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LITHOSPHERE 2008

FIFTH SYMPOSIUM ON THE STRUCTURE, COMPOSITION AND EVOLUTION OF THE LITHOSPHERE IN FINLAND

PROGRAMME AND EXTENDED ABSTRACTS

edited by

**Toivo Korja, Katriina Arhe, Pertti Kaikkonen, Annakaisa Korja,
Raimo Lahtinen and Juha Pekka Lunkka**

**University of Oulu
Linnanmaa Campus
Oulu, November 5-6, 2008**

Helsinki 2008

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Keywords (GeoRef Thesaurus, AGI): lithosphere, crust, upper mantle, Fennoscandia, Finland, Precambrian, Baltic Shield, symposia

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PREFACE

The Finnish National committee of the International Lithosphere Programme (ILP) organises every second year the LITHOSPHERE symposium, which provides a forum for lithosphere researchers to present results and reviews as well as to inspire interdisciplinary discussions. The fifth symposium - LITHOSPHERE 2008 - will have 38 presentations. Extended abstracts (this volume) will give a good overview on current research on structure and processes of solid Earth. This symposium has three special themes; the first studies how lithospheric processes affect climate and environments, the second emphasizes lithosphere's effects on metallogeny and the third highlights lithospheric research in the north as a part of the International Polar Year activities. The symposium will focus at the following themes:

Theme 1: Structure, composition and evolution of crust
Theme 2: Structure, composition and evolution of upper mantle
Theme 3: International Polar Year: lithospheric studies
Theme 4: Impact of the dynamics of the crust and upper mantle on glaciation and Quaternary climate
Theme 5: Lithosphere and metallogeny
Theme 6: Open Forum

The two-day symposium is hosted by the University of Oulu and it will take place at the Linnanmaa campus area in November 5-6, 2008. The participants from the Universities of Helsinki, Turku and Oulu, the Geological Survey of Finland and the Finnish Geodetic Institute will present their results in oral and poster sessions. The invited talks are from the Luleå University of Technology, Sweden and from the Geological Survey of Denmark and Greenland (GEUS). Posters prepared by graduate- or postgraduate students will be evaluated and the best one will be awarded.

This special volume ***"LITHOSPHERE 2008"*** contains the programme and extended abstracts of the symposium in alphabetical order.

Oulu, October 20, 2008

Toivo Korja, Pertti Kaikkonen, Annakaisa Korja,
Raimo Lahtinen and Juha Pekka Lunkka

Lithosphere 2008 Organizing Committee

LITHOSPHERE 2008 Symposium Programme

Wednesday, November 5

09:00 - 10:00 Registration at the University of Oulu, auditorium GO101, Linnanmaa, Coffee

10:00 - 10:05 Opening of the symposium (Organising Committee)

10:05 - 11:45 **Session 1: Impact of the dynamics of the crust and upper mantle on glaciation and Quaternary climate**
Chair Juha Pekka Lunkka

10:05 - 10:30 **M. Poutanen and the DynaQlim Group**
DynaQlim – ILP Regional Coordination Committee

10:30 - 10:55 **S. Gregersen** [Invited]
Who knows about irregularities in uplift in Scandinavia in time scales tens, hundreds, thousands of years? Help DynaQlim, please!

10:55 - 11:20 **A. Pasanen, J.P. Lunkka and N. Putkinen**
Preliminary reconstruction of the White Sea during the late Younger Dryas

11:20 - 11:45 **H.E. Ruotsalainen**
Recording deformations of the Earth by using an interferometric water level tilt meter

11:45 - 12:45 Lunch

12:45 - 16:10 **Session 2: Structure, composition and evolution of crust (Part I)**
Chair Pertti Kaikkonen

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Shear Zones and Fault Rocks in Deeper Parts of the Continental Crust

13:10 - 13:35 **A. Korja, P. Kosunen and P.J. Heikkinen**
Lateral spreading of the Svecofennian Orogen

13:35 - 14:00 **O.T. Rämö, I. Mänttäri, H. Huhma, M. Niin and J. Pokki**
~1635-Ma bimodal rapakivi volcanism of the Island of Suursaari, Gulf of Finland, Russia

14:00 - 14:25 **L. J. Pesonen, T. Elbra, R. Karlqvist, I. Lassila and E.Hæggström**
Seismic velocities of the Outokumpu deep drill core and FIRE profile samples: what do the rocks tell us?

14:25 - 14:50 **T. Lindholm and A. Luttinen**
Geochemical mapping of the Häme dyke swarm, southern Finland

14:50 - 15:20 Coffee

15:20 - 15:45 **O. Eklund**
Prolonged polybaric evolution of post- and anorogenic granites.
15:45 - 16:10 **I.T. Kukkonen and L.S. Lauri**
Rapakivi granite magmatism in the Fennoscandian Shield: Heat source, palaeotectonic reconstructions and implications to supercontinent development

16:10 - 17:25 **Session 3: Structure, composition and evolution of upper mantle**
Chair: Ilmo Kukkonen

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Composition of the upper mantle beneath the Lapland-Kola orogen (northern Fennoscandian shield) obtained by 3-D modelling of Bouguer anomaly
16:35 - 17:00 **J. Woodard, R. Kietäväinen and I. Boettcher**
Biotite and fluorapatite macrocrysts in Paleoproterozoic lamprophyres in Fennoscandia: xenocrysts from the subcontinental lithospheric mantle?
17:00 - 17:25 **T. Korja, M. Smirnov and L.B. Pedersen**
Western margin of the Fennoscandian Shield - magnetotellurics across the Caledonides in Jämtland, Sweden and Tröndelag, Norway

17:25 - 18:00 Break

18:00 - 18:30 **Posters with oral introductions (á 2 minutes; at auditorium GO101)**
Chair Lauri Pesonen

P01 **T. Elminen**
Rheology and kinematic conditions during rapakivi magmatism demonstrated from fault structures and patterns
P02 **S. Heinonen, H. Schjins, D. Schmitt, P. Heikkinen and I. Kukkonen**
Processing of high resolution reflection data of Outokumpu
P03 **T. Hyvönen, T. Tiira, O. Valtonen, A. Korja and K. Komminaho**
Indications of seismic anisotropy in the crust of the central Fennoscandian Shield
P04 **A. Korja, P.J. Heikkinen, Y., Roslov, N. Ivanova, M. Verba and T. Sakoulina**
North European Transect - a preliminary compilation.
P05 **P. Koskinen and O. Valtonen**
Solid earth geophysics field course 2007
P06 **E. Kozlovskaya, T. Janik, J. Yliniemi and P. Heikkinen**
Petrological crust-mantle boundary vs. seismic Moho in the central Fennoscandian Shield: constraints from collocated wide-angle and near-vertical seismic profiles
P07 **E. Kozlovskaya, H. Silvennoinen, T. Jämsen and POLENET/LAPNET Working Group**
POLENET/LAPNET - a multidisciplinary seismic array research in northern Fennoscandia
P08 **M. Malm, L.J. Pesonen and P.J. Heikkinen**
Seismic Research of Impact Craters and the Seismic Velocity Analysis of the Keurusselkä Impact Structure, Central Finland

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P13 **K. Vaittinen, T. Korja and P. Kaikkonen**
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P14 **H. Valppu, K. Strand and A. Huusko**
Time-series analysis of Plio-Pleistocene Prydz Bay sediments for indicating dynamic ice sheet behaviour

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Thursday, November 6

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Chair Annakaisa Korja,

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Polar magnetic anomalies and apparent susceptibilities as a part of World Magnetic Anomaly Map 2008

09:25 - 09:50 **H. Silvennoinen, E. Kozlovskaya, J. Yliniemi and T. Tiira**
Interpretation of wide-angle reflection and refraction recordings of Vibroseis signals and 3D gravity modelling along FIRE4 profile, northern Finland

09:50 - 10:15 **P. Heikkinen, I.T. Kukkonen, A. Suleimanov and N. Zamoshnyaya**
Seismic image of the Fennoscandian Shield along the Baltic Sea - White Sea Transect

10:15 - 10:45 Coffee

10:45 - 12:00 **Session 5: Structure, composition and evolution of crust (Part II)**
Chair Olav Eklund

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Archean geology of the Western Karelian Province
11:10 - 11:35 **R. Lahtinen**
Paleoproterozoic tectonics of the Fennoscandian Shield - some key questions
11:35 - 12:00 **E. Kozlovskaya, M. Majdański, M. Świeczak, M. Grad**
Interpretation of geoid anomalies in the contact zone between the East European Craton and the Palaeozoic Platform in Poland

12:00 - 13:00 Lunch

13:00 - 15:00 **Session 6: Lithosphere and metallogeny**
Chair Raimo Lahtinen

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Poster Awards
Final Discussion
Concluding Remarks

EXTENDED ABSTRACTS

Prolonged polybaric evolution of post- and anorogenic granites

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To receive detailed information about the history of coarse porphyritic ganites from different tectonic settings (post- and anorogenic), mineral inclusions in quartz and K-feldspar megacrysts were studied and compared to matrix mineralogy. It appeared from the results that several disequilibrium features; different ages, differences in chemical and isotope compositions, differences in pressure and temperature, exist between megacrysts and the matrix. The megacrysts were formed in mid-crustal magmachambers some 30 Ma before the emplacement of the crystal saturated granite magmas in the upper crust. Anorogenic granites are known to represent crystallization in reduced environments (low Mg# of the mafic silicates). However, the mineral chemistry of mafic silicates in K-feldspar megacrysts from rapakivi granites is in contrast to this. The minerals have high Mg# and are enriched in Ba and Sr – typical features for post-orogenic shoshonitic rocks. This don't rule out the possibility that there may be a petrogenetic connection between post- and anorogenic granites.

Keywords: lithosphere, Fennoscandia, polybaric crystallisation

1. Introduction

After the accretionary stage, the Fennoscandia was hit by the Sarmatian shield and the juvenile crust in the accretionary arc complex of southern Finland was affected by low pressure (~5 kbar) high temperture (~750°C) metamorphism 1.85 to 1.79 Ga. Subsequently after the metamorphism, during the orogenic collapse, the crust was invided by small intrusions of high Ba-Sr granites and shoshonitic lamprophyres and their plutonic equivalents 1.79 – 1.76 Ga (Lahtinen et al, 2003).

In the Sulkava area the age of the granulite metamorphism (4 kbar) was dated to 1799±19 Ma (Pb-Pb in sillimanite) and 1794.7±4.6 (U-Pb in monazite) (Baltybaev et al, 2006). A granitic dyke crosscutting the granulite with contact metamorphic pressure on 2.5 kbar at 1795±5 Ma (Niiranen, 2000; Nykänen, 1988). These data indicate a rapid uplift of the crust (about 6 km) over a short period.

The apparence of the magmatic rocks formed during the post-orogenic event are lamprophyric dyke swarms in NE direction (Woodard and Eklund 2007), small granitic stocks and granitic ring-intrusions with radial lamprophyres and their plutonic equivalents (Eklund et al 1998) and carbonatites that appear as tiny dykes in fenitisized areas (Woodard and Hölttä 2005).

The anorogenic magmatic event in the Fennoscandian shield took place rougnhly 1.6-1.5 Ga (Rämö and Haapala 1995). The rocks formed were massif anorthosites, norites, gabbros, diabase dyke swarms, quartz feldspar porphyry dykes and rapakivi granite batoliths. Magma mixing between the different rock types indicate coeval magmatism between mantle and crustal melts over extensive areas (Andersson and Eklund 1994, Eklund et al 1994; Salonsaari 1995;).

To reveal weather the megacrysts of the granites are in equilibium (age, PT, chemical) with the matrix and the PT of the host rocks, several surveys have been undertaken to identify the history of the megacrysts.

2. Results

Postorogenic granites

A combination of geochemistry, isotope geochemistry and thermobarometry indicate that the mafic shoshonitic rocks and the carbonatites were generated in a metasomatized lithospheric mantle. The mantle was metasomatized during the subduction stage of the Svecofennian orogeny (Andersson et al. 2006). The shoshonitic magma intruded the upper crust through dykes formed in extensional setting perpendicular to the regional orogenic stressfield. In areas with higher heat flow (the accretionary arc-complex of southern Finland), the shoshonitic magmas where emplaced in the middle crust and differentiated into syenites and granites (Eklund et al. 1998; Konopelko et al. 1998). These mid-crustal chambers were reactivated 30 Ma later by the influx of mafic shoshonitic magma. The bimodal magmatic system invaded the upper crust forcefully forming ring intrusions (Eklund and Shebanov 2005).

Anorogenic granites

Thermobarometrical analyses indicate crystallization of mafic magmas at different levels of the crust, starting from the moho-border and ending with the formation of ignimbrites (Shebanov and Eklund 1997; Eklund et al. 1996).

