987) named the corresponding zone as 'Suhmura Thrust Zone', extending in an NNW-SSE direction from Hammaslahti district (Suhmura township) via the eastern contact of the Sotkuma dome to Juuanvaarat region in the north (Fig. 2). Nevertheless, the Suhmura Thrust Zone is not a solitary, distinct fault plane, but rather a spatially indefinite system of subparallel anastomosing thrusts (for further details see Ward, 1987; Sorjonen-Ward, 2006).

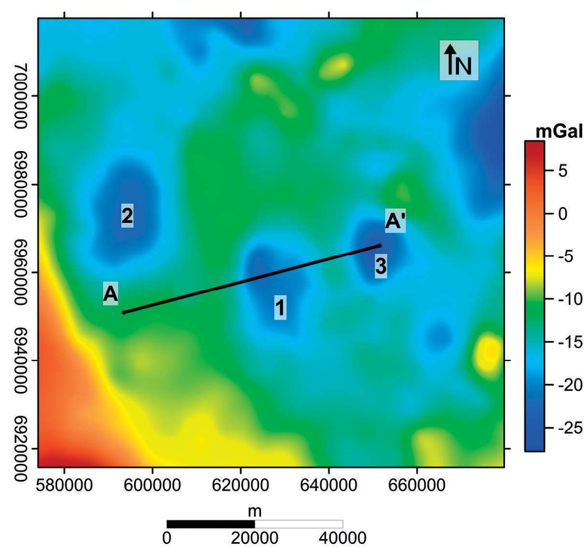


Figure 3. Bouguer anomaly map of the study area and the profile A–A' interpolated from the Fennoscandian Bouguer anomaly grid. Locations of the basement inliers are indicated (1: Sotkuma dome, 2: Maarianvaara inlier and 3: Kontiolahti dome).

3. Methodology

We started our research by making structural interpretation and by compiling the geological cross-sections. In the next phase, we adjusted the sections in accordance with the results of the geophysical modelling. Finally, we made a 3D-model of the study are by connecting cross-sections with tie lines using Gemcom Surpac software. Finally, we generated a 3D block-model visualizing the morphology and depth of the basement-cover interface.

The study area is one of the most densely mapped areas in Finland, and the amount of different geological information and geoscience data is overwhelming. The geological modelling utilized: (1) the previous interpretations and structural reviews (e.g. Gaál et al., 1975; Koistinen, 1981; Ward, 1985, 1987; Kohonen, 1995), (2) geological maps; both published (e.g. Huhma, 1971; Laiti, 1985) and unpublished (e.g. Ward, 1985; Outokumpu company archive maps, field maps of the corresponding author), (3) field reports (e.g. Kohonen et al., 1989). The geological interpretation was supported by geophysical anomaly maps with prominent features corresponding to the mapped geological units. Some key locations within the Sotkuma dome were field checked during the final stages of the tardy research project. The overall framework for the structural modelling was adopted from Kohonen (1995). The resolution of the resulting E-W oriented geological cross-sections was selected to display the uppermost 10 km of the crust.

The geophysical conclusions are based on aeromagnetic data, regional gravity data and detailed gravity profiles around the Sotkuma dome. The low-altitude aeromagnetic maps are representations of the data measured by the Geological Survey of Finland. These data are acquired with 40 m average flight altitude, traverse separation 200 m and flight direction E-W (Airo, 2005).

The WSW – ENE oriented regional gravity profile represents, from east to west, the Kontiolahti dome, Höytiäinen Belt, Sotkuma dome and the Outokumpu Area (see Figs. 2–5). The data used in regional modelling was the Fennoscandian 2.5 km x 2.5 km Bouguer anomaly grid (IGSN 71 gravity system, GRS80 normal gravity formula, Bouguer density 2670 kg/m^3; Korhonen et al., 2002). In Finland, the grid is based on the observations of the Finnish Geodetic Survey and the Geological Survey of Finland. Four detailed Bouguer anomaly profiles (see Figs. 6 to 11) with a station spacing of 20 m were measured on ground surface across the boundaries of the Sotkuma basement inlier by the Geological Survey of Finland (FOGN gravity system, normal gravity formula 1930 with an additional subtraction of 14.00 mGal, Bouguer density 2670 kg/m^3; Elo, 2013). The reader should note that there is a difference of approximately 9 mGal in the Bouguer anomaly levels of the two systems.

The detailed profiles allow local anomalies, caused by overburden thickness variations or by individual mafic dykes, to be identified and modelled. Their amplitude together with curvature contain more information on the zero levels and the Sotkuma dome geometry than the regional data. On the other hand, the profiles are limited in length to the vicinity of the contact between the basement and the sedimentary cover.

Bouguer anomaly maps are widely used in geological applications, because they display, in a straightforward way, lateral density variations in overburden and bedrock. Total gravity is predominantly influenced by the mass and figure of the Earth, regional and local topography and acceleration due to the Earth's rotation, but density variations of bedrock and overburden in the immediate vicinity of measuring points also cause the force of gravity to vary in a discernible way. Measured gravity values are reduced into gravity anomalies in such a way that features under study stand out as clearly and correctly as possible.

The gravity profiles were modelled using the maximum and minimum density contrasts between the Archaean basement gneisses and Proterozoic cover rocks, which gives a good estimate of the

Table 1. Density data for the study area rocks

Study area rock type	Density (kg/m³)	Standard deviation	Number of density determinations	Reference
Mica schist*	2745 (mean)	88	1367	Puranen et al. (1978)
Mica gneiss*	2724 (mean)	87	1927	Puranen et al. (1978)
Gneissose granite*	2630 (mean)	59	2453	Puranen et al. (1978)
Granite gneiss*	2651 (mean	63	563	Puranen et al. (1978)
Outokumpu Area cover rock	2700 (mean) 2725 (modal)	51	368	Ruotoistenmäki and Tervo (2006)
Höytiäinen Belt cover rock	2715 (mean) 2700 (modal)	70	183	Ruotoistenmäki and Tervo (2006)
Sotkuma Dome basement rock	2654 (mean) 2630 (modal)			Ruotoistenmäki and Tervo (2006)
Outokumpu Area cover rock 1	2720 (average)			Leväniemi (2016)
Outokumpu Area cover rock 2	2740 (average)			Leväniemi (2016)
Basement rock	2670 (average)			Leväniemi (2016)
Outokumpu Area cover rock	2721 (mean)	131	457	This paper
Höytiäinen Belt cover rock	2710 (mean)	72	199	This paper
Sotkuma Dome basement rock	2638 (mean)	47	23	This paper

*Data covering whole Finland

uncertainty in modelling. Modelling with the maximum density contrast results in minimum estimates for the depth extents of the cover rocks, which is one of the most reliable parameters to be obtained from the gravity data.

Puranen et al. (1978) examined the densities of more than 30 000 rock specimens in the petrophysical data base of the Geological Survey Finland. The used density contrasts are a recapitulation of the studies by Puranen et al. (1978), Ruotoistenmäki and Tervo (2006) and Leväniemi (2016). We analyzed density data outside and inside the Sotkuma dome with the results shown in Table 1. Even though for a single rock type it is easy to assign a definite density value, for larger volumes containing several rock types the volumetric share of each rock type is not exactly known while, in addition, neither the average nor the mode of the sampled densities can be guaranteed to be precise. In this study, the minimum and maximum densities (kg/m³) for the cover rocks (2720 and 2740 in the Outokumpu Area; 2710 and 2720 in the Höytiäinen Belt) and for the basement (2630 and 2650) were used. No density data were available for the modelled mafic units, so their density was optimized at the intermediate stage of modelling, and finally fixed to be 2910 kg/m³, which is within the normal density range for mafic intrusive rocks (Puranen et al., 1978).

In gravity modelling, the initial model, consisting of polygonal cross-sections with appropriate strike lengths, was set according to the geological framework and made simple enough for constrained optimization, using minimal number of bodies and faces and linear or nearly linear zero level. At the final stage, the zero level, the location and dip of the contacts and the depth extent of the bodies were optimized to minimize the difference between the measured and calculated anomalies. The modelling was done using the maximum and minimum density contrasts. For the detailed profiles, we include only the figures of the modelling with the maximum density contrast, but the conclusions are based on the modelling with both the density contrasts.

4. Thickness of the cover sequence; a regional outline

The thickness of the cover sequence in North Karelia has been speculated on since the classic studies by Wegmann (1928) and Väyrynen (1939). The FIRE reflection seismic program (2001–2005) was anticipated to solve the question definitively, but the contact between the basement and the cover is hard to depict reliably from the seismic data (Sorjonen-Ward, 2006). The reason is plausibly the pervasive metamorphic recrystallization of the sedimentary cover and resulting disappearance of the originally distinct lithological boundary.

The cover thickness in North Karelia has not previously been regionally modelled as a surface. Even if numerous structural interpretations and schematic cross-sections are available (e.g. Wegmann, 1928; Väyrynen, 1939; Gaal et al., 1975; Park & Doody, 1991), many old interpretations lack the vertical scale. The variation of the presented structural interpretations is large, both in the suggested deformation style and in the range of the cover thickness estimates. For example, the schematic, basement thrust slice dominated profiles by Park & Doody (1991) suggest mid-crustal depth (>20 kms) for the B–C interface between the Sotkuma dome and Outokumpu, whereas the recent papers from the Outokumpu Area (Lahti et al., 2016; Heinonen et al., 2016) estimate the cover thickness around 5 km. Lahti et al. (2016) present an E–W profile from the Miihkali area (~20 km north of the Sotkuma dome; for location see Fig. 2) transecting the N-parts of both the Outokumpu Area and the Höytiäinen Belt. Heinonen et al. (2016) provide detailed geophysical and geological modelling along the Sukkulansalo National Test Line (SNTL) at the SE flank of the Maarianvaara inlier. Their geological cross-section is extended from the SNTL towards SE up to the Sotkuma basement inlier (for location see Fig 2). In their interpretation the B–C interface and the lowermost part of the cover sequence are complicated by assumed intrusions of the Maarianvaara type granite.

The Sotkuma and Kontiolahti domes cause distinct negative anomalies in the Bouguer anomaly map (Fig. 3), and here we present a new gravity modelling with two sets of petrophysical parameters along profile A–A' (Fig. 4A). Between the Sotkuma and Kontiolahti domes (Höytiäinen Belt) the schists are squeezed and buttressed between the basement blocks to form a steeply west dipping, tight outlier of the cover (Fig. 4B; see also Kohonen, (1995). The estimated cover thickness is 6.3 ± 2.4 km, with an abrupt change some 6 km from the exposed eastern margin of the Sotkuma basement inlier. We propose that this zone corresponds to one of the major Suhmura thrust zone faults at the regional scale (see Figs. 4 and 6).

In the western part of the profile A–A' (between Sotkuma and Outokumpu) the B–C interface appears to be geometrically simple compared to the complex, polyphase fold structures of the cover (e.g. Koistinen, 1981). According to the interpretation by Kohonen et al. (2003) the cover within the Outokumpu Province forms an open synformal structure with dips 50 to 70 degrees at the eastern limb (Sotkuma dome) and 20 to 30 degrees at the western limb towards the Maarianvaara granite/ basement block. The thickness of the cover is modelled to be 4.3 ± 1.1 km.

Compared to the local thickness of the Archean crust (> 40 km) and to some previous estimates and models (e.g. Bowes et al., 1984; Park & Doody, 1991), our gravity modeling suggest that the cover is thin. Even accepting the uncertainty of the model, it seems implausible that the cover thickness would exceed 10 km anywhere along the profile.

The 3D block-model (Fig. 5) reflects the geometries of the structural modelling along geological cross-sections (see Electronic Appendices). The geological cross-sections of the upper crust, in turn, represent one structural summation of the region. In short, the presented block-model is an explicit geological model which was adjusted to be consistent with the overall outcome of the geophysical modelling. The model visualizes the interpreted variation of the cover thickness within the study area and provides a regional framework for the Sotkuma dome as a part of the B–C interface.

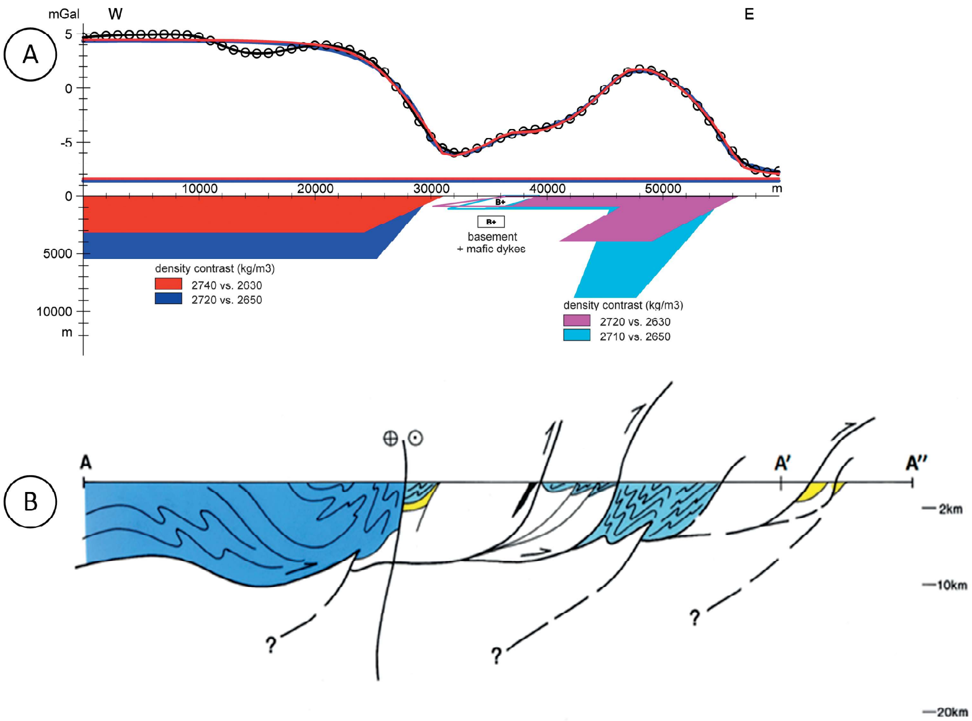


Figure 4. A) Gravity modelling along the profile A–A' (see Figs. 2 and 3) using high (red) and low (blue) density contrasts. The curve with open circles in black represents the interpolated regional Bouguer anomaly, red and blue curves and lines are the calculated anomalies and the zero levels of the respective models consisting of polygonal cross-sections with a strike length of 20 km. The blue curve is partly masked by the red curve. The profile crosses obliquely the western contact of the Sotkuma dome which makes the dip appear gentler than it is in reality. B) Schematic geological interpretation along the profile A–A''. The section displays the overall structural set-up of the region. The depth of cover outliers corresponds to that of the ultimate maximum estimate. Note the difference in length between the profiles A–A' and A–A''.

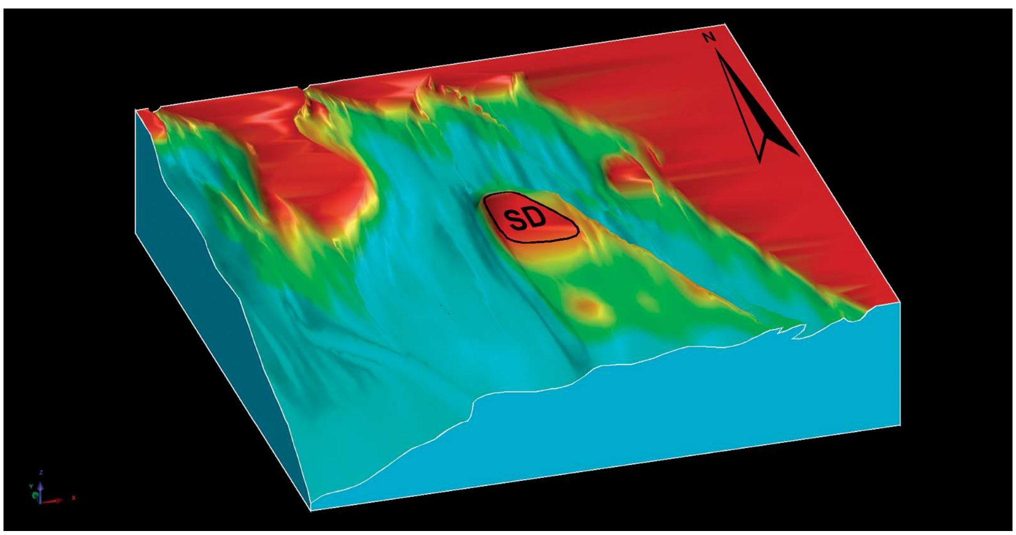


Figure 5. A schematic 3D block-model visualising the interpreted morphology and depth of the basement-cover interface. The location of the mapped basement-cover boundary defining the present map extent of the Sotkuma dome (SD) is indicated.

5. The Sotkuma dome: a case study

5.1. General features

The Sotkuma dome is a peculiar geological feature. In geological maps it resembles the classic 'mantled gneiss domes' (cf. Eskola, 1948) of the Ladoga region (see Fig.1), but the shape is more irregular and it is not symmetrically mantled by the lower-most cover sequence. Several sections across the Sotkuma dome in an E-W direction (across the structural trend of the Höytiäinen Belt) are available (e.g. Wegmann, 1928; Bowes et al. 1984; Park & Doody, 1991) and all those assume a thrust fault as the eastern margin of the inlier. This far no profiles in N-S direction have been presented and thus the overall 3D geometry of the inlier has remained unclear.