Thermobarometrical data from an extensive study on the rapakivi texture (ovoial K-feldspar megacrysts mantled with oligoclase-andesine and resorbed quartz megacrysts in a fine grained matrix) indicate that the megacrysts were formed in the middle crust, at 5 – 6 kbar depth. The results also indicate that this unknown protolith or “protorapakivi” at depth was heated to about 780°C before ascent to the upper crust. At 780ºC and 5 kbar, the liquid proportion in an A-type magma is high enough that it can start to ascent (around 35%). The geochemistry and ^{i}Sr and εNd indicate that the core zone of the K-feldspar megacrysts crystallised from a magma with shoshonitic affinity more than 30 milj. years before the transportation to the upper crust, figure 1. (Eklund and Shebanov 1999; Shebanov et al. 2000).

3. Conclusions

The Svecofennian post-orogenic as well as the anorogenic granitic magmas have a polybaric emplacement history. The megacrysts in the investigated rocks were initially formed in the mid-crust in some kind of a magma chambers. These chambers were later reactivated and the crystal saturated magmas invaded the upper crust 30 Ma later or more. The post-orogenic intrusions were forcefully emplaced into the upper crust in a fluidized system while the anorogenic granites invaded the upper crust as a crystal saturated dry magma. In both cases the transportation to the upper crust was associated with mafic magmatism. The anorogenic ignimbrites were formed as a cosequence of magmatic boiling in sub-surface magma chambers as a consequence of influx of mafic magmas into the chamber.

The formation of the rock types investigated does not represent single magmatic events. In both cases it seems that the initial rock formation took place in the middle crust over a long period before the crystal saturated granitic magmas started to ascend to the upper crust.

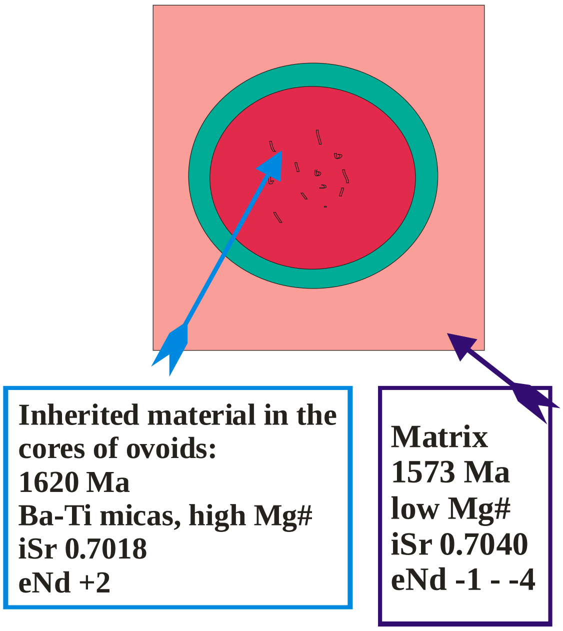

Figure 1. Example of disequilibrium features between the core zone of a K-feldspar megacrysts and the matrix in the Järppilä rapakivi aplite (Vehmaa batolith, SW Finland). Dark red = K-feldspar megacryst, about 3 cm in size. Green = plagioclase rim. Light red = granitic matrix. The megacrysts was crystallised in the mid-crust (about 5 kbar) and the matrix in the upper crust, less than 1 kbar.

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Who knows about irregularities in uplift in Scandinavia in time scales tens, hundreds, thousands of years?Help DynaQlim!

Søren Gregersen

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Discussions are intriguing on uplift of Scandinavia. The patterns in time scales of 10s, 100s and 1000s of years show some similarities and some differences. Geodetic observations exist. Those describe the phenomenon in 10s – 100s of years scale. Earthquake observations in seismology are of relevance to the same time scales. Geological studies of dated shore lines describe the postglacial earth-surface motion in a quite different time scale of 100s – 1000s of years. There is a need for integration of these observations geographically. Some observations in the various time scales are available. Others are being gathered in the lithosphere project DynaQlim: Upper mantle dynamics and Quaternary climate in cratonic areas.

1. Background

My geodesist colleagues are making more and more definitive observations of the uplift pattern of Scandinavia and the surrounding subsidence. Methods are improving from levelling and sea level observations, where observations improved as period of observation grew from tens of years to more than hundred years, to GPS measurements nowadays. Several DynaQlim papers present the good modern picture of these time scales. This good reference pattern is in the present paper displayed together with the longer term geological pattern of thousands of years since the Ice Age, i.e. approx 10 000 years. The comparison of the two patterns shows that the differences in the broad scale picture are small. This emphasizes that it is the same phenomenon which uplifts Scandinavia in the time scales tens, hundreds and thousands of years.

This being said I point to an irregularity, namely that the uplift was so fast right after the Ice Age, that it caused stresses which were dominating the stress release in the lithosphere, while now, 10,000 years later the plate motion stresses are those that determine the stress field and stress release.

2. Stresses in the lithosphere of various time scales

For a description of the stresses in the Scandinavian lithosphere the uplift pattern may well be of some significance. But from a point of view of seismology, which can give information of the same short time scales as the geodetic observations, the uplift is one factor of several, which are dominated by the stresses caused by the present lithospheric plate movements (Gregersen and Voss 2009; Olesen et al. 2004; Bungum et al. 1991; Lindholm et al. 2000; Gregersen, 1992). The earthquake geography in Scandinavia has been discussed e.g. by Gregersen et al. (1991). It is displayed in Figure 1. Like displays of earthquake activity in other parts of the world it does not matter much which is the time period displayed. The general pattern is the same in any time period, while small details can be different. The figure shows that the earthquake activity is most concentrated along the Norwegian coast and continental margin, along the Swedish east coast, and in and around the Oslo Fiord. It is well established that the earthquake activity in Denmark is the southern limitation of the Scandinavian seismicity (Gregersen et al., 1998). And there are no recent earthquakes in Jylland in the middle of Denmark. It is also established with good credibility that the earthquake activity is smaller in northern Germany, in Poland and in the Baltic states (e.g. Grünthal et al, 2008). In the latter areas the seismograph coverage has until recently been significantly poorer, so the information in the map is influenced by less sensitivity to small earthquakes. But there is not much doubt that the Kaliningrad events of 2004 are very unusual for the coast of Poland, Russia and Lithuania (Gregersen et al. 2007). The map in Figure 1 should be complete down to magnitude 4.

Also shown in Figure 1 are short heavy lines in northern Norway, Sweden and Finland. These show the locations of large postglacial faults, which are convincingly argued to be developed in large earthquakes (e.g. Lagerbäck, 1991; Olesen, 1991; Olesen et al. 2004). The dating of these earthquakes is very accurate via disturbances of sediments in liquefaction, and counting of varve layers. Coincident with the liquefaction phenomena are large landslides, which support the interpretation of these large faults as signs of earthquakes 9.000 years ago.

The central part of the uplift area is indicated in Figure 1 for comparison to the earthquake pattern. I have in several papers argued that there is no correlation between the uplift pattern and the earthquake geography (Gregersen, 2002; Gregersen and Voss, 2008). In the mentioned papers we have argued that the stresses have changed drastically during the 10.000 years of these investigated phenomena. Right after the Ice Age the uplift was dominating, while now the plate motions in plate tectonics sense are dominating. Besides by the lack of correlation of the seismicity and the uplift pattern this is demonstrated by the overwhelming regularity of the compressional orientations of focal mechanisms in the area as well as other data of the World Stress Map Project (Zoback et al 1989, 1992; Poutanen et al., 2009). Northwest – southeast compression is dominating, along the absolute lithosphere plate motions, although also many other scattered compression orientations are found. We note that the same conclusion of change of dominating stress is emphasized also by Mörner (2003) with overlapping as well as different arguments.

3. Uplift pattern and irregularities

The description of the general uplift pattern are the works of many scientists over the years (e.g. Mertz, 1924 and Paasse, 1996). The geological uplift pattern is a generalisation of all of these investigations (Mörner, 2003). When one looks at a smaller area one finds irregularities in the curves. Various claims of irregularities have been postulated though. Geological signs of motion, which have been promoted, are the following:

Læsø, Denmark by Hansen (1994) investigating sand deposits of ages less than 10,000 years. This location is in the Kattegat Sea between Sweden and Denmark.

West coast of southern, as well as northern Sweden by Mörner (2003). Several locations on the Swedish west coast have been pointed out. The signs of geological movement are faults and rock deformation in a few cases, and in many incidences rock slides and liquefaction in several stratigraphic layers. The evidence is not as overwhelming as in northern Sweden in the layers from the end of the Ice Age (e.g. Lagerbäck, 1991).

North Jylland, Denmark. In the recent paper by Sørensen et al. (2009) it is indicated that the northern grouping of the earthquakes in the Skagerrak between Norway and Denmark is happening in the Tornquist Zone, which is one of the most significant geological lineaments in Scandinavia (e.g. Gregersen et al. 2006 and 2008).

Also further southeast the Tornquist Zone between Danmark and Sweden, is delineated by small earthquakes (Fig. 2) (Gregersen et al. 1998; Jensen et al. 2002). In the middle of

Denmark no earthquakes have been found. And this has given rise to previous statements (e.g. Gregersen et al. 1998) that this part of the Tornquist Zone is not active. Recent geological as well as geodetic investigations modify this (Gregersen and Voss, 2009). Here is presented a bend in the uplift pattern in all investigated time scales from 10s to 10,000s of years (Lykke-Andersen and Borre 2000; Gregersen and Schmidt 2001). The bend is just where earthquakes are missing, so we tend to describe this bending as a creep phenomenon. In Skaane, southern Sweden repeated GPS measurements by Pan et al. (1999) have indicated differences on the two sides of the Tornquist Zone.

Rügen, Germany. And this bending phenomenon in the middle of Denmark does not stand alone. When the evidence was presented recently in a conference, the authors have been told of a similar observation by Dietrich (personal communication, 2008) of a systematic, and repeated change in trend in geodetic levelling in the island of Rügen in northern Germany. The location is marked in Figure 5 by a circle. These are the kinds of observations we seek in Project DynaQlim.

Karelia, Russia. Many faults in Karelia have been interpreted as postglacial earthquakes, with supporting evidence in rock falls/land slides (Lukashov, 1995).

4. Resulting status

Overall coincident uplift pattern of all time scales 10s, 100 s, 1000s and 10,000 years confirmed in Scandinavia.

Some geodynamics irregularities are found. They may be connected to earthquakes or to slower creep. Hopefully more is to be disclosed in Project DynaQlim by further investigations.

The question to the scientists in this Finnish lithosphere meeting is whether any of you know about similar irregularities in Finland?

Acknowledgments:

Many students have over the years contributed to the computation of the Danish earthquake locations. My colleague H.P. Rasmussen has made many of the P and S arrival readings.

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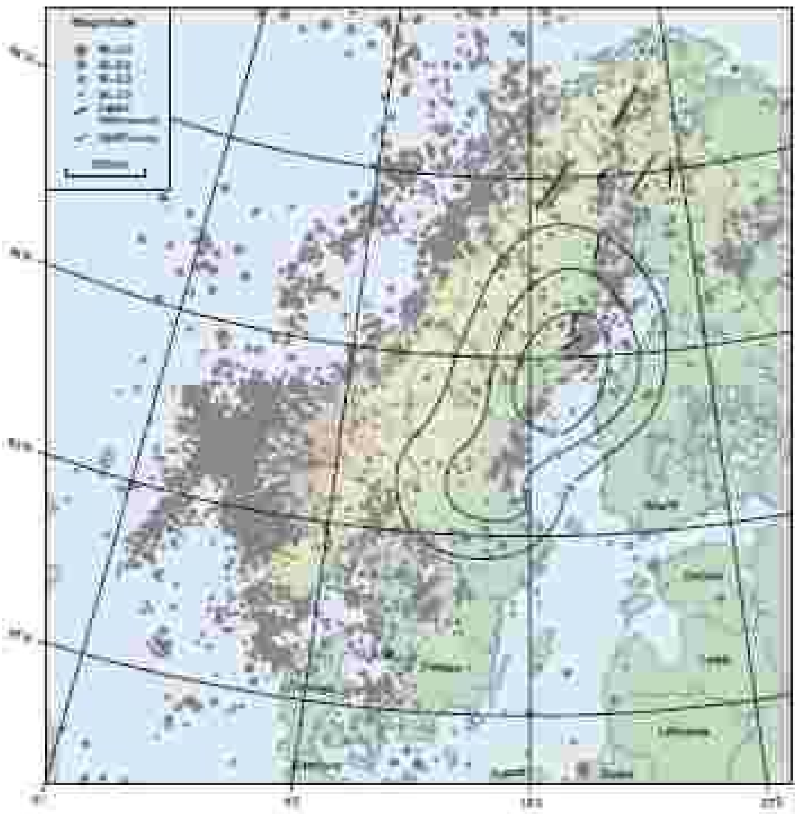

Figure 1. Map of the earthquake geography in Scandinavia covering the years from JAN 1970 to DEC 2004. Earthquakes in the Danish area are extracted from the GEUS earthquake catalogue and earthquakes located outside this area are extracted from the Scandinavian catalogue from Helsinki University. The earthquake magnitude scale is given in the upper left corner. The contours show the area of maximum postglacial uplift (Scherneck et al., 2001).Very thick black lines show the large postglacial faults of age close to 9.000 years (Lagerbäck, 1991. Updated earthquake files for Denmark are available in home page www.geus.dk under seismology. From Gregersen and Voss (2008).

1.98 Ga Pechenga ferropicrites and related Ni-Cu sulfide deposits in the Kola Peninsula, Russia: a review

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Synvolcanic Ni-Cu sulphide deposits of the Pechenga ore field are located in the lower parts of differentiated, sill-like ultramafic-mafic bodies generated from a hydrous, Fe-rich primitive magma called ferropicrite. These bodies were intruded into a thick sequence of sulphide-bearing pelitic sediments. Most robust evidence for crustal contamination during ore formation is provided by Os isotopes which show a distinctly more radiogenic signature for ore-bearing intrusions compared to barren layered lava flows. Although it is generally thought that sulphide-rich country rocks (black shales) played a significant role in ore formation, at least some sulphide saturation already took place at lower crustal levels as indicated by the PGE-depleted nature of the Ni-Cu ores and occurrence of Ni-Cu sulphides in feeder dykes cutting underlying mafic volcanic rocks. A mantle plume origin for ferropicritic magma is consistent with the chemical and isotopic data, but not with the lack of crustal doming before the ferropicritic magmatism.

Keywords: Ni-Cu deposits, ferropicrite, Pechenga, Kola Peninsula, Russia

Economically important magmatic Ni-Cu sulphide deposits at Pechenga, northwestern Russia, were discovered in the 1920s and have been mined uninterruptedly for the past 60 years. The ore deposits are associated with concordant or subconcordant, sill-like mafic-ultramafic bodies (gabbro-wehrlites) which occur within a 0.6-1.0-km-thick Pilgujärvi Sedimentary Formation composed of sulphide- and graphite-rich greywackes and shales. The thickness of the magmatic bodies generally varies from 5 to 250 m and reaches a maximum of 470 m. The number of the Ni-Cu deposits of economical interest exceeds 20. Weak sulphide dissemination has also been found in ultramafic dykes belonging to a magma conduit system that cuts the underlying sequence of basaltic pillow lavas. Within the sedimentary formation, the ore-bearing intrusions are located at two levels, in the lower part of the formation in the eastern segment of the ore field and in the upper part in the western segment of the ore field. It is uncertain whether all the ore-bearing bodies are intrusive in nature as the Fe- and Ti-rich primitive parental magma, called ferropicrite (Hanski, 1992), also produced extrusive rocks in the area, including layered lava flows and thick agglomeratic fragmental deposits.

Primary magmatic Ni-Cu ore with an average Ni/(Ni+Cu) ratio of 0.70 occurs as disseminated or massive sulphides at the base of mafic-ultramafic bodies. In addition, there are breccia ores, which are tectonic mixtures of massive ore and country rock fragments, and vein-impregnations in footwall schists. The sulphur isotope composition of sulphides in the Ni-Cu ores varies laterally in the Pechenga region: $\delta^{34}S$ is normally close to the mantle value (-1 to +2‰) in deposits of the western ore field and higher (+3.5 to +5‰) in deposits of the eastern ore field. In the sedimentary sulphides, $\delta^{34}S$ is also variable falling in the range of -6 to +24‰ with the lower values representing earlier and higher values later stages of diagenesis (Melezhik et al. 1998). Osmium isotope data demonstrate pronounced crustal contamination as the ore-bearing intrusions have radiogenic Os isotope compositions with the initial γOs values falling between +45 and +250. These are clearly higher than +6 which was obtained for non-mineralized layered lava flows (Fig. 1). Assimilation of high-U/Th pelitic material is also reflected in the $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ systematics of the intrusions. Multiple lines of evidence point to the importance of assimilation of S-rich sedimentary material in the formation of magmatic Ni-Cu sulphide mineralization. However, there is field evidence that at least some sulphide segregation took place already in the magma conduits before the ascending magma reached the level of the Pilgujärvi Sedimentary Formation. In addition, the relatively PGE-depleted nature of the sulphide phase suggests that the magma became sulphide-saturated at depth (Barnes et al. 2001). The magma chambers seem to have behaved as dynamic open systems, as deduced from high sulphide/silicate ratios in individual mafic-ultramafic bodies and observed differences in γOs values between chrome spinel and sulphide separates, and therefore the contamination process did not necessarily take place *in situ*.

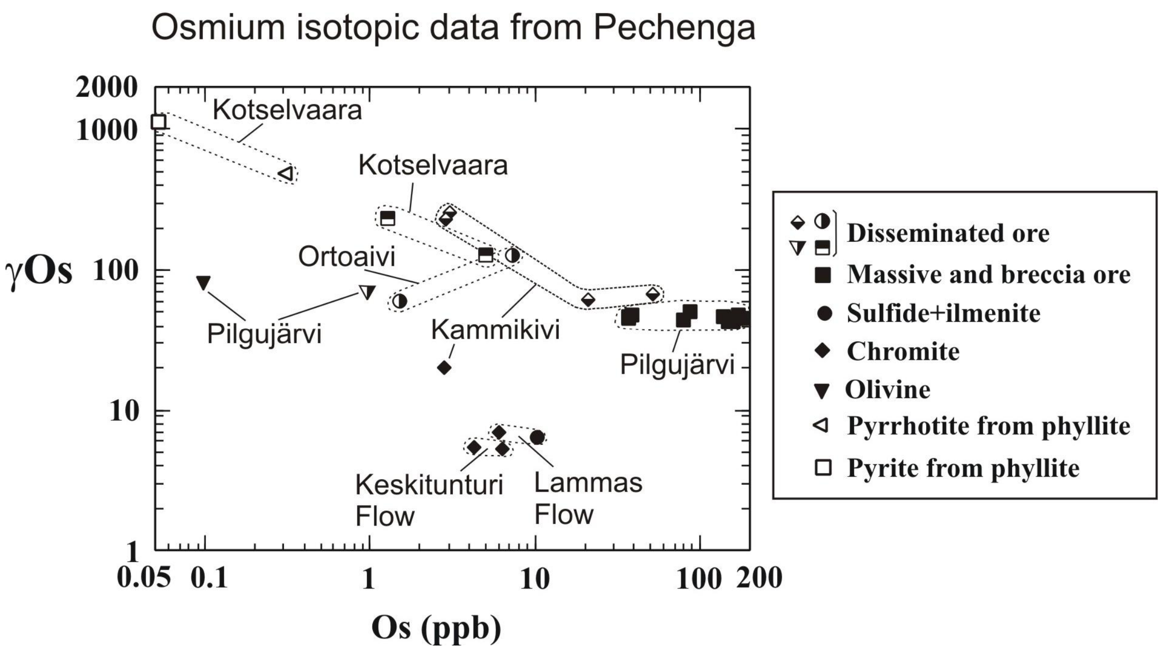

Figure 1. Os isotope data on mineral separates and whole-rock ore samples from the Kotselvaara, Ortoaivi, Kammikivi and Pilgujärvi intrusions, two layered lava flows (Lammas, Keskitunturi) and sedimentary sulphides from Kotselvaara (data from Hanski, 1992, and Walker et al., 1997).

The ferropicritic parental magma for the ore-bearing intrusions was derived from an unusual Fe-rich mantle source (Hanski, 1992), but the detailed nature of this source and its history is still unclear. Other unsolved issues include the low phosphorus content of the magma as compared to other incompatible elements, and the significance of kaersutite that is a common mineral in ferropicritic rocks. The source of volatiles in this primary igneous amphibole can be metasomatised subcontinental mantle or a volatile-bearing plume (Fiorentini et al., 2008). Furthermore, even though many features of ferropicritic magma, including high MgO and OIB-like trace element and isotopic (Nd, Os) characteristics, suggest a mantle plume origin, there is no field evidence for a considerable lithospheric uplift and doming, in response to the ascent of a mantle plume head, that would be expected to have taken place before the ferropicritic magmatism started.

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Seismic Image of the Fennoscandian Shield along the Baltic Sea - White Sea Transect

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Keywords: reflection seismics, crustal structure, Fennoscandia

The Baltic Sea - White Sea transect is an 1120 km long profile across the Precambrian Fennoscandian Shield. The backbone of the transect is formed of three deep seismic reflection profiles. The first two lines, FIRE 1 and 2 (860 km in total), form the NE-SW running southern part of the transect from the Finnish-Russian border to the southern coast of Finland. The deep seismic reflection data along these profiles were was acquired by the FIRE (Finnish Reflection Experiment) consortium - the Geological Survey of Finland, and Universities of Helsinki and Oulu, with Russian Spetsgeofizika S.G.E. as a contractor. The consortium carried out seismic reflection surveys in Finland in 2001-2003 on four lines with a total length of 2135 km. The northeastern part of the transect, Kem-Uchta line (EU-4), extends from the White Sea to the Finnish border. It was shot by Spetsgeofyzika in 1999 as a part of the Russian program of deep reflection seismic studies. The transect begins from the Belomorian greenstone belt in the east, crosses the Archaean Karelian craton and the Paleoproterozoic Western (WAC) and Southern Finland Arc Complexes (SAC). The transect gives a comprehensive view on the geological evolution of crust and uppermost mantle across the Fennoscandian Shield. It images the break-up of the Archaean craton and the subsequent growth of the continent during the Lapland-Kola (1.94-1.86 Ga) Svecofennian orogenies (1.92-1.79 Ga).

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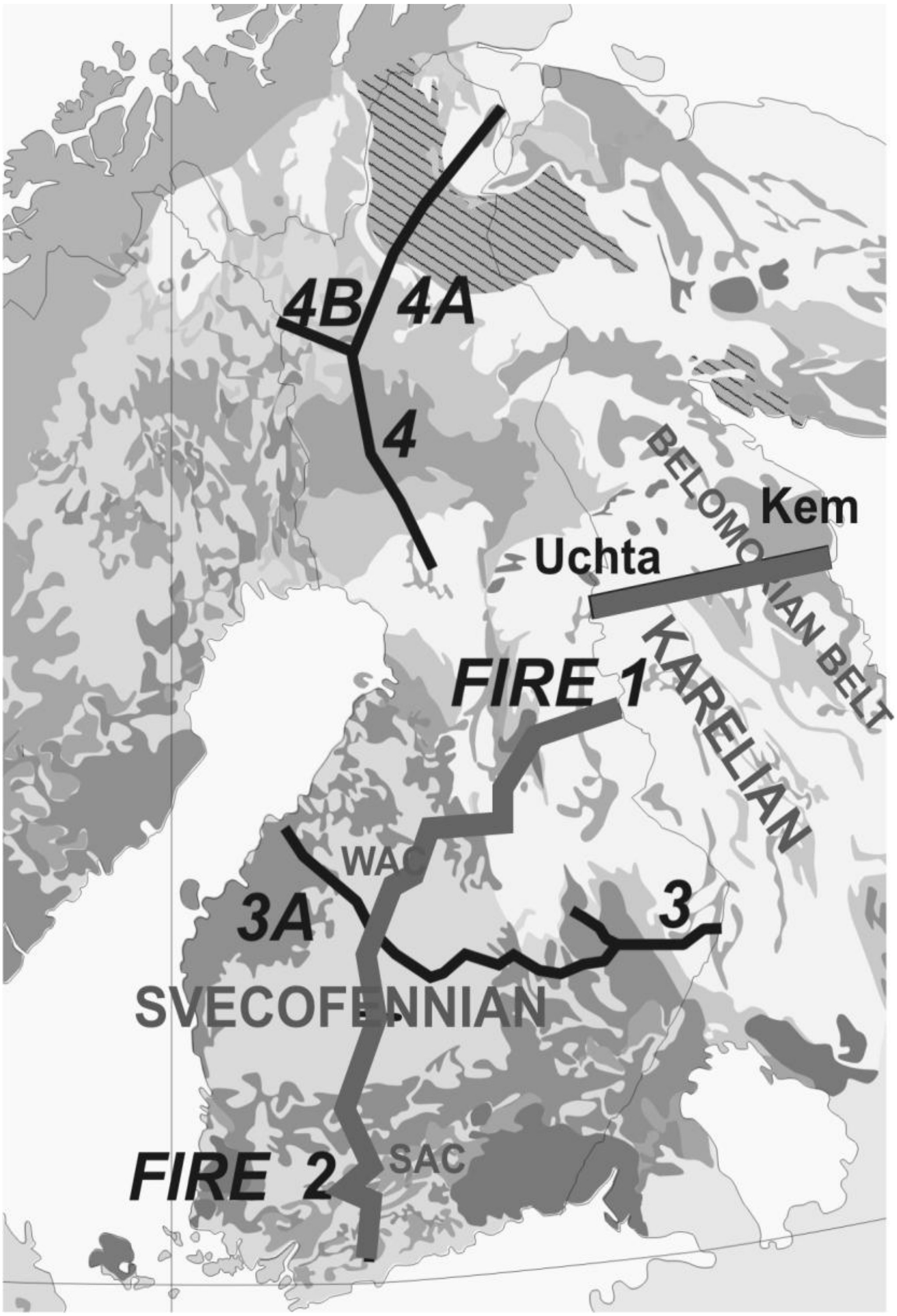

Figure 1. Location of the seismic reflection lines along the Baltic Sea – White Sea transect.