The lithology of the Sotkuma dome is dominated by granitoids with a more or less gneissic appearance. The eastern and northern parts consist mainly of granodiorites (partly porphyritic) with some leucogranites; gneissic to migmatitic granitoids are more typical in the southwestern parts. At the eastern and northern margins of the dome elongated mafic intrusions, traditionally termed metadiabase dykes, are abundant (Fig. 6). The cover sequence consists mainly of psammitic mica schists containing semipelitic intercalations. Along the dome margins sporadic remnants of coarse clastics (arkosic quartzites and various types of conglomerates) have been reported. The details of the lithology around the dome have been described by Mattila (1971), Huhma (1975) and Äikäs (1990a).

The geometry of the B–C interface around the Sotkuma dome was modelled using gravity and aeromagnetic data. In the aeromagnetic map (Fig. 7), the basement area with granitoid rocks shows weak anomaly patterns (low relief), with some strong anomalies associated with magnetite-bearing mafic dykes and weak anomalies due to paramagnetic mafic dykes. The areas with Paleoproterozoic metasedimentary rocks show more variation. The Outokumpu Area is characterized by sinuous, layer parallel belts of anomalies and localized strong magnetic anomalies due to the lensoid serpentinites. The Höytiäinen Belt generally shows weak anomaly patterns though linear, bedding-parallel anomalies (pyrrhotite bearing graphitic layers) are present in the central parts (upper right part of Fig. 7).

With the exception of the eastern margin, a fairly continuous aeromagnetic anomaly caused by graphitic, sulfide-bearing schist or a calc-silicate rock (skarn) horizon encloses the dome. At the margin of the dome, the mafic dykes are clearly of two types: in the northern part they cause strong aeromagnetic anomalies (nearly 3000 nT at the altitude of 40 m) indicating ferrimagnetic minerals, while most of the dykes cause barely discernible aeromagnetic anomalies due to paramagnetic minerals. The strike of the dykes is nearly parallel with respect to the exposed B–C interface (the Sotkuma dome margin).

5.2. Detailed gravity profiles

The gravimetric models (Figs. 8–11) are shown for the maximum density contrast, the line with open black circles represents the measured Bouguer anomaly in the old system of the Geological Survey of Finland, as explained earlier. The models consist of polygonal cross-sections perpendicular to each profile with strike lengths chosen so that the cover rocks enclose the Sotkuma dome as a 3D structure. Each calculation was done for the whole structure.

The interpretation of the detailed gravity profile 1 (Fig. 8) indicates basement-cover interface dip of 70° to 80° to the north at the northern contact of the Sotkuma dome. The minimum cover thickness is 3.7 km and with the minimum density contrast, the estimated thickness would be more than 5 km.

The steep northern contact and the NE-nook of the dome in particular are of special interest here. The strongly ferrimagnetic mafic intrusions (Figs. 6 and 7) show geophysical signatures identical to the gabbroic intrusions of the nearby Koli area in

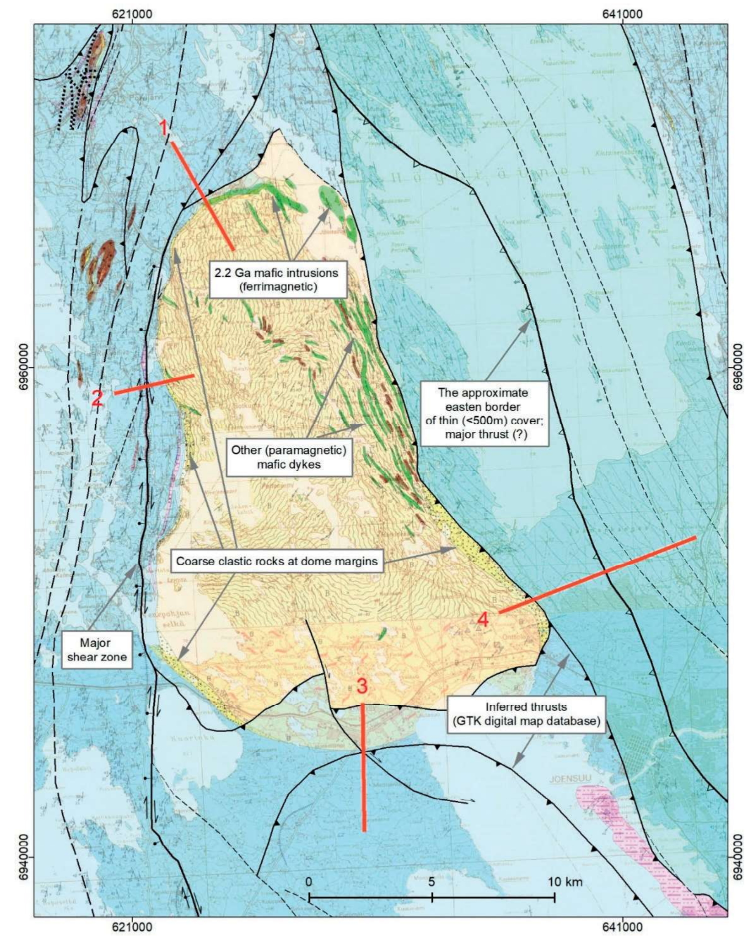


Figure 6. Geological map combination (printed map sheets overlain by digital GTK dataset) of the Sotkuma basement inlier. Locations of the detailed ground gravity profiles are shown. The inferred thrusts and other essential features are highlighted. The poor exposure of the southern margin is reflected in the dissimilarity of the geological compilations (the digital dataset and the printed map sheet 4223). Note the pattern of the structural trend lines (printed maps) within the basement. The map extent corresponds to that of Figure 7. For the original map compilations with detailed legends see the GTK digital map database (reference: Bedrock of Finland) and the printed map sheets 4223 (Laiti, 1985) and 4224 (Huhma, 1975).

the east (for location see Fig. 2). These differentiated, sill-like gabbros have been studied in detail and dated (age ~2.2 Ga; see Vuollo & Piirainen, 1992; Vuollo & Huhma, 2005; Hanski et al., 2010). These intrusions have a specific geological setting and nearly diagnostic magnetic signature and have been widely used as regional stratigraphic markers in eastern Finland.

Along the western contact a discontinuous 'basal formation' with coarse arkosic rocks, minor calc-silicates and calc-silicate cemented conglomerates and breccias have been reported (Mattila, 1971; Huhma, 1975). The contact between the basal formation and the cover schist is not exposed. The cover schist next to the contact displays shearing and a strong lineation plunging consistently SSW.

Gravity modelling along the profile 2 (Fig. 9) gives basement-cover interface dip of 75° to 80° to the west and minimum cover thickness greater than 1.6 km at the western end of the profile increasing to the west. With the minimum density contrast, estimated thickness is more than 4 km increasing to the west.

The southern margin of the basement dome is practically unexposed and even the location of the surface contact is vague. According to the gravity modelling, the surface contact is located at about 1.5 km along the profile with the basement-cover interface dipping 50° to 65° to the south (Fig. 10). The calculated minimum cover thickness is greater than 1.7 km; with the minimum density contrast, the estimated thickness is 4.4 km. Unlike profile 2, profile 3 indicates no consistent increase of the cover

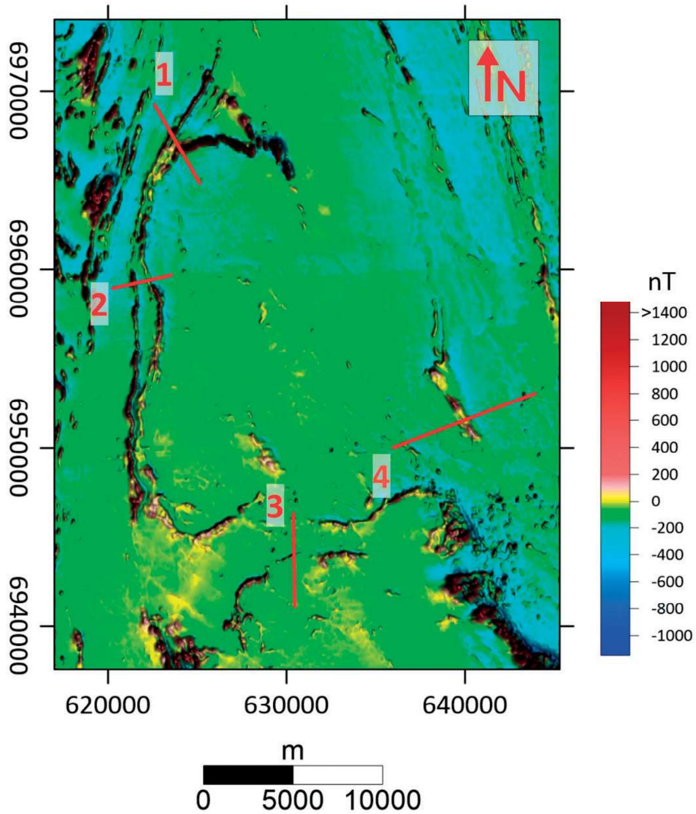


Figure 7. Low-altitude aeromagnetic map of the Sotkuma area with the locations of the detailed ground gravity profiles 1, 2, 3 and 4. Data: Geological Survey of Finland (Airo, 2005).