Processing of high resolution reflection data of Outokumpu

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New tentative approach is needed for processing of high resolution seismic data acquired in hardrock areas like Outokumpu, Finland. Careful static corrections and velocity analysis are essential part of improvement of the data quality and preservation of high frequencies used in survey. In the processing of the Outokumpu high resolution reflection data, static corrections were done using a tomographic model of the near surface layers. Method had many improvements compared to the conventional refraction statics method. Sonic log and VSP data were needed as a basis for velocity analysis to create reliable velocity estimates for the survey area.

Keywords: seismic reflection data, data processing, static corrections, Outokumpu

1. Introduction

Hardrock environments host the substantial fractions of Earth's mineral wealth. Classical nonseismic geophysical methods like electromagnetic, induced-polarisation, potential field and radiometric techniques are well suited to shallow (< 500 m) mineral exploration, but are constrained by limitations of their sensibility and resolving power with increasing depth. Reflection seismic methods have been used more than 70 years to explore sedimentary basins for hydrocarbons (Eaton et al., 2003). Recently, the use of the seismic exploration in the hardrock environments has been increasing. Seismic data acquisition, processing and interpretation need to be tailored to serve better regional geological mapping, mineral prospecting, mine planning, finding long term storage solutions for nuclear waste and other applications used in hardrock environment.

Outokumpu is a classical ore province in the eastern part of Finland famous for its unconventional sulphide deposits with economic grades of Cu, Zn, Co, Ni, Ag and Au. Sulphide deposits were targets of active mining from 1913 to 1988. Recently, interest in Outokumpu-type ores has aroused again (Peltonen et al., 2007) as base metal reserves have been declined. History of active geophysical research also makes Outokumpu an ideal place to test suitability of seismic surveys to mineral prospecting.

2. Field work

In 2004-2005 a 2,5 km deep borehole of International Continental Scientific Drilling Program (ICDP) was drilled in Outokumpu and in May 2006 a high resolution seismic survey was conducted to further refine the geological model of the area. Survey included reflection/refraction profiles, a zero-offset VSP (Vertical Seismic Profiling), a far offset VSP and a multi-azimuth multi-depth walk-away VSP. The IV Minivib^{TM} owned by University of Alberta was used as a vibroseismic source. Source employed a linear upsweep of 8 seconds with frequencies 15-250 Hz. Single component 14 Hz surface geophones and a 3C downhole geophone were used as receivers. Shot point spacing of 20 m and receiver spacing of 4 m were used in the reflection profiles.

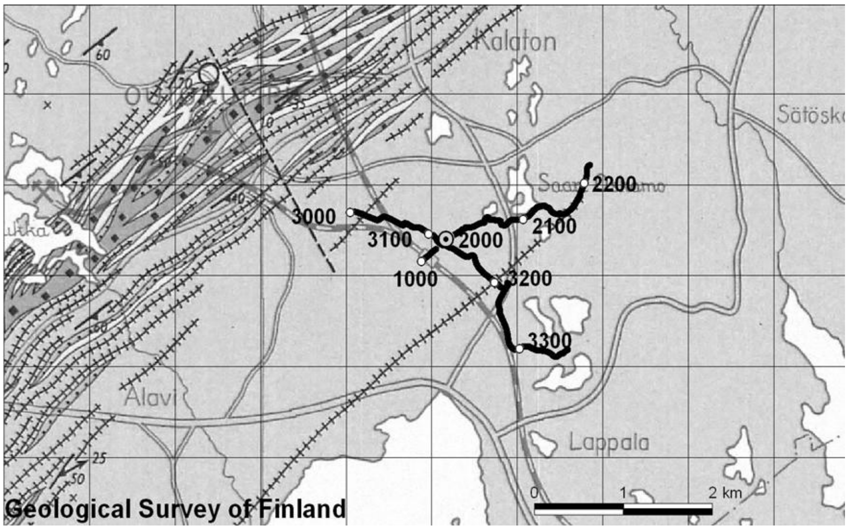

Figure 1. Seismic soundings were done on two crooked lines marked in map with numbers. The location of deep drill hole is marked with circle.

Reflection survey of May 2006 was done in two lines, the north-east (NE) and the south-east (SE) line. The surface lines were remarkably crooked, which causes problems to processing of 2D data. In several sites vibroseismic source could not be used because of buried pipelines, residential areas or an inaccessible shot location. This caused severe gaps in to the SE line and resulting deficient CMP fold inflicted the low quality of the reflection seismic data.

3. Processing

Improperly processed seismic data can mask important geological features even if no mistakes happened in data acquisition. For example, usually discontinuous reflections from fracture zones can be missed if large static shifts are present (Eaton et al., 2003). Processing of the Outokumpu data included basic gain corrections and band-pass filtering. Special attention was paid for careful static corrections and velocity analysis.

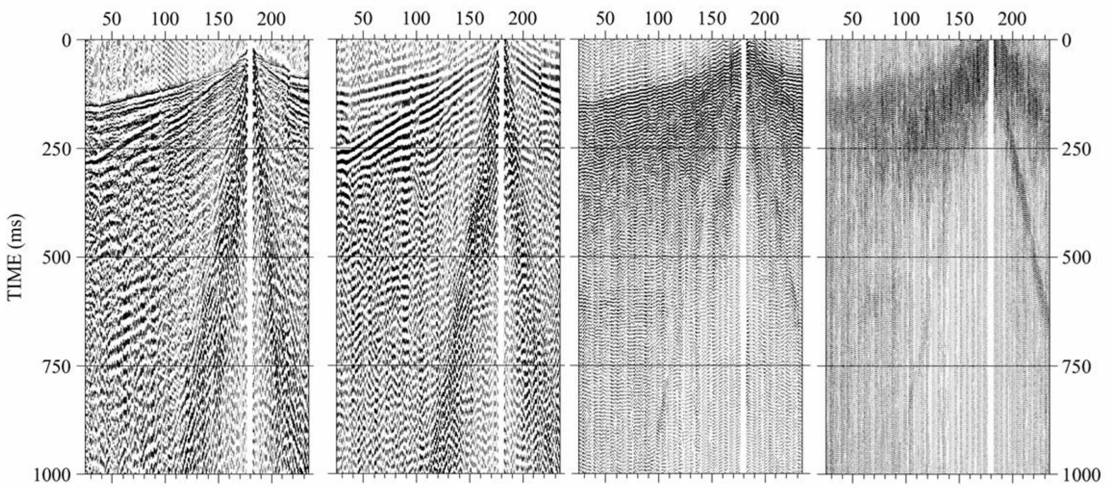

Figure 2. Unprocessed field record 2028 and signal response in different frequency bands, 30-40 Hz, 100-150 Hz and 210-220 Hz. Ormsby filter with 10 Hz linear ramps was used to

filter the data shown. Reflection between 500-750 ms is most clearly seen in frequency band 100-150 Hz.

To optimise a quality of seismic data it is important to select a proper band-pass filter. Signal response to different frequencies is shown in figure 2. Hardly any reflections are visible in unprocessed data. Air wave and ground roll are dominating low frequencies (< 50 Hz). In high frequencies (> 220 Hz), signal is attenuating fast and no reflections can be seen. Shallow reflections (< 1000 ms) are still detectible in frequencies as high as 200 Hz.

Static corrections are used to correct the time delays caused by near surface layer. In Outokumpu, the need for static corrections was substantial due to rough topography and variations in thickness and seismic velocity in overburden. Static corrections were done by using a tomographic approach, where refraction data set was used in conjunction with Colin Zelt's RAYINVR algorithm (Zelt et al., 1992) to invert for layer thickness and P-wave velocity. The resulting 2-layer model of the near surface was used to calculate appropriate static corrections for each shot and receiver locations using fixed datum elevation of 80 m. The calculated values were applied to the reflection data in two parts, first part before and second after NMO-corrections. Tomographic approach proved to reveal a better solution than standard refraction static approach, as proven in figure 3.

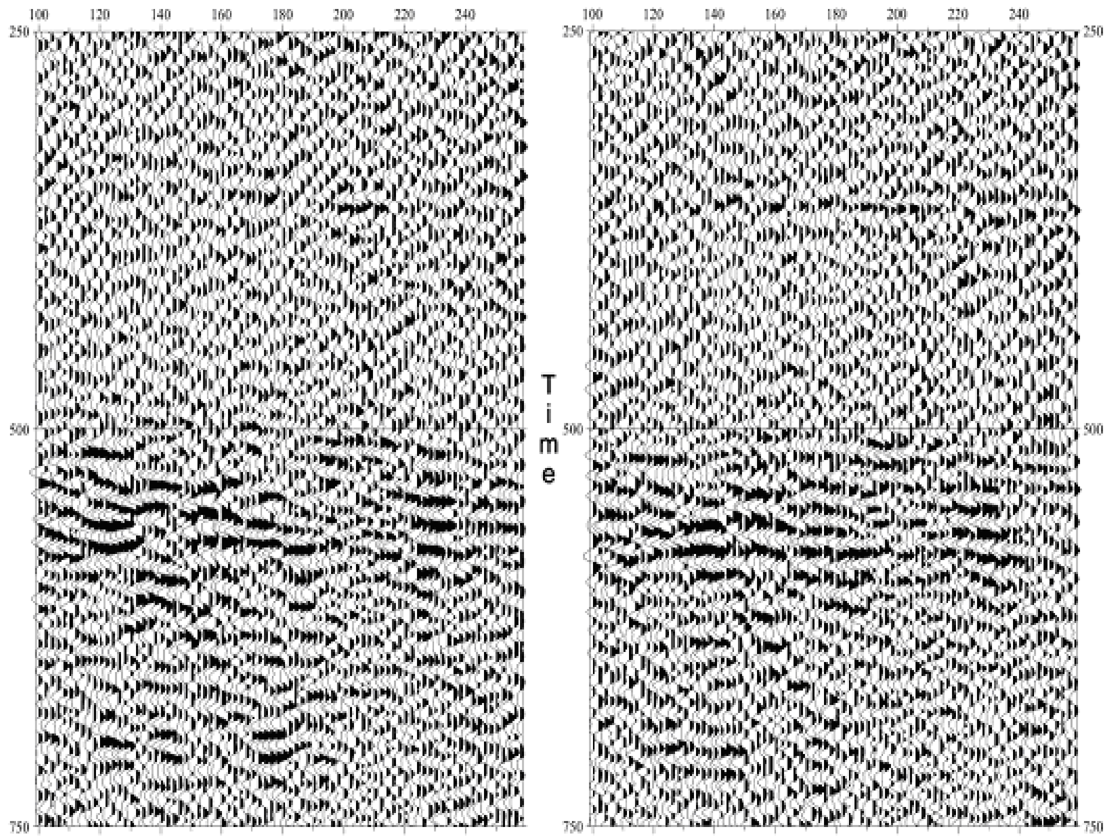

Figure 3. Unmigrated stack with refraction static correction (left) and tomographic static corrections applied (right). Refraction static corrections were done by using Hagedoon's method.

Unlike in sedimentary basins, density and seismic velocity changes are not dependent in hardrock environment. The changes of velocity are also small and thus the velocity analysis of seismic reflection data acquired in hardrock environment is very challenging. High seismic velocities and short cable length also dilute resolution of velocity analysis (Yilmaz, 2001). The survey lines of Outokumpu were only ~2 km long and picking of the exact velocity turned out to be troublesome, as reflection hyperbolas are not clearly visible in the CMP-gathers and the velocity spectra do not show explicit values of maximum coherence. Both the VSP-survey and the sonic log measurements done in deep drill hole were used to improve the quality of velocity analysis of the Outokumpu data.

Careful processing of the data of the NE survey line resulted in a CMP stack of good quality. Through accurate static corrections and careful velocity analysis also high frequencies were preserved in seismic sections and good alignment of reflections was provided. Successful processing of SE survey line failed because of poor data quality resulted from sparse CMP-fold.

4. Conclusions

Static corrections are essential part of processing of high resolution seismic reflection data acquired in hardrock environment. Conventional methods to static corrections are mainly developed for hydrocarbon exploration and are not completely suitable for data acquired in the hardrock terraines. In our work, a tomographic near surface model was used to calculate the static corrections and it proved to be superior to the conventional method. To provide a reliable velocity field it was necessary to use VSP and sonic log data as the basis of the velocity analysis.