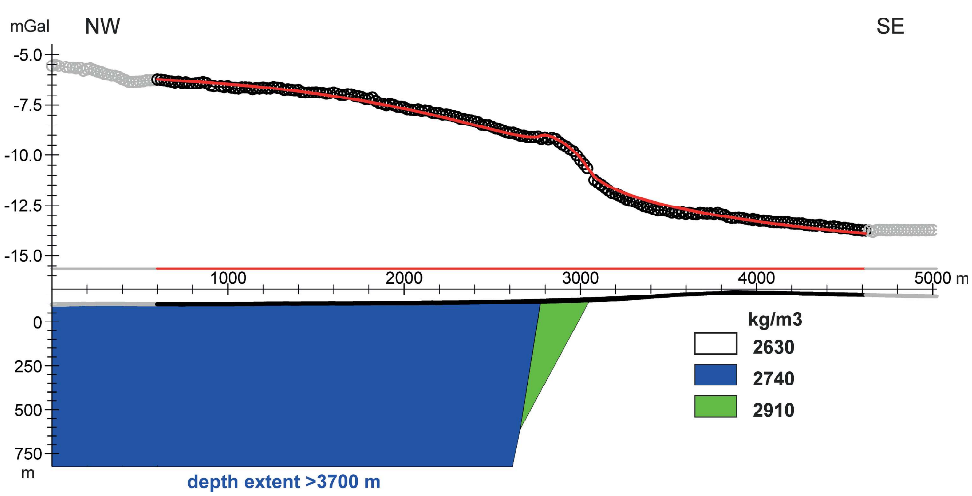


Figure 8. Maximum density contrast model for the detailed gravity profile 1. The calculated anomaly and its zero level are shown in red and the measured anomaly in black. The blue area represents Outokumpu cover rocks, green mafic rocks and the background (white) corresponds to the granitoid basement.

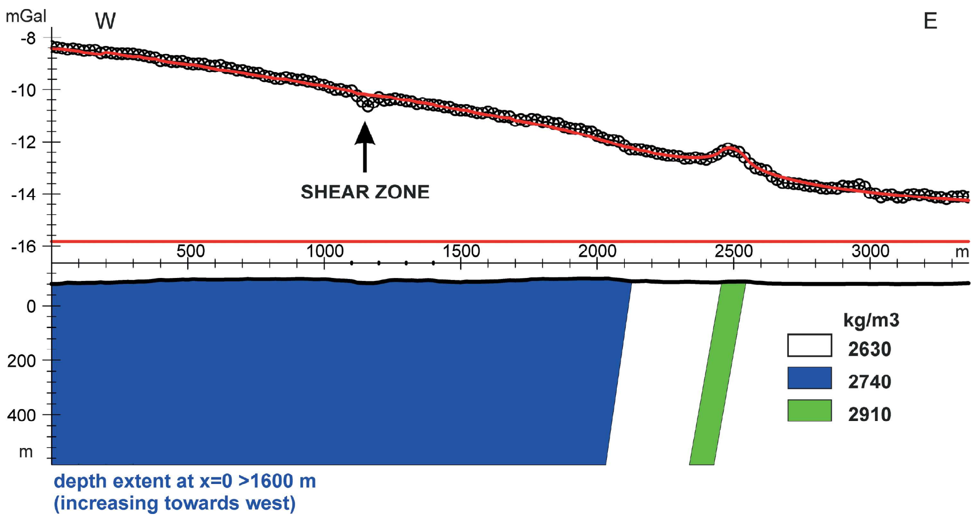


Figure 9. Maximum density contrast model for the detailed gravity profile 2. The calculated anomaly and its zero level are shown in red and the measured anomaly in black. The blue area represents Outokumpu cover rocks, green mafic rocks and the background (white) corresponds to the granitoid basement.

thickness with the increasing distance from the dome contact (Figs. 10 and 12).

Since the early interpretations (e.g. Wegmann, 1928; Väyrynen, 1939) the eastern margin of the Sotkuma dome has been understood as a thrust fault. The Sotkuma dome and the tiny basement inlier at Hammaslahti (see Fig. 2) are located along the major Suhmura thrust zone (Ward, 1987; Sorjonen-Ward, 2006). Therefore, the eastern contact is structurally more complicated compared to the other margins of the dome. Here the main composite structure in the cover schists, consisting of bedding and foliation, dip some 30° to 40°west (towards the dome; Huhma, 1971, 1975). These features are interpreted to reflect westwards dipping tectonic slices of basement thrust over the cover mica schist next to the dome (Figs. 4 and 11).

The granitoids and abundant metagabbros ('metadiabase dykes') were observed to show localized, narrow shear zones dipping steeply to WSW, but generally the basement rocks show no strong shearing or penetrative tectonic fabric even at the proximity of the mapped eastern dome contact. Huhma (1975) reported easterly (outward) dipping bedding in coarse clastic metasediments, cross-cut by prominent westerly (inward) dipping foliation. This, together with the overall transposition (SSE-NNE) of the basement granitoids (see structural trend lines in Fig. 6), indicates that both the basement and the cover rocks were subjected to ductile deformation and the B–C interface here locally dips to the east.

The eastern dome margin was modelled as a step-like reverse fault (or thrust fault) geometry (Fig. 11). According to the profile 4 interpretation, the thickness of the cover, being shallow on the western side, increases suddenly to more than 1.8 km on the eastern side. With the minimum density contrast, the cover thickness increases to more than 3.2 km.

5.3. Origin of Sotkuma basement inlier

The NNE trending, west-dipping foliation and locally east dipping (or even overturned?) B–C interface at the eastern margin indicates thrusting towards the E or NE as an important factor

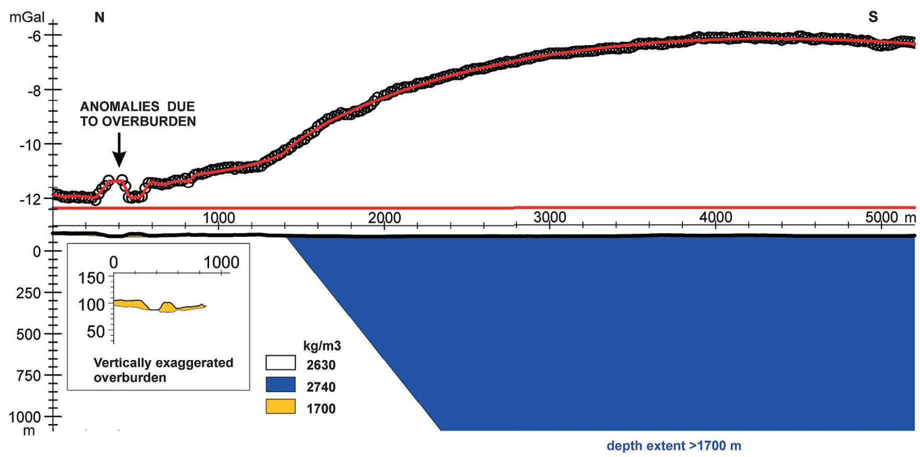


Figure 10. Maximum density contrast model for the detailed gravity profile 3. The calculated anomaly and its zero level are shown in red and the measured anomaly in black. The blue area represents Outokumpu cover rocks while the orange color represents overburden. The background (white) corresponds to the granitoid basement.

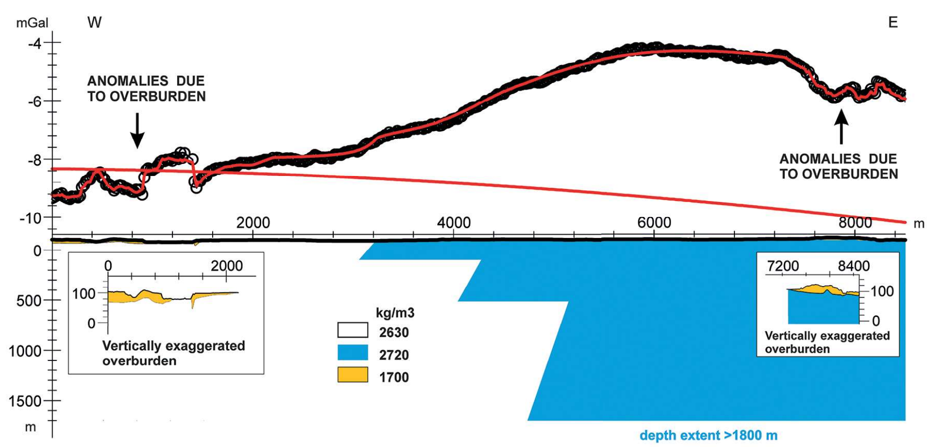


Figure 11. Maximum density contrast model for the detailed gravity profile 4. The calculated anomaly and its zero level are shown in red and the measured anomaly in black. The light blue area represents Höytiäinen cover rocks while the orange color represents overburden. The background (white) corresponds to the granitoid basement.

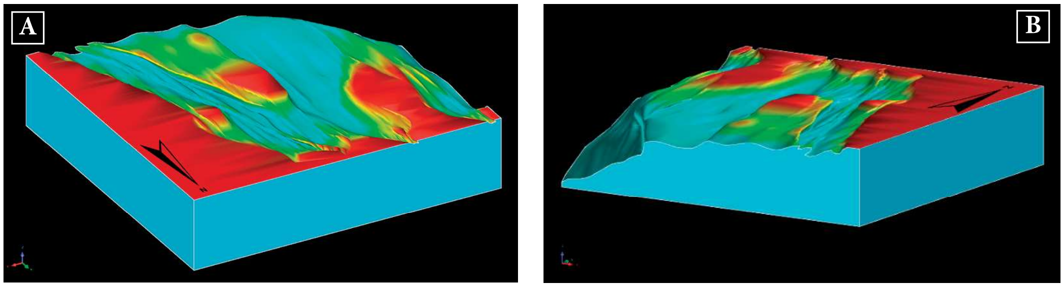


Figure 12. Two snap-shots (see also the same 3D block-model in Figure 5) visualizing some details of the modelled morphology of the Sotkuma dome (in the middle). A) The northern margin is interpreted as abruptly deepening B–C interface; viewed from the NE B) The west dipping eastern margin with the main fault parallel to the overall structural trend of the Höytiäinen Belt. Note the very thin cover on eastern side of the mapped basement-cover boundary; viewed from the SE. (For the closer views of the model – see Electronic Appendices.)

controlling the present form of the dome. The general feature of the gravity modelling around the dome is that the cover thickness seems to decrease from the north towards the south (see Fig. 12). However, the modelled geometry and the observed structural features of the Sotkuma dome leave space for alternative explanations.

The steeply dipping geometry of the B–C interface at the northern margin of the dome restricts the applicability of a simple structural explanation based solely on an antiformal fold or a basement involving thrust-ramp with an NNW-SSE strike. With a thrusted wedge of basement breaching the cover, the most expected map (plan section) geometry would be an elongated arcuate thrust slice rather than the roughly triangular form of the Sotkuma inlier. By assuming a sidewall ramp (or transfer zone) at the northern margin (Fig. 13, Model A) however the observed geometry can be achieved, but the lack of shearing or other observed structures transverse to the major NNW-SSE strike makes this alternative implausible.

Alternatively, if the abundance and pattern of the mafic dykes along the northern and eastern margin manifest the role of early rifting and extensional normal faults in the generation of the basement block structure, an alternative model with the observed geometry can be envisaged. The ferrimagnetic mafic intrusions at the northern margin (see Fig. 6) play the key role both in the preferred explanation for the inlier geometry and in the proposed genetic model for the Sotkuma dome.

The ferrimagnetic intrusions are correlated to the 2.2 Ga gabbros in the Koli area. The emplacement of the 2.2 Ga mafic intrusions is related (Kohonen & Marmo, 1992) to a major intracratonic rifting stage of the Karelia Craton. The rifting caused significant vertical movements and changes in the basin systems with a major depositional unconformity related to the 2.2 Ga rifting. The unconformity has been reported both from the adjacent Koli area (Kohonen & Marmo, 1992) and from the Kainuu Belt (the Nenäkangas unconformity; see Laajoki, 2005 and references therein). In the Koli area the sill-like gabbros display at Kuusjärvi (for location; see Fig. 2) lateral ramp-like, across-strike features and, most importantly, these rift-related (gabbro emplacement stage) geometries correlate here with the mapped B–C interface geometry (for details; see Fig. 35 in Kohonen & Marmo, 1992). At the N-margin of the Sotkuma dome even the magnetic anomaly pattern with apparent strike-slip offsets resembles the Koli area example.

We conclude, that the steep northern margin originally represents a normal fault from early basin stages. The preferred geometry modified by the later thrust faults is presented in Figure 13 (Model B). The model allows thin-skinned tectonic style without major involvement of the

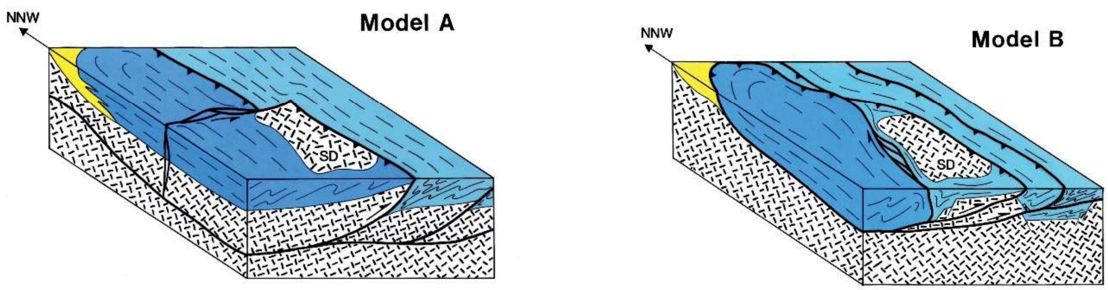


Figure 13. Schematic block diagram models addressing the observed geometry of the Sotkuma Dome. Model A assumes a lateral ramp related to a thrust system involving the basement. In Model B the major detachment is located at the basement-cover interface and horst structure, formed during the previous rift stage, is detached from the basement.

basement complex and offers a sound alternative to the previous diapiric (Brun, 1980) and the fold interference (Park, 1981) explanations.

In terms of geological evolution, the precursor of the Sotkuma dome is thus understood as the northern part of a large basement block relatively uplifted during the early extensional basin formation stage about 2.2–2.0 Ga ago (corresponding to the age of rift-related mafic intrusions in eastern Finland; Vuollo & Huhma, 2005; Huhma et al., 2018). The accurate geometry of the post-rift pattern of basins and horst blocks is not possible to reconstruct, but the spatial connection of rift-related mafic dykes and the basin set-up is widely acknowledged both regionally (e.g. Ward, 1988; Kohonen & Marmo, 1992; Kohonen, 1995) and across the Fennoscandian shield (e.g. Melezhik, 1991; Melezhik & Hanski, 2013). The craton margin, previous basins and the relatively uplifted basement blocks (Fig. 14) were later modified by thrusts during the stages of crustal shortening (Kohonen, 1995).

The area south of the Sotkuma dome, between Liperinsalo and Hammaslahti (Fig. 2) is poorly exposed but all the observations show very gentle or nearly horizontal foliation and bedding planes (Laiti, 1985; Ward, 1985, 1987) – a feature very different from both the Höytiäinen Belt in the east and the steeply dipping, approximately N–S trending shear zone extending south from the

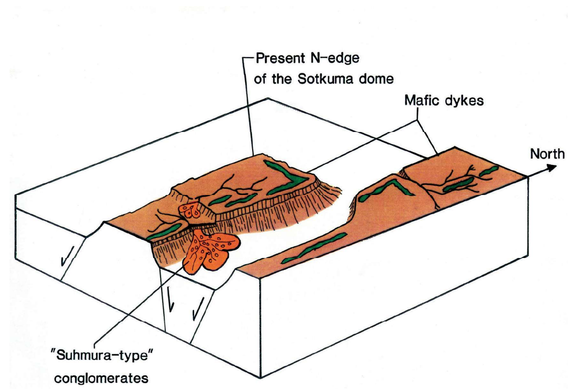


Figure 14. A simplified block-diagram illustrating the assumed basement topography created by early extensional movements.

western contact of the dome (Figs. 2 and 6). The most apparent structural interpretation is to assume a cover thrust sheet detached from the rheologically competent basement block. The sub-horizontal structures possibly indicate proximity of the basement below the assumed detachment surface. The explanation, if true, would be soundly in accord with the idea of the Sotkuma dome as part of a much larger 'basement high' block with minor shortening during the collisional stage. Nevertheless, according to the gravimetric modelling the cover thickness may well locally exceed 2 kilometres between the Sotkuma and Oravisalo basement inliers.