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Indications of seismic anisotropy in the crust of the central Fennoscandian Shield

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A seismic velocity structure and a Vp/Vs ratio model of the crust of south-central Finland were inverted by a seismic tomography method using P- and S-wave travel time data. The velocity images reveal varying high and low velocity bodies that can be associated with different geological terranes. Clear indication of structural seismic anisotropy was found studying P-wave residuals of the inverted isotropic model in the crust beneath the Central Finland Granitoid Complex (CFGC). The different crustal anisotropic patterns were seen in the territories of the Proterozoic Svecofennian orogen and the Archaen Karelian craton.

Keywords: seismic anisotropy, seismic tomography, v_P, crust, Finland

1. Introduction

Seismic anisotropy means that the elastic properties of a medium are direction dependent. This makes the oscillation velocity to vary with the oscillation direction. Because P-, S- and surface waves have differing particle motions they respond differently to anisotropic media. Since S- and surface waves oscillate perpendicularly to their propagation direction they divide into fast and slow polarisations. This decomposition -*shear wave splitting*- corresponds to birefringence of optical wave. Due to P-waves oscillate parallel to the propagation direction they do not split but have simply one propagation direction faster than the other ones. The velocities of the surface waves have been observed to be similarly azimuthally dependent.

Seismic anisotropy is generally due to tectonic processes. By reorienting crystals, lattices, cracks and microcracks an inhomogeneous stress field creates elastically fast direction parallel to foliation planes (Fig 1.). Because the Fennoscandian shield has tectonic history of several deformation processes, it is plausible that anisotropic structures occur there. The structural anisotropy was studied by mapping the azimuthal dependence of the P-wave residuals after a tomography inversion (Hyvönen et al., 2008).

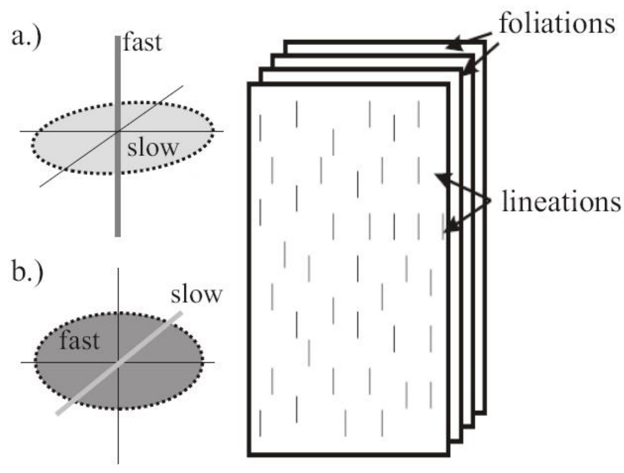

Figure 4. Hexagonal structural anisotropy can be generated by two types of fast directions in foliation planes. Fast directions are marked with dark grey and slow directions with light grey. a.) The fast anisotropic axes are within the foliation plane parallel to the lineations and slow directions form a plane orthogonal to the fast axes. b.) The fast directions form a plane parallel to the foliations and the slow direction axes are orthogonal to the foliation planes.

2. Tomography inversion

The local seismic tomography method Jive3D (Hobro, 1999) was used to image the 3-D terrane distribution within the central parts of the Svecofennian orogen in southern and central Finland. Three-dimensional crustal P- and S-wave velocity models and a Vp/Vs-ratio model were inverted (Hyvönen et al., 2007; 2008). In the modelling process three types of travel time data was used: local events recorded by the SVEKALAPKO seismic tomography array, controlled seismic shots recorded at portable stations and non-controlled chemical explosions recorded at the permanent seismic stations.

After the tomography modelling by Hyvönen et al. (2007), the travel time data have been doubled and new updated models have been inverted (Hyvönen et al., 2008). Consequently, the well resolved area expanded: more details were introduced to the image and the lateral velocity resolution was improved. The tomography modelling reveals several crustal blocks including granitoid areas surrounded by schist belts and their continuations at depth. The Archean bedrock is usually characterized by higher velocities than the Paleoproterozoic bedrock.

3. Indications of seismic anisotropy

The seismic anisotropy of the upper and the middle crust was studied by mapping the directional means of the P-wave residuals after the tomography inversion. An implication of the regional azimuthal anisotropy was observed when the residuals were of an opposite sign in two orthogonal directions. For example, in the CFGC area the residuals were negative in the NW-SE direction and positive in the orthogonal direction.

The different tectonic terranes of the study area were recognised in the seismic anisotropy modelling. The Archean Karelian craton and the Paleoproterozoic Svecofennian orogen were identified by their differing P-wave residual patterns. An observable crustal seismic anisotropy was detected in both of the tectonic domains (Hyvönen et al., 2008).

4. Discussion and conclusions

The fast direction of the structural anisotropy was observed to be in NW-SE direction in the CFGC area (Hyvönen et al., 2008). The preliminary results suggest the fast anisotropic direction to be parallel to the dominating direction of the lineations in the CFGC area (Kilpeläinen et al., 2008) as well as to the direction of the reflectors seen in the FIRE reflection seismics study (Korja et al., 2008).

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Archaean geology of the Western Karelian Province

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Keywords: Archaean, TTG, greenstone belt, amphibolite, sanukitoid, metamorphism

The Archaean of the Fennoscandian Shield mainly consists of rocks that belong to the TTG association (covering about 80% of the area), with greenstone belts, paragneiss areas and migmatitic amphibolites. The Archaean of Fennoscandia is traditionally divided into Murmansk, Kola, Belomorian and Karelian Provinces (Fig. 1, Slabunov et al., 2006; Hölttä et al., 2008). Large parts of these provinces were reworked in the Paleoproterozoic Svecofennian and Lapland–Kola collisional orogens (Kontinen et al., 1993; Daly et al., 2006; Bibikova et al. 2001). Lobach-Zhuchenko et al. (2005) and Slabunov et al. (2006) divided the Karelian Province into three terranes that have many lithological, structural and age differences. These are the Vodlozero terrane, the Central Karelian terrane and the Western Karelian terrane. Mesoarchaean 2.8-3.2 Ga rocks are common in the Vodlozero and Western Karelian terranes, whereas on the basis of existing age determinations both granitoids and greenstones in the Central Karelian terrane are Neoarchaean, c. 2.76-2.72 Ga, although some of them contain reworked Mesoarchaean crustal material.

The Western Karelian terrane comprises much of eastern Finland and the westernmost part of Russian Karelia. Migmatitic TTG orthogneisses and amphibolites predominate, with small medium to low pressure granulite areas in the western part of the terrane. Crustal architecture inferred from seismic data, as well as bedrock structural data, suggest thrust stacking and transpression during late orogenic deformation around 2.70 Ga. Tectonic transport was towards NE and SE, with evidence that the Western Karelian terrane was emplaced eastwards over the Central Karelian terrane (Kontinen & Paavola, 2006). In the Central Karelian terrane high abundances of greywackes and 2.74-2.72 Ga basalt-andesite-dacite-rhyolite series volcanic rocks in the Ilomantsi and Khedozero-Bolsheozero greenstone belts indicate that they represent arc type tectonic settings, whereas mafic volcanic rocks in the Kostomuksha and Kuhmo greenstone belts resemble more plume type magmas (Sorjonen-Ward, 1993; Vaasjoki et al., 1993; Puchtel et al., 1998).

In the Western Karelian terrane rocks whose zircon ages are > 3.0 Ga are rare, existing only from the Iisalmi (3.2-3.1 Ga) and Pudasjärvi (3.5 Ga) terranes (Mänttäri & Hölttä, 2002; Mutanen & Huhma, 2003). The oldest volcanic rocks are found in the northern part of the Suomussalmi greenstone belt, 2.96-2.94 Ga (Luukkonen et al., 2002), and some nearby TTGs and migmatites are of the same age (Käpyaho et al., 2007; Mikkola, unpublished data).

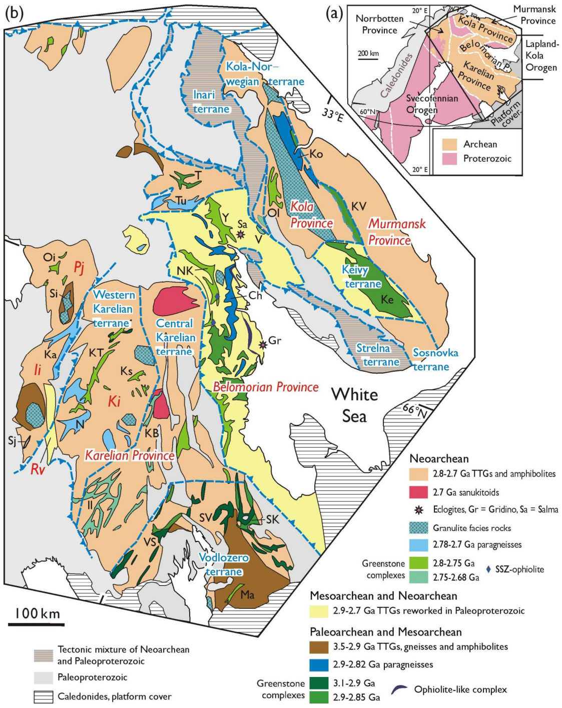

Figure 1. Generalised geological map of the Archaean of Fennoscandia (Hölttä et al., 2008).

However, all dated volcanic rocks in the Tipasjärvi, Kuhmo, Suomussalmi and Oijärvi greenstone belts yield ages of 2.84-2.75 Ga. Mesosomes of migmatites and TTG orthogneisses outside the greenstone belts give similar ages (Hyppönen, 1983; Luukkonen 1985; Vaasjoki et al., 1999; Käpyaho et al., 2006, 2007; Lauri et al., 2006).

The ion probe and TIMS U-Pb age determinations on zircon grains from mesosomes of paragneisses from various parts of the Western Karelian terrane constrain deposition of the protolith wackes to c. 2.71 - 2.69 Ga. Trace element and U–Pb data from the Nurmes paragneisses suggest that the source terrains comprised mainly 2.75–2.70 Ga TTG and/or sanukitoid-type plutonic and mafic volcanic rocks. The presence of MORB-type volcanic intercalations in Nurmes wackes suggests they were deposited in a back- or intra-arc setting (Kontinen et al., 2007).

The TTGs form four major geochemical groups on the basis of their major and trace element compositions. One group has relatively low SiO_2, elevated Mg, low Sr/Y ratio and high HREE indicating garnet-free source. Another group has high SiO_2, low Mg, low HREE and high Sr/Y ratio that suggest garnet-bearing basaltic source. Rocks belonging to the third group have positive Eu anomalies, strongly fractionated REE patterns with HREE mostly below detection limits, high Sr/Y and Zr/Sm ratios and low abundances of compatible elements and Fe and Mg. The fourth group are high-Ba-Sr sanukitoids that are generally younger (2.74.2.72 Ga) than other TTGs. Their low SiO_2 and high K_2O and MgO contents suggest an origin by melting in an enriched mantle source. Compared with the surrounding areas the Central Karelian terrane has higher abundances of sanukitoids which are lacking in the Belomorian and Vodlozero terranes and are rare in the Western Karelian terrane. (Bornhorst et al., 1993; Vaasjoki et al., 1993; Bibikova et al., 2005; Halla, 2005; Lobach-Zhuchenko et al., 2005; Käpyaho et al., 2006).

Migmatitic amphibolites form two major geochemical groups. Basaltic rocks belonging to the first group have flat or HREE depleted trace element patterns, resembling those of mid-ocean ridge basalts. In the second group basaltic rocks are enriched in LREE and LIL elements. They have a negative trough in Nb, like island arc basalts. Compatible elements, especially Ni but also Cr are low in LREE enriched group. Andesitic amphibolites have similar trace element contents with LREE enriched basaltic amphibolites, indicating that they belong to the same magma system, which may represent island arc magmatism or dykes that intruded into TTGs and were contaminated with the crustal material.

The Western Karelian terrane was metamorphosed in upper amphibolite facies and granulite facies conditions. Exceptions are the inner parts of greenstone belts which still often have mid or lower amphibolite facies mineral assemblages, well preserved primary structures and only a little or no migmatisation. Medium pressure granulites, metamorphosed at c. 9-11 kbars and 800-900°C are found only in the Iisalmi block (Hölttä & Paavola, 2000). In the Siurua area there are mafic granulites whose metamorphic pressures and temperatures were c. 5-6 kbars and 700-800°C (Lalli, 2002). On the basis of U-Pb ages on titanites, monazites and zircons from granulites and migmatite leucosomes this took place at 2.71-2.62 Ga, coevally with the emplacement of the youngest granitoids (Hölttä et al., 2000; Mänttäri & Hölttä, 2002; Mutanen & Huhma, 2003; Käpyaho et al., 2006; Lauri et al., 2006; Käpyaho et al., 2007).