Field observations around the Sotkuma dome, in Liperinsalo (a domal structure with exposed coarse clastics cf. Väyrynen, 1954; Luukkonen

& Lukkarinen,1986; Äikäs, 1990b) and in the Rääkkylä – Hammaslahti district (Suhmura- type conglomerates along the Suhmura thrust zone; Ward, 1988) all indicate an absence of ortho-quartzites and other lithologies typical of the lowermost cover sequences in the Kiihtelysvaara (Pekkarinen, 1979) and Koli areas (Kohonen & Marmo, 1992) in the east. This suggests that some fundamental features of the present B–C interface geometry (Fig. 5) are plausibly inherited from the early rift basin stage. The alternative geometric set-ups for the Höytiäinen Belt depository and subsequent tectonic reactivation have been discussed and summarized by Sorjonen-Ward (2006).

6. Discussion

6.1. Comparison of basement inliers in North Karelia

According to our generalized 'reactivated horst block model' the *Sotkuma dome* – as we see it in geological maps today – represents the northern-most part of a much larger basement high area. The present Sotkuma basement dome geometry is explained as the interplay of (1) a relatively uplifted basement block due to extensive horst formation some 2.2 to 2.0 Ga ago, (2) partial detachment of the cover during the early stages of thrusting, and (3) brittle to semi-ductile basement involvement during the later phase of crustal shortening. The effect of fold interference appears to be minor and any features suggesting diapiric uplift were not recognized.

The horst block as the dome predecessor is supported by the abundance (c. 2.1 Ga) of diabase dykes at the western margin of the dome and by the ramp-like geometry of the (c. 2.2 Ga) diabase at the northern part of the dome. The observed stratigraphic sequence is in accord with the presented model. The geometry and other features of the steep northern margin of the Sotkuma Dome are difficult to explain sensibly by applying a simple thrust ramp model or as a fold interference pattern.

The partial detachment of the cover explains the distinct difference between the structural style in the basement rocks within the dome and strongly sheared and multiply folded schists in the west. Furthermore, at the southern flank of the dome the cover thickness is considerably less compared to the western, northern and eastern sides. The southern cover schists commonly show sub-horizontal foliations possibly indicating a gentle thrust sheet detached from the shallow basement complex.

The west-dipping geometry with basement thrust over the cover schists and the structural field observations strongly support the old concept of the thrusted eastern margin of the Sotkuma dome. However, the easternmost outcrops within the dome do not show protomylonites or other features typical of major basement involving thrust zones within the study area. Our modelling suggest that the major Suhmura thrust zone is plausibly located some 2–6 km east of the mapped Sotkuma dome contact.

We have summarized the characteristics of the North Karelia and Ladoga basement inliers (domes) in Table 2. The eastern *Kontiolahti dome* is a perfectly oval-shaped window of the Archean basement, but stratigraphically the cover surrounding the dome is not symmetric like in the 'mantled gneiss domes'. In the west, south and southeast the dome is bordered by the semipelitic schists (Höytiäinen Belt) representing high stratigraphic levels, but in the north the cover consists of the lowermost stratigraphic units of the cover sequence (Kyykkä Group and Koli Fm.; Kohonen & Marmo, 1992). Similar to the Sotkuma dome, the eastern contact is understood as a thrust fault with strongly sheared, partly protomylonitic cover quartzites dipping west underneath the basement inlier (Kontiolahti dome). The northern continuation of the thrust and stratigraphic details can be found in Kohonen and Marmo (1992).

The observed features of the Kontiolahti dome do not fit to models assuming simple fold interference as the origin for the structure. However, the late sinistral shear zones (Ward &

Table 2. Summary of observed characteristics and proposed genetic models of the Lake Ladoga – North Karelia basement domes.

Features	Ladoga N domes	Sotkuma	Kontiolahti	Maarianvaara	Juojärvi domes
Observed features:					
'Mantled'	++				
Symmetric elliptical form	++	++	+++		+
Domal foliation pattern	+++	+	+		
Anatectic migmatite core	++				?
Late-tectonic granites in core	?			++	++
Proposed genetic models:					
Diapirism	++	+	+	+	
Fold interference	+			++	++
Thrust (ramp)		++	+	+	+
Basin stage normal fault		+		+	

Observed features:
+++ = characteristic; ++ = typical; + = present; ?= unclear
Previously proposed genetic models:
++ = common or dominant; + = presented in literature
Genetic models preferred by authors:
Green cell = suggested major factor; grey cell = suggested secondary factor

Kohonen, 1989; Kohonen, 1995) and the related anticlockwise rotation (Kohonen et al., 1991) within the Höytiäinen belt potentially had an impact on the present rounded map geometry of the dome. A geometrically similar but much smaller round shaped map feature, interpreted as an interference structure (thrust followed by sinistral strike-slip shear) was described by Kohonen et al. (1990) in the quartzites of the Pankavaara area (see Fig. 2 for location), some 20 km to the north of the Kontiolahti dome.

Unlike most authors, Park & Doody (1991) labelled the *Maarianvaara inlier* near Outokumpu as one of the domes. The fold interference origin by gentle (D2) thrusts and upright (D3) folds has been described by several authors (Koistinen, 1981; Park & Bowes, 1983; Park & Doody, 1991). Nevertheless, the potentially different factors in respect of the Maarianvaara dome genesis are discussed by Park & Doody (1991). In summary they presented a hypothetical five-step model including features from syndepositional fault scarps via several deformation stages to the late stage diapiric uplift related to Maarianvaara granite emplacement.

The western *Juojärvi domes* have been interpreted as a fold interference pattern involving early basement thrust slivers and subsequent cross-folding (e.g. Park & Bowes 1983; Ruotoistenmäki & Tervo, 2006). Koistinen (1993) underlined the role of the assumed thin, partly rootless thrust sheets of the underlying basement complex.

Stretching and advanced prolate strain within the basement involving thrust sheets might offer an alternative geometric explanation for the Juojärvi domes. Prominent, and locally dominant, SW plunging stretching lineations are common in the Juojärvi – Maarianvaara – Luikonlahti area in the western part of the study area. Around the Juojärvi domes evidence for advanced prolate strain is provided by the strongly elongate conglomerate clasts (Huhma, 1975; Koistinen 1993). The outlined alternative model, with advanced structural transposition parallel to the NE tectonic transport, would be basically similar to the sheath folds described by Park (1988) from the Luikonlahti – Niinivaara area some 30 km north of Juojärvi.

6.2. Thickness of the cover sequence

The cover thickness estimates from the Miihkali section (Lahti et al., 2016) and from the section along the Sukkulansalo National Test Line (Heinonen et al., 2016) are in accordance with our gravity modelling in the Outokumpu Area. In addition, both our work and the interpretation of the Miihkali section indicate that the overall B–C interface geometry may be less complex than previously supposed. In our model (Fig. 5), the cover forms an open synformal structure dipping steeply to the W at the eastern limb (next to the Sotkuma dome) and moderately to the SE at the western limb (next to the Maarianvaara basement inlier; see Figs. 1 and 2 for location). Taken together, the recent interpretations exhibit a change from models with a system of alternating basement thrust slices and up to 20 km deep cover synforms (e.g. Bowes et al, 1984; Park & Doody, 1991; Koistinen, 1993), towards models with less vigorous geometries and shallower overall depths of the B–C interface.

Within the Höytiäinen Belt the basement involving thrust zones, responsible for the jagged map pattern of the basement–cover contact in the northern part of the study area (Juuanvaarat in Fig 2; for more detailed maps see Koistinen, 1981; Kohonen et al., 1989), plausibly continue as SSW-NNW oriented steps of the B–C interface also under the cover sequence. However, the regional gravity station interval is approximately 5 km and structural details of the B–C interface below the kilometres thick pile of deformed cover rocks cannot be verified. However, the presented surface (B–C interface) modelling provides an improved reference for further regional and structural interpretations.

6.3. Sotkuma inlier – one of the gneiss domes?

Since the emergence of the mantled gneiss dome concept (Eskola, 1948), various different models for the basement inliers have been discussed and applied. The original idea of partial melting and related diapiric rise was supported by Brun (1980). At the other extreme for theories of gneiss dome formation are models assuming simple thrust ramp origin without any melting or major ductile folding of the basement. The most common approach to dome pattern interpretations has been fold interference - with or without partial melting or thrusting as part of the explanation. The fold interference origin of a certain basement gneiss dome structure (e.g. Fischer & Olsen, 2004), even within the Karelia region (Polyanskii & Efremov 1989), is well proven, but it seems that in detailed terms, each basement inlier may have a unique history displaying features of different genetic models (for a review of gneiss dome geometries and genetic models, see Yin, 2004).

In conclusion, we suggest the existence of a huge basement block (Figs. 12 and 14) extending from Sotkuma to the Oravisalo basement window in the SW corner and along the southern continuation of the Suhmura thrust zone to the tiny basement inlier and adjacent coarse clastics in the vicinity of Hammaslahti township to the SE (see Figs. 1 and 2). A similar idea was originally proposed by Ward (1987, 1988) as a part of his depositional model for the southern Höytiäinen Belt.

Finally, it is noteworthy that unlike the 'classic domes' (Eskola, 1948) of the Lake Ladoga region, none of the domes within the study area (Fig. 2) are 'mantled' with a symmetrical rim of overlying supracrustal cover sequence. Furthermore, Whitney et al. (2004) describe the characteristics of a gneiss dome as: (1) an anatectic migmatite core and (2) a domal foliation pattern. The first is absent in all cases and the second is not strikingly evident anywhere but is possibly detectable in parts of the Kontiolahti and Sotkuma domes (Table 2). Consequently, even the validity of the term 'dome' may be questioned within the study area and the neutral term 'basement inlier' might be more appropriate.

Instead of a one common 'gneiss dome' model, it appears that within the Karelia Province individual basement inliers may have resulted from the reactivation of a pre-collisional horst, basement involving thrusting, polyphase deformation and possibly even by diapirism – or a combination of these depending on structural style and, especially, basement ductility within the region.

7. Conclusions

Interpretation of gravity data is useful in the modelling of major lithological (and stratigraphic) boundaries even when the density contrast between the units is not very large. The method is important in Eastern Finland, where the metamorphic recrystallization has obliterated the seismic signature of the B–C nonconformity. The modelled Paleoproterozoic supracrustal cover sequence is a thin veneer, compared to the thickness of the underlying Archean crust (over 40 km). It seems implausible that the cover thickness would exceed 10 km anywhere within the study area.

Around the Sotkuma basement inlier the B–C interface dips steeply (in the north and west) or moderately (in the south) outwards. The eastern margin forms a step-like structure interpreted as westward dipping thrust slices of the basement gneiss. The Sotkuma inlier is understood as the northernmost part of a large 'basement high' area extending beyond the Oravisalo basement inlier in the south. Neither a simple thrust ramp origin nor a dome-and-basin structure (due to polyphase ductile folding) is favoured by the modelled geometry and the structural features of the Sotkuma inlier.

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Supplementary Data

Electronic Appendices A–C for this article are available via Bulletin of the Geological Society of Finland web page.

References

Äikäs, O., 1990a. Sotkuman uraani-fosforiesiintymät Polvijärvellä. Geologial Survey of Finland, Report M 19/4224/-90/1/60, 29 p.

Äikäs, O., 1990b. Liperinsalon uraani-fosforiesiintymät Liperissä. Geologial Survey of Finland, Report M 19/4223/-90/1/60, 36 p.

Airo, M-L. (ed.) 2005. Aerogeophysics in Finland 1972–2004: Methods, System Characteristics and Applications. Geological Survey of Finland, Special Paper 39. 197 p.

Bedrock of Finland [Electronic resource]. Bedrock of Finland scale-free/BEDROCK.Bedrock_Map_FDS, Geological Survey of Finland [referred 21.09.2018].

Brun, J.-P., 1980. The cluster-ridge pattern of mantled gneiss-domes in eastern Finland: evidence for large-scale gravitational instability of the Proterozoic crust. Earth Planet Science Letters 47, 441–449. https://doi.org/10.1016/0012-821X(80)90032-1

Brun, J.P., Gapais, D. & Le Theoff, B., 1981. The mantled gneiss domes of Kuopio (Finland): interfering diapirs. Tectonophysics 74, 283–304. https://doi.org/10.1016/0040-1951(81)90194-3

Bowes, D.R., Halden, N.M., Koistinen, T.J. & Park A.F., 1984. Structural features of basement and cover rocks in the eastern Svecokarelides, Finland. In: A. Kröner & R. Greiling (eds.): Precambrian Tectonics Illustrated, pp. 147–171.

Elo, S., 2013. Gravimetrian uudet standardit ja GTK:n päivitetty APV-rekisteri. (The new gravity standard and the updated regional gravity data base of the Geological Survey of Finland). Abstrakti-kokoelma (toim. M. Lahti), Sovelletun geofysiikan XIX neuvottelupäivät, 24.–25.9.2013, Eurajoki, Sarja B, Nro 96, ISBN 978-952-9618-93-4, 29–33 p. https://docplayer.fi/809746-Sovelletun-geofysiikan-xix-neuvottelupaivat-24-25-9-2013.html

Eskola, P., 1948. The problem of mantled gneiss domes. Quaterly Journal of Geological Society of London 104, 461–476. https://doi.org/10.1144/GSL.JGS.1948.104.01-04.21

Fischer, G.W. & Olsen, S.N., 2004. The Baltimore Gneiss domes of the Maryland Piedmont. In: Whitney, D.I. et al. (eds.) Gneiss domes in orogeny. Geological Society of America Special Paper 380, 307–320. https://doi.org/10.1130/0-8137-2380-9.307

Gaál, G., Koistinen, T. & Mattila, E., 1975. Tectonics and stratigraphy of the vicinity of Outokumpu, North Karelia, Finland. Geological Survey of Finland, Bulletin 271, 67 p.

Hanski, E., Huhma, H. & Vuollo, J., 2010. SIMS zircon ages and Nd isotope systematics of the 2.2 Ga mafic intrusions in northern and eastern Finland. Bulletin of the Geological Society of Finland 82, 31–62. https://doi.org/10.17741/bgsf/82.1.002

Heinonen, S., Kontinen, A., Leväniemi, H., Lahti, I., Junno, N., Kurimo, M. & Koivisto, E., 2016. Sukkulansalo National Test Line in Outokumpu: A ground reference for deep exploration methods. Geological Survey of Finland, Special Paper 59, 163–188.

Huhma, A., 1971. Polvijärvi. Geological map of Finland 1: 100 000, pre-Quaternary rocks, sheet 4224. Geological Survey of Finland.

Huhma, A., 1975. Outokumpu, Polvijärvi, Sivakkavaara. Explanation to the Geological map of Finland 1: 100 000, pre-Quaternary rocks, sheets 4222, 4224, 4311, 151 p. (in Finnish with English summary).

Huhma, H., Hanski, E., Kontinen, A., Vuollo, J., Mänttäri, I., and Lahaye, Y., 2018. Sm–Nd and U–Pb isotope geochemistry of the Palaeoproterozoic mafic magmatism in eastern and northern Finland. Geological Survey of Finland, Bulletin 405, 150 p.

Kohonen, J., 1995. From continental rifting to collisional crustal shortening – Paleoproterozoic Kaleva metasediments of the Höytiäinen area in North Karelia, Finland. Geological Survey of Finland, Bulletin 380, 79 p.

Kohonen J. and Elo S., 1991. Archean Sotkuma Dome in North Karelia, eastern Finland; a geophysical study and geological interpretation. In: Metamorphism, Deformation and Structure of Crust. Abstracts. Res Terrae, Series A, 5, 32 p.

Kohonen, J. & Marmo, J., 1992. Proterozoic lithostratigraphy and sedimentation of Sariola- and Jatuli-type rocks in Nunnanlahti-Koli-Kaltimo area, eastern Finland; implications for regional basin evolution models. Geological Survey of Finland, Bulletin 364, 67 p.

Kohonen, J.J., Tuukki P.A. & Vuollo J.I., 1989. Nunnanlahden – Kuhnustan – Ahmovaaran alueen geologia. Pohjois-Karjalan malmiprojekti, University of Oulu, Report 23, 132 p.

Kohonen, J., Pernu, T. & Mursu, J., 1990. Kvartsiittien (Jatuli) ja kiilleliuskeiden (Kaleva) kontaktivyöhykkeen geologiset ja geofysikaaliset piirteet Kontiolahden – Ahmovaaran – Nunnanlahden jaksolla Pohjois-Karjalassa. Pohjois-Karjalan malmiprojekti, University of Oulu, Report 26, 32 p.

Kohonen, J., Luukkonen, E. & Sorjonen-Ward, P., 1991. Nunnanlahti and Holinmäki shear zones in North Karelia: evidence of a major early Proterozoic strike slip fault within the Archean basement. In: Autio, S. (ed.) Geological Survey of Finland Current Research 1989-1990. Geological Survey of Finland, Special Paper 12, 11–16.