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Polar magnetic anomalies and apparent susceptibilities as a part of World Magnetic Anomaly Map 2008

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World Magnetic Anomaly Map (1:50 mill) was first published in 2007. Updated edition of the WDMAM (1:25 mill) will be released this year. The digital map consists of overlays of varying resolution, of magnetic anomalies, crustal magnetization and apparent susceptibility. All data will be freely available.

Keywords: magnetic anomaly, lithosphere, polar, World

1. General

International Association of Geomagnetism and Aeronomy (IAGA) and Commission for Geological Map of the World (CGMW) published the Magnetic Anomaly Map of the World, scale 1:50,000,000 in 2007. (Korhonen et al 2007). In polar areas this map consisted of elder polar magnetic anomaly map grids, oceanic profiles, satellite data and a forward modeled magnetic anomaly set, calculated from ocean floor magnetisation model to fill gaps. The map presents wavelengths shorter than c. 2600 km, fitted with MF5 crustal magnetic anomaly model (Maus et al. 2007) and was compiled by a method proposed by Hemant et al 2007.

2. Arctic magnetic anomaly map

An Arctic and North Atlantic magnetic anomaly map was compiled by CGS in 1996 and has been freely available since that. Its data set was used to compile the WDMAM2007 (1:50 mill). A new co-operational project between Russia, USA, Canada and the Nordic Countries compiled a new magnetic anomaly map in 2004-2008. The map was released at 33rd IGC in Oslo, August 2008 (Gaina and Werner 2008). Its grid was used to compile the WDMAM2008 for Arctic area.

3. Antarctic magnetic anomaly map

The ADMAP project collected and compiled Antarctic magnetic anomaly data since 1990's (Golynsky et all 2006). The original data and metadata was released at SCAR2008 on a DVD. Coordinates and metadata of this DVD-set were used to recompile the first version of ADMAP for the WDMAM2008.

3. Use of maps

The polar magnetic anomaly maps offer an opportunity to interpret polar geology in a comparable way. Apparent magnetic susceptibility facilitates delineating magnetic geological units and comparing magnetic structure with mid latitudinal and equatorial magnetic anomaly regions. Most important failure in the WDMAM2008 is sparse oceanic data around Antarctica and in southern oceans. New measurements are encouraged to be made and old data sets urged to get released for public use.

4. Characteristics of WDMAM2008

- Scale 1:25 000 000, comparable to World Geological Map of CGMW, 4th Edition
- More details, 2 km and 1 km resolution overlays, where available
- Demonstration of finer overlays
- Updated data coverage: new national and regional sets, new polar sets
- Updated oceanic data set
- Updated satellite model, MF6
- Updated oceanic anomaly model
- Global lithospheric magnetization model derived from anomaly data
- WDMAM2008 is a contribution to eGY 2007-2008 and international Polar year.

5. Important issues to develop WDMAM and its polar parts in future

- More detailed and extensive coverage
- Common availability conditions of data
- Geomagnetic reduction models and practices
- Improved definition of the normal field
- Global definition of magnetic anomaly
- Global definition of magnetic survey and grid metadata
- Improved forward models to patch gaps in total field data
- Advanced lithospheric magnetization models derived from measured anomalies
- Geological models based on magnetic anomalies and other geoinformation.

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North European Transect – a preliminary compilation

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A nearly continuous, 3600 km long, NE-running North European Transect (NET) is combined from the existing deep seismic reflection data sets in the Baltic Sea (BABEL, 1600 km), Northern Finland (FIRE 4-4A, 580 km) and Barents Sea (1-AR, 1440 km). Geologically the North European Transect covers the transition from Phanerozoic Europe to Precambrian Europe and back to the Phanerozoic Barents Sea Shelf. Northern Europe grew around Baltica in several tectonic episodes that involved the formation and destruction of Columbia/Hudsonland, Rodinia and Pangea supercontinents. The paleoplateboundaries are traversed by subvertical transparent zones suggesting transpressional and trantensional environments.

Keywords: Fennoscandia, Baltic Sea, Barents Sea, reflection seismic, BABEL, FIRE, 1-AR

1. Introduction

Continental lithosphere covers less than one third of the Earth's surface. The growth of these rigid, buoyant continents takes place at convergent plate boundaries, where material is added via subduction and/or via accretion of smaller and bigger fragments of island arcs, sedimentary basins or continents. The process of merging the independently arriving lithospheric entities with the rim of a continental plate is complex and has three phases - precollisional, collisional and postcollisional - each of which will leave different tectonic markers. The first phase brings in material and the second one accretes the material to the continent, and the last phase determines whether the terrane is destroyed or preserved in the geological record. The interior parts of continental plates are also subject to plate tectonic forces acting on the peripheral rims of the plate and/or to mantle plume activity.

The northern part of the Europe plate is composed of Baltica and Barentsia paleoplates. In the following we will study the formation of the Baltica-Barentsia plate. We will try to identify the processes involved with the help of a large scale deep seismic reflection transect – North European transect (NET; Fig. 1). Geologically the North European Transect covers the transition from Phanerozoic Central Europe to Precambrian Northern Europe and back to the Phanerozoic Barents Sea shelf/platform. The geological area, over which the transect runs, has been involved in the formation and destruction of three super continents: Columbia/Hudsonland, Rodinia and Pangea supercontinents (Table 1).

2. Seismic profiles

The transect (NET) has been compiled from pre-existing deep seismic on- and off-shore reflection profiles BABEL, FIRE and 1-AR. The NE directed, nearly continuous 3600 km long profile, traverses Baltic Sea (BABEL, 1600 km), Northern Finland (FIRE 4-4A, 580 km) and Barents Sea (Russian Arctic, 1-AR, 1440 km). The southernmost point of the NE-striking transect is in the Bay of Lybeck, Germany (BABEL A) and the northern most is on Franz Joseph Land (Line 1-AR).The BABEL marine reflection profiles run through the Baltic and Bothnian Seas (BABEL A,B,C,1,3&4; Abramowitz, 1997; Korja and Heikkinen, 2005). The traverse continues onshore with FIRE 4-4A (Pattison et al., 2006) across northern Finland and

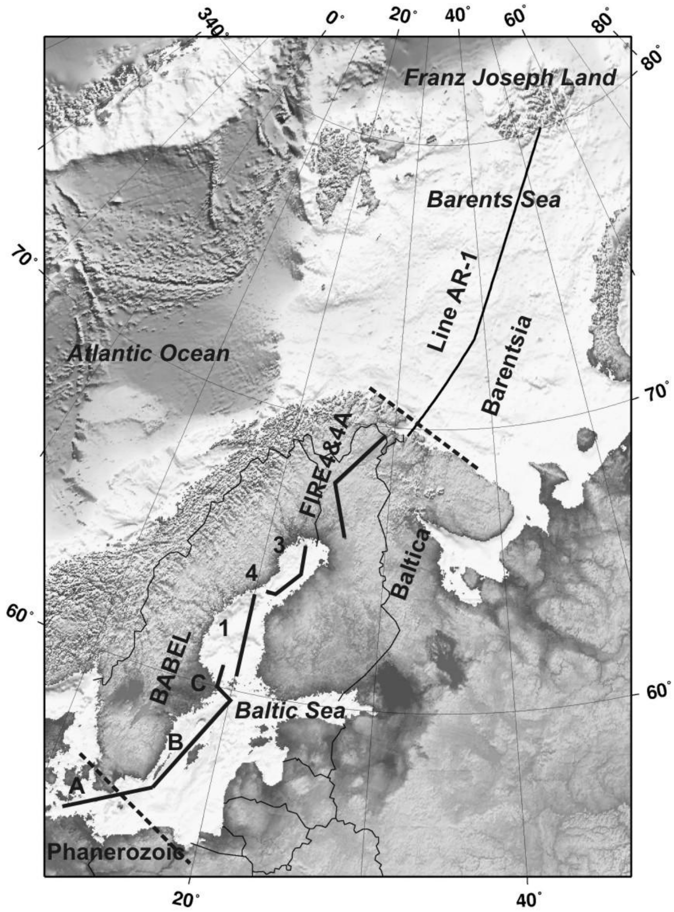

Figure 1. The location of the reflection seismic lines along the North European Transect (NET).

continues with the onshore part of the line 1-AR close to the northern coast of the Kola Peninsula. Line 1-AR runs through the Barents Sea and connects the superdeep hole-3 on the Kola Peninsula (Zapolarny, Russia) with the hole 1-Hayes on Franz Joseph Land (Dvornikov, 2000; Ivanova et al., 2006). Line 1-AR is 1440 km long and it includes 1330 km and 110 km of offshore and onshore profiles, respectively.

The transect shows differences in regional reflectivity patterns, e.g. in thinner areas the Moho is well reflective and in thicker areas it is interpreted from the gradational disappearance of crustal reflectivity. In the Barents Sea, the Moho boundary has been determined from wide-angle reflections. Rift-related grabens are characterized by 33-36 km – thick crust. The reflective image of the deep crust is highly dependent on the thickness of the sedimentary cover. Sedimentary cover is few hundred meters in the Baltic sea, few tens of meters in the land areas and few kilometers in the Barents Sea area. In the Barents Sea area, the seismic image is dominated by the layered structure of the sedimentary basins and the middle and lower crust are poorly imaged. In the shield areas, the seismic sections are tuned to image the structures within the basement whereas the sedimentary cover is poorly imaged.

3. BABEL

BABEL C, 1, and 4&3 image, how the core of Baltica was formed by sequential accretion of microcontinents and arc terranes at in the vicinity of an old continental margin during the Svecofennian Orogeny ~1.9-1.8 Ga (Savo-Lapland, Fennia, Svecobaltic Orogens; Lahtinen et al., 2005; Korja et al., 2006). When Baltica joined the Columbia supercontinent, new terranes were added to its southern edge in the Sveocbaltic Orogeny (~1.8 Ga) (BABEL B, A; Abramovitz, 1997; Korja and Heikkinen, 2008). The thinning of the thickened accreted crust began during the lateral spreading of the orogens. It continued during the dispersal of the Columbia, during which Baltic Sea failed rift was formed (Korja et al., 2001), rapakivi granitoids were intruded and sedimentary basins were developed. On BABEL A, the paleoplate margin of Columbia is characterised by a series of subvertical faults indicating oblique shearing. On BABEL AC, an extended plate margin structure has been imposed on the Rodinian additions (Sveconorwegian; Abramovitz, 1997). Pangean additions (Variscan-Caledonian) make up the crust beneath BABEL A1-AC. Major crustal thinning takes place along a series of subvertical faults across the Trans-European Suture Zone marking the transition from Phanerozoic to Proterozoic Europe.

Table 1. Tectonic events in the North European Transect area compiled from Nikishin et al., 1996 and Bogdanova et al., 2008.

Formation of Columbia/Nuna/Hudsonland:
Assembly of the nucleus of Baltica,
    Svecofennian Orogeny, 1.9-1.8 Ga
    Lapland-Kola Orogen, 1.9 Ga
Baltica joins Columbia supercontinent;
    Nordic Orogeny, Svecobaltic Orogeny, 1.8 Ga
Break-up of Columbia
Rifting of Columbia,
    basin formation and bimodal magmatism, 1.65-1.35 Ga (Early Riphean)
    Development of passive margins and cratonic aulacogens:
        Peri-Timan basin, Bothnian basin, 1.35-1.05 Ga (Middle Riphean)
Development of passive margins, 1.2 Ga
Formation of Rodinia:
Accretion at Baltic margin, Sveconorwegian Orogeny 1.13-0.90 Ga (Late Riphean)
Baltica joins Rodinia: Baltica collides with Laurentia 0.98-0.96 Ga
        Basin formation continues in the foreland
Break-up of Rodinia;
Rifting of Rodinia, basin formation and magmatism, 0.8 Ga – 0.56 Ga
    Opening of Iapetus Ocean (0.56 Ga) in the west
    Opening of the Tornquisvt Sea/Rhein Ocean in the south
Timanide-Pechora Orogen in the north,
    collision of Baltica with Barentsia and Pechora 0.62-0.53 Ga
Formation of Pangea
Closure of Iapetus Ocean,
    North-Atlantic-Arctic Caledonian Orogeny,
    Baltica collides with Laurentia, 0.42 Ga
        extension continues in eastern foreland basins (Barents Sea)
    Lomonosov orogen ??, North Barents Sea collides with Arctica, 0.39-0.35 Ga
        deltaic sedimentary complexes on the carbone platform
    Eastern Barents Sea in NNE-SSW
        is back-arc basin to Magnitogorsk arc 0.39-0.35 Ga
Closure of Rhein Ocean,
    Variscan Orogeny, 0.30-0.25 Ga,
        Laurussia collides with Gondwana-land,
        Baltic Sea is foreland basin
Closure of Uralian Ocean;
    North Uralides 0.26-0.21 Ga,
        Siperia collides with Laurussia,
        Barents Sea is foreland basin
Break-up of Pangea
Accelerated rifting of Pangea,
    Arctic-North-Atlantic rifting (0.25-0.20 Ga),
        uplift of Fennoscandia
    Late stage of north Uralide orogen,
    inversion of the Devonian rifts Late Jurassic (0.16-0.14 Ma)
Opening of the North Atlantic (0.07 Ga)

4. FIRE 4&4A

FIRE 4&4A (Pattison et al., 2006; Korja and Heikkinen, 2008) suggests that the northern part of the Fennoscandian Shield is a collage of older continental fragments and intervening basins that have been welded together in Svecofennian Lapland-Savo (south) and Lapland -Kola orogens (north). The Lapland-Kola orogen record the collision of Baltica and Laurentia during the compilation of the Columbia supercontinent. The collisional structures were later overprinted by extensional events probably associated with the dispersal of Columbia.