Kohonen, J., Elo, S., Paananen, M., 2003. Modelling of basement-cover interface (Archean / Paleoproterozoic) in North Karelia, Eastern Finland. In: Kukkonen, I. (ed.) Syväseisminen heijastusluotaushanke FIRE 2001–2005. Workshop, 12.2.2003, Espoo, Otaniemi. Ohjelma ja abstraktit. GTK Espoo, Report Q10.2/2003/1.

Koistinen, T. J., 1981. Structural evolution of an early Proterozoic strata-bound Cu-Co-Zn deposit, Outokumpu, Finland. Earth and Environmental Science Transactions of The Royal Society of Edinburgh 72, 115–158.

Koistinen, T., 1993. Heinävesi. Explanation to the Geological map of Finland 1: 100 000, pre-Quaternary rocks, sheet 4221, 64 p. (in Finnish with English summary).

Korhonen, J. V. Aaro, S.; All, T.; Elo, S.; Haller, L. Å.; Kääriäinen, J.; Kulinich, A.; Skilbrei, J. R.; Solheim, D.; Säävuori, H.; Vaher, R.; Zhdanova, L.; Koistinen, T., 2002. Bouguer anomaly map of the Fennoscandian Shield: IGSN 71 gravity system, GRS80 normal gravity formula. Bouguer density 2670 kg/m^3, terrain correction applied. Anomaly continued upwards to 500 m above ground: scale 1: 2 000 000. Espoo; Trondheim; Uppsala; Moscow: Geological Survey of Finland: Geological Survey of Norway: Geological Survey of Sweden; Ministry of Natural Resources of Russia.

Kukkonen, I. T. & Lahtinen, R. (eds.) 2006. Finnish Reflection Experiment FIRE 2001–2005. Geological Survey of Finland, Special Paper. Geological Survey of Finland. 43, 247 p.

Laajoki, K., 2005. Karelian supracrustal rocks. In: Lehtinen, M. et al., (eds.), Precambrian geology of Finland – Key to the Evolution of the Fennoscandian Shield. Elsevier Science B.V., Amsterdam, pp. 279–342.

Lahti, I., Leväniemi, H., Kontinen, A., Sorjonen-Ward, P., Aatos, S. & Koistinen, E., 2016. Geophysical surveys of the Miihkali area, Eastern Finland. Geological Survey of Finland, Special Paper 59, 113–138.

Lahtinen, R., Korja, A. & Nironen, M., 2005. Paleoproterozoic tectonic evolution. In: Lehtinen, M. et al., (eds.), Precambrian geology of Finland – Key to the Evolution of the Fennoscandian Shield. Elsevier Science B.V., Amsterdam, pp. 481–531.

Laiti, I., 1985. Kontiolahti. Geological map of Finland 1: 100 000, pre-Quaternary rocks, sheet 4223. Geological Survey of Finland.

Leväniemi, H. 2016. Petrophysical parameters and potential field modelling in the Outokumpu Belt. Geological Survey of Finland, Special Paper 59, pp. 67–96.

Luukkonen, E. & Lukkarinen. H., 1986. Explanation to the stratigraphic map of Middle Finland. Geological Survey of Finland, Report of Investigation 74, 47 p.

Mattila, E., 1971. Sotkuman kupolin NW-reunan geologisesta rakenteesta. M.Sc. Thesis (unpublished). University of Turku.

Meletzhik, V.A., 1991. An evolutionary model for Precambrian sedimentary basins of the Baltic shield, International Geology Review 33(6), 515–524.

Melezhik, V.A. & Hanski, E.J., 2013. Palaeotectonic and Palaeogeographic Evolution of Fennoscandia in the Early Palaeoproterozoic. In Melezhik, V.A. et al. (eds.) Reading the Archive of Earth's Oxygenation Volume 1: The Palaeoproterozoic of Fennoscandia as Context for the Fennoscandian Arctic Russia – Drilling Early Earth Project, 111–178.

Nironen, M., Lahtinen, R. & Koistinen, T., 2002. Subdivision of Finnish bedrock – an attempt to harmonize terminology. Geologi 54 (1), 8–14. (in Finnish with English summary).

Park, A., 1981. Basement gneiss domes in the Svecokarelides of eastern Finland: discussion. Earth Planet Science Letters 55, 199–203.

Park, A. F., 1988. Geometry of sheath folds and related fabrics at the Luikonlahti mine, Svecokarelides, eastern Finland. Journal of Structural Geology 10(5), 487–498. https://doi.org/10.1016/0191-8141(88)90036-3

Park, A.F. & Bowes, D.R., 1983. Basement-cover relationships during polyphase deformation in the Svecokarelides of the Kaavi district, eastern Finland. Earth and Environmental Science Transactions of The Royal Society of Edinburgh 74, 95–118.

Park, A.F. & Doody, J.J., 1991. Structural styles in the deep levels of an Early Proterozoic foreland thrust belt. In Lewry, J.F. & Stauffer, M.R. (eds.) The Early Proterozoic Trans-Hudson Orogen of North America. Geological Association of Canada, Special Paper 37, 465–482.

Pekkarinen, L.J., 1979. The Karelian formations and their depositional basement in the Kiihtelysvaara – Värtsilä area, East Finland. Geological Survey of Finland, Bulletin 263, 141 p.

Polyanskii, O.P. & Efremov, V.N., 1989. Diagnosis of dome-like structures in the Northern Ladoga Region on the basis of thermodynamic data and tectonophysical analysis. Geologiya i Geofizika 30, 43–47.

Puranen, R., Elo, S. & Airo, M-L., 1978. Geological and areal variation of rock densities, and their relation to some gravity anomalies in Finland. Geoskrifter 10 (Aarhus University), 123–164.

Ruotoistenmäki, T. & Tervo, T., 2006. Geophysical Characteristics of the Outokumpu Area, SE Finland. Geological Survey of Finland, Report of Investigation 162, 37 p.

Sorjonen-Ward, P., 2006. Geological and structural framework and preliminary interpretation of the FIRE 3 and FIRE 3A reflection seismic profiles, central Finland. In: Kukkonen, I. & Lahtinen, R. (eds.) Finnish Reflection Experiment FIRE 2001–2005. Geological Survey of Finland, Special Paper 43, 105–159.

Vuollo, J. & Piirainen, T., 1992. The 2.2 Ga old Koli layered sill: The low-Al tholeiitic (karjalitic) magma type and its differentiation in northern Karelia, eastern Finland. Geologiska Föreningens i Stockholm Förhandlingar 114, 131–142

Vuollo, J. and Huhma, H., 2005. Paleoproterozoic mafic dikes in NE Finland. In: Lehtinen, M., Nurmi, P.A. & Rämö, O.T. (eds.) Precambrian Geology of Finland. Key to the Evolution of the Fennoscandian Shield. Elsevier Science B.V., Amsterdam, 193–235 p.

Väyrynen, H., 1939. On the geology and tectonics of the Outokumpu ore field and region. Bulletin de la Commissione Geologique de Finlande 124, 91 p.

Väyrynen, H., 1954. Suomen kallioperä. Otava, Helsinki, 260 p.

Ward, P., 1985. Deposition and deformation at a lower Proterozoic cratonic margin in south-eastern Finland. Academic Ph.D. dissertation (unpublished).

Ward, P.G., 1987. Early Proterozoic deposition and deformation at the Karelian craton margin in southeastern Finland. Precambrian Research 35, 71–93. https://doi.org/10.1016/0301-9268(87)90046-5

Ward, P., 1988. Early Proterozoic Kalevian lithofacies and their interpretation in the Hammaslahti – Rääkkylä area, eastern Finland. In Laajoki K. & Paakkola J. (eds.) Sedimentology of the Precambrian formations in eastern and northern Finland. Geological Survey of Finland, Special Paper 5, 29–48.

Ward, P. and Kohonen, J., 1989. Structural provinces and style in the Proterozoic of North Karelia: Preliminary correlations and discussion. In Autio S. (ed.) Geological Survey of Finland Current Research 1988. Geological Survey of Finland, Special Paper 10, 23–29.

Wegmann, C.E., 1928. Uber die Tektonik der jungeren Faltungen in Ostfinnland. Fennia, 50(16), 1–22.

Whitney, D.L., Teyssier, C. and Vanderhaeghe, O., 2004. Gneiss domes and crustal flow. In Whitney, D.I. et al. (eds.) Gneiss domes in orogeny. Geological Society of America, Special Paper 380, 15–34. https://doi.org/10.1130/0-8137-2380-9.15

Yin, A, 2004. Gneiss domes and gneiss dome systems. In Whitney, D.I. et al. (eds.) Gneiss domes in orogeny. Geological Society of America, Special Paper 380, 1–14. https://doi.org/10.1130/0-8137-2380-9.1