5. Line 1-AR

Russian Arctic line 1-AR focuses on the Phanerozoic sedimentary cover of the Barents Sea Basin (Dvornikov, 2000; Ivanova et al., 2006). The line images the transition form Paleoproterozoic Baltica to Neoproterozoic Barentsia. As part of the Rodinia supercontinent formation, Baltica collided with Barentsia resulting in Timanide orogeny. The suture zone is transposed by subvertical fault zone indicating transtensional or transpressional tectonic setting at the plate margin. During the break-up of Rodinia an aborted rift was formed within the Barentsia. Later peripheral tectonic events modified the interior parts of Barentsia that acted first as a back arc basin and later as a foreland basin to the Uralian and Caledonian orogen during the formation of the Pangea supercontinent (Nikishin et al., 1996; Bogdanova et al., 2008).

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Lateral spreading of the Svecofennian Orogen

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The FIRE1-3 seismic reflection sections display a frozen image of orogenic thickening and lateral spreading. The decoupling of the upper, middle and lower crust during spreading resulted in the formation of layered superstructure-infrastructure of the crust.

Keywords: Lateral spreading, Svecofennian, reflection seismic, Paleoproterozoic

1. Introduction

During thickening, part of the kinetic energy of plate movement is transformed into potential and thermal energy of the thickened crust, whose potential energy level is raised relative to its surroundings. Lateral spreading of the orogen to the sides tends to equilibrate the potential energy differences instantly and thus the orogenic crust is thinned and adjacent crust is thickened (Rey *et al.* 2001). Beaumont *et al.* (2001) have suggested that thermal weakening results in the formation of orogenic superstructure-infrastructure (Culshaw et al. 2006) of large hot orogens and is partially responsible for at least enhancing the layering of the crust.

The uppermost crystalline crust always deforms in brittle mode along discrete shear planes. The deformation mode changes gradually from discrete to more pervasive plastic deformation as the depth changes from upper to lower level. Concurrently, the fold structures change from upright to flat lying. This gradual change is deformation style may be one of the reasons why reflection sections are dominated by low angle structures at depth, whereas the exposed surface is dominated by upright folds. Lower lever of deformation is reached already in amphibolite facies, and thus areas with regional amphibolite/granulite metamorphism, like the Precambrian cratons, are expected to be characterized by pervasive low angle fabrics.

At surface Fennoscandian Shield is a typical Precambrian orogen with a 10-15 km deep erosion level characterized by granitoids and highly deformed supracrustal units metamorphosed under upper amphibolite or lower granulite facies conditions at 1.89-1.87 Ga. Recently, a high resolution deep seismic survey (FIRE) across the Paleoproterozoic Svecofennian orogen in Central Finland (Kukkonen et al. 2006) revealed a layered crust with deformational features characteristic of collision followed by extension (Korja and Heikkinen 2008). Here we study how much of the crustal reflection structure could have been formed by lateral spreading (Korja and Heikkinen 2009).

2. Interpretation of seismic data

The FIRE profiles display three crustal layers with different reflection properties: upper, middle and lower. The upper crust is associated with velocities of 5.8-6.2 km/s and vp/vs ratios of 1.68-1.70, the middle crust with 6.3-6.6 km/s and 1.71-1.74 and the lower crust with 6.8-7.6 km/s and 1.74-1.76, respectively (Korja et al. 1993; Hyvönen et al. 2006). The layers are separated by subcontinuos subhorizontal reflective boundaries interpreted as detachment surfaces.

The lower crust has a subdued and patchy subhorizontal reflectivity that dies out at the lower crust - upper mantle boundary – the Moho boundary. The subhorizontal reflectivity pattern suggests a ductile environment during the deformation of the lower crust and the lack of reflective Moho boundary suggests the crust-mantle boundary not to have been a major deformation zone during the thinning of the crust.

The upper crust is generally detached from the middle crust via a subhorizontal, highly reflective surface. The middle crust has two components: large blocks of poorly reflective background material boarded by high amplitude, shallow to steeply dipping crustal-scale reflections and smaller scale, high amplitude reflections. The crustal-scale reflections, mostly listric in shape, sole out at the boundary between the middle and lower crust. These reflections have previously been interpreted to image crustal-scale stacking (Sorjonen-Ward 2006; Korja and Heikkinen 2008). But they could also be interpreted to image sets of extensional faults in which case the structural pattern is reminiscent of an asymmetric simple shear rift with listric shear zones propagating towards the NW (Wernicke 1985).

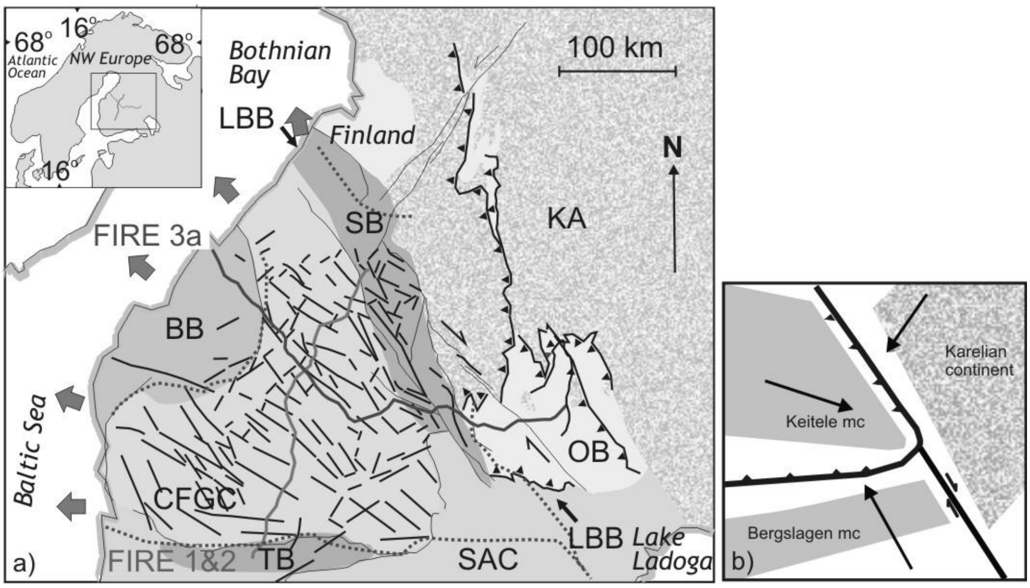

Figure 1. Tectonic setting of the FIRE1-3 profiles after Korja et al. (2009). a) FIRE 1-3 reflection lines on a schematic tectonic map of the central part of the Svecofennian orogen. The blue arrows indicate the spreading direction of the orogen. The major tectonic units are: BB – Bothnian Belt; CFGC – Central Finland Granitoid Complex; KA – Archean Karelian domain; OB – Outokumpu Belt; SAC – Southern Finland Arc Complex; SB – Savo Belt and TB – Tampere Belt. LBB – Ladoga-Bothnian Bay wrench fault zone is indicated with arrows. b) A schematic plate tectonic reconstruction before a double sided collision. The plate movement vectors are shear wave anisotropy directions from the lithospheric mantle (Plomerova et al. 2007), interpreted as paleo-stress vectors. The velocities of the plates are tentative. The geometry of the triple junction resembles that of the electrical conductors in Fig 1a.

The smaller scale reflections are arranged as herringbone structures on FIRE 1&2 and as westward ramping anticlinal structures on FIRE3a (Korja et al., 2008), both indicative of mid-crustal flow Culshaw *et al. (*2006). On a three-dimensional block diagram, the mid-crustal structures seem to be dipping south indicating southward movement. On FIRE 1&2, the middle crust images symmetrical thinning, upwarping of the lower crust and subvertical crustal faults dipping symmetrically towards the centre, which leaves the crustal structure reminiscent of a pure shear rift. On FIRE3a, the listric structures could also be interpreted to image sets of extensional faults in which case the structural pattern is reminiscent of an asymmetric simple shear rift with listric shear zones propagating towards the NW (Wernicke 1985).

The upper crust (0-12 km) displays fine layering with fine-scale deformation patterns. On profile FIRE3a, the uppermost crust displays listric reflections flattening at a subhorizontal surface, interpreted as a detachment surface, between the depths of 8 and 12 km. In the perpendicular direction, along FIRE 1&2, the same listric reflections are imaged as subhorizontal reflection surfaces, above which reflections mimicking half grabens and graben and horst structures are found and from where some near-vertical transparent zones spin off. The detachment surface is gently inclined southwards and it may reach the surface at Elämäjärvi macrostructure at Pihtipudas (Kilpeläinen et al., 2008; Korja et al., 2009). The listric reflections are associated with pervasively deformed and stretched rocks dipping E-SE , the transparent zones are associated with steeply dipping shear zones striking SE-NW (Kilpeläinen et al., 2008; Korja et al., 2009).

3. Discussion

The rheological behaviour of the middle crust is further complicated by the increased amount of melt. The migmatite is able to flow as viscous fluid as soon as the amount of melt is sufficiently high that the rock loses its solid framework (Vanderhagen 2001). During this anatectic phase, the middle crust is easily deformed and flow structures - midcrustal thrust ramps on FIRE3a and fishbones on FIRE 1&2 - develop and the crust thins by spreading laterally both forward and sideways. The melting event and the contemporaneous development of the superstructure-infrastructure (Culshaw et al. 2006) enhanced the initial layering of the crust. The infrastructure may extruded to the surface, where it would form the anticlinal cores of cores complxes (Beaumont et al, 2001; Culshaw et a al., 2006). Such structures may be found in the Kyyjärvi deformation zone and Vaasa migmatite complex (Korja et al., 2009).

The upper crustal material also slides away from the thickening centre (two-sided orogen and orogenic triple point; Fig. 1b) via the listric upper crustal shear zones and associated transfer zones and via low angle normal faults. The regional average of the plunging directions of lineations in the northern part of the Central Finland Granitoid Complex (Kilpeläinen et al. 2008) image persistent movement either towards or away from the Ladoga - Bothnian Bay wrench fault zone (LBB; Fig. 1). The few observations that we have from the area indicate that the hanging wall was moving towards the west, suggesting that the upper crust was moving upwards and westwards. This direction of spreading is also suggested by the sequential overlapping (younging) of listric shear zones and the formation of extensional duplexes.

4. Conclusions

The coeval continental convergence from both east and south (Fig. 1B) probably resulted in extreme over-thickening of the Svecofennian crust and lithosphere. Over-thickening was partially compensated by frontal and sideways spreading of the orogen away from the triple point. The spreading and thermal relaxation resulted in orogenic collapse, during which the crustal material was rearranged and superstructure-infrastructure of the crust was formed. The crust attained its present layered structure, where HT-LP amphibolite facies rocks characterize the uppermost crust, granulite-facies rocks the middle and lower crust.

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Western margin of the Fennoscandian Shield - magnetotellurics across the Caledonides in Jämtland, Sweden and Tröndelag, Norway

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Our study focuses on determining the electrical conductivity of the accretionary wedge of the Caledonian orogen, the underlying carbonaceous alum shales, the Proterozoic basement and the deep western margin of the cratonic Fennoscandian lithosphere. We use data from 60 broad-band magnetotelluric soundings along a 270 km long profile in Jämtland, Sweden and Tröndelag, Norway across the Central Scandinavian Caledonides. 2D inversion of the Jämtland section of the profile has revealed an electrically conducting layer beneath the Caledonides imaging alum shales on top of the Proterozoic basement. Preliminary inversion of the Tröndelag section shows that conductor extends 70 km to the west in Norway. The geometry of the conductor suggests that the Caledonian accretionary wedge thickens in a step-wise manner from c. 1 km to 15 km towards the west. The upper crust of the Proterozoic basement in east is homogeneous and resistive from surface down to 15 km. Lower crust and uppermost mantle in the easternmost part of the profile are very resistive whereas in west they are two to three orders of magnitude more conductive. The increase of average crustal conductivity is related to Caledonian processes or later opening of the Atlantic Ocean that have affected also the lower crust. A c. 100 km wide region of enhanced conductivity at the depth of c. 100-150 km is detected under the Caledonides. Conductor is absent beneath the eastern part of the profile and, according to new data from Tröndelag, also in the western part of the profile. In both regions the depth to the top of the first mantle conductor is 250-300 km.

Keywords: Electrical conductivity, crust, lithosphere, Caledonides, magnetotellurics

1. Introduction

The Scandinavian Caledonides are a part of the Caledonian orogen that extends from Ireland and Scotland northeastwards through the western part of Scandinavia to Svalbards in the Arctic Ocean. The Late Silurian collision of the continents Baltica and Laurentia resulted in the shortening and imbrication of the stretched western margin of Baltica. Simultaneously, the accretionary wedge of Neoproterozoic and Early Palaeozoic rocks was emplaced on the top of the subducted and underthrust Baltica (Hurich et al. 1989). Remnants of this orogen are preserved today as a relatively thin veneer above the Proterozoic basement in an 1800 km long and up to 400 km wide thrust and fold belt, the Scandinavian Caledonides, along the western margin of Scandinavia (Figure 1).

The underlying Proterozoic (Precambrian) basement evolved in a series of orogenies in Palaeo- and Mesoproterozoic time (Gorbatschev and Bogdanova 1993). In Neoproterozoic time, the cratonized Baltica was modified by extensional events, which finally lead to the break-up of Baltica, development of a passive western margin of Baltica and opening of the Iapetus Ocean c. 608 Ma ago (e.g. Gee, 1982). In Neoproterozoic to Early Palaeozoic time, large parts of Baltica were covered by fluvial to marine sediments including black organic carbonaceous shales. The latter, so-called alum shales, comprises one of the most widespread lithostratigraphic units in Scandinavia (Bergström and Gee 1985). The Mesozoic to Cenozoic extensional event that lead to the opening of the Atlantic Ocean and the Neogene uplift of the margin are the last events that have affected the region.

Recently several geophysical studies have been carried out along an E-W directed transect across the Scandinavian Caledonian fold belt (Fig. 1). Studies include broad band (0.001 – 20000 s) electromagnetic soundings in Jämtland (Korja et al., 2008), seismic reflection (Hurich et al. 1989; Juhojuntti et al., 2001) and refraction profilings (Schmidt et al. 1996). Also integrated thermo-rheological and potential field modelling has been carried out to study lithospheric structure in the passive margin area (e.g. Pascal et al., 2007).

Figure 1. Main geological units of Fennoscandia (Gorbatchev and Bogdanova, 1993) and the location of the Jämtland-Tröndelag magnetotelluric profile (thick blue line) in central Sweden and Norway.

2. Measurements, data and inversion

Magnetotelluric measurements cover a 160 km long profile in Jämtland Sweden (Korja et al., 2008) and a new 110 km long profile in Tröndelag, Norway (Figure 1). Data were collected at 60 broad-band MT sites (periods from 0.001 s to 1000 s) and at 20 long period LMT sites (10 - 20000 s), the latter coincide with broad-band MT sites. For inversion magnetotelluric sites were projected onto a profile perpendicular to the strike direction of N40°E obtained from the strike analysis. No static shift correction for apparent resistivity data was applied but apparent resistivity was downweighted by applying an error floor of 90% compared with an error floor of 5% on the phase data. Data were inverted using the Occam type REBOCC 2D inversion code (Siripunvaraporn and Egbert 2000). In our approach we have selected to invert the determinant average of the impedance tensor together with tipper data (Pedersen and Engels, 2005). The total normalised rms-misfit of the final model is 2.

Final 2D inversion model of the Jämtland section is shown in Figures 2 and 3. Crustal part of the model is shown in Figure 2, where reflection seismic data (Juhojuntti et al. 2001) is superimposed on top of the resistivity model. Entire inversion model is shown in Figure 3. Models image highly conducting alum shales that dip from surface in west to the depth of c. 2-3 km in west. Models reveal also a highly resistive Svecofennian basement to the east of the Caledonian Front (CF) and suggest that highly resistive rocks (Revsund granites at surface) extend far to the west beneath the Caledonides.

The two most striking features in the long period model (Fig. 3) are the resistive lithosphere in the eastern part of the profile and a deep conductor beneath the entire profile.

There are no indications on conductors in lithosphere in the first 200 km in the Precambrian part of the profile. The depth to the top of the surface of the deeper conductor varies considerably along the profile. In the central part the top of the conductor is at the depth of c. 100 km while in the eastern end of the profile it reaches the depth of c. 250-300 km. New preliminary data from Tröndelag, Norway suggests that the top of the deep conductor is at the depth of 250-300 km also in the western part of the Jamtland-Tröndelag profile.

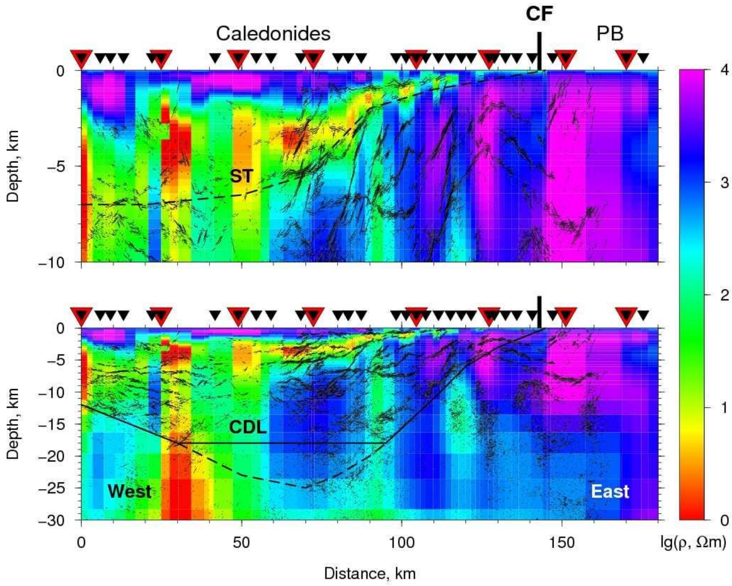

Figure 2. Reflection seismic data (Juhojuntti *et al*. 2001) superimposed on top of the final resistivity model. CF – Caledonian Front, PB – Precambrian Basement (Svecofennian). Thin solid black line in the lower panel labelled as CDL is preferred Caledonian Deformation Line from Juhojuntti *et al.* (2001). In the upper panel the dashed black line labelled as ST denotes the sole thrust. Figure from Korja et al., 2008.

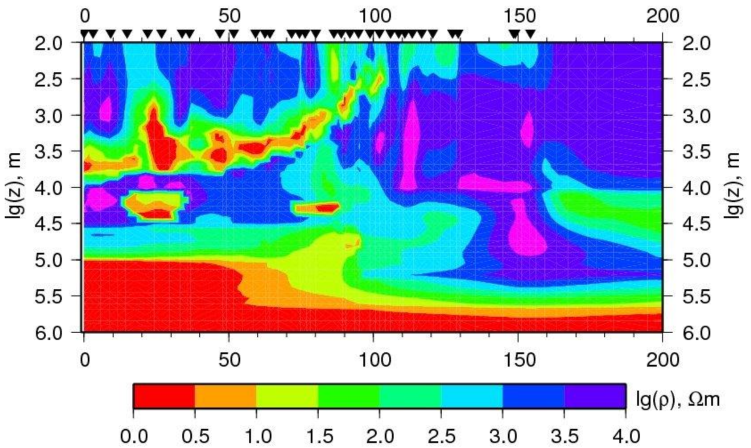

Figure 3. Resistivity model of the Jamtland section of the profile. Logarithmic depth scale.

3. Conclusions

Magnetotelluric data from 60 sites along a 270 km long profile across the Caledonian orogen has revealed the following features:

Caledonides. A westward dipping and electrically highly conducting layer beneath resistive Palaeozoic rocks of the Caledonian orogen images alum shales, the autochthonous

Cambrian carbon-bearing black shales. Based on the correlation of electrical conductivity and seismic reflectivity models, we suggest that the sole thrust deepens considerably from c. 1 km to c. 15 km towards the west.

Precambrian basement. In the east, the upper crust of the Precambrian basement is homogeneous and resistive from the surface down to 15 km and can be associated with the Revsund granites. The resistive upper crust extends 60 km further to the west from the Caledonian Front and represents Rätan granites. The lower crust and uppermost mantle in the easternmost part of the profile are very resistive whereas in west they are two to three orders of magnitude more conductive. The increase of average crustal conductivity is related to the Caledonian processes or later opening of the Atlantic Ocean that have affected also the lower crust

Upper mantle. A region of enhanced conductivity is detected at the depth of c. 100-150 km under the Caledonides in the western border of the Fennoscandian Shield. The conductor is absent beneath both in the eastern and western parts of the profile or is detected at the depth of more than 250-300 km.

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Solid earth geophysics field course 2007

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A field course in solid earth geophysics was held for the second time in September 2007 as a collaboration between the Geophysics Division of the University of Helsinki, Institute of Seismology, Laboratory of Geoenvironmental Technology at Helsinki University of Technology and the Geological Survey of Finland (GTK). The course was led by laboratory manager Jalle Tammenmaa from Helsinki University of Technology, and featured a host of highly qualified teachers from the participating institutes. Twelve students had the opportunity to participate in diverse geophysical field measurements in the rainy woods of Kerkkoo, Southern Finland.

Keywords: field course, applied geophysics, Kerkkoo

1. Introduction

In 2003, during the XIV "Sovelletun geofysiikan neuvottelupäivät" seminar in applied geophysics Research Director Pekka Nurmi from the Geological Survey of Finland suggested a new field course to be organized in solid earth geophysics. The idea was to have the students and the teachers of the two universities, the University of Helsinki and Helsinki University of Technology, come together in collaboration with GTK to learn more about the field of applied geophysics. The course was estimated to increase synergy and was approved as financially worthwhile. The planning was left to a work group led by Prof. Lauri J. Pesonen from the University of Helsinki. Other members of the group were Tarmo Jokinen, Jukka Lehtimäki and Markku Peltoniemi.

The field course was organized for the first time in 2004 (Piispa et al., 2004) by Prof. Lauri J. Pesonen. An old test line in Perä-Pohjakka (Lehtimäki, 1980) on the border of Askola and Kerkkoo was chosen as the location for the measurements and experts from the organizing institutes were in charge of the teaching. The course was considered a success and was incorporated into the teaching curricula of both universities.

During September 16-21, 2007 the course took place for the second time[4], this time under the leadership of laboratory manager Jalle Tammenmaa from the Helsinki University of Technology. In the future the course will take place every two or three years, depending on the number of students willing to participate.

The location was the same as previously and accommodation for the students and instructor Jalle Tammenmaa was provided by Prestbacka catering manor in Askola. Prestbacka's delicious meals and daily sauna were a welcome counterpoint to the long and chilly excursions in rainy woods.

[4] Participating students: Michal Bucko, Manuel Cantos, Niamh Collins, Eeva Huuskonen, Antti Kivinen, Paula Koskinen, Risto Pietilä, Edmundo Placencia, Emma Riikonen, Anniina Saarinen, Timo Salmensaari and Outi Valtonen. Instructors: Meri-Liisa Airo, Seppo Elo, Tero Hokkanen, Taija Huotari, Tarmo Jokinen, Fredrik Karell, Markku Peltoniemi, Reijo Sormunen, Heikki Säävuori and Jalle Tammenmaa.

2. Course objectives and methods

The aims were to teach the students the geophysical background of the measured quantities, familiarise them with different types of geophysical equipment and field measurement methods as well as teach them some basic data analysis and interpretation techniques.

The measurements were conducted along a test line running across a distinct electromagnetic anomaly that was first found in the 1970s in the sulphide ore exploration survey in the Perä-Pohjakka area. The following methods were used:

- gravimetric methods
- petrophysical sampling
- galvanic methods and induced polarization
- magnetometric and Slingram-electromagnetic surveys
- seismic methods
- ground-penetrating radar

The students were divided into four groups, each of which was in charge of two methods. The groups then had to give an oral presentation, interpret their results and write a report.

3. Conclusion

A field course such as this provides students with a unique opportunity to see the more practical side of their field of study. University studies are often very theoretic and while it's important to understand the basics and background of geophysical phenomena, it is also good to have an insight into how the information you're trying to absorb has been gathered in the first place. Not to mention the importance of getting a preview of your possible future work methods. It allows students to meet and socialize with experts in their field of studies as well as other students, who may someday be their colleagues.

Acknowledgements:

A big thank you on behalf of all the participating students goes to all the organizers, especially Jalle Tammenmaa, Lauri J. Pesonen, Reijo Sormunen, who patiently taught a dozen people how to use all the equipment, all the quest instructors and teachers and last but not least to Merja Anttila from Prestbacka manor.

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Figure 1. Rainy days in Kerkkoo with Jalle Tammenmaa in the middle. Photo courtesy of Jalle Tammenmaa.

Figure 2. Risto Pietilä operating the gravimeter. Photo by Jalle Tammenmaa.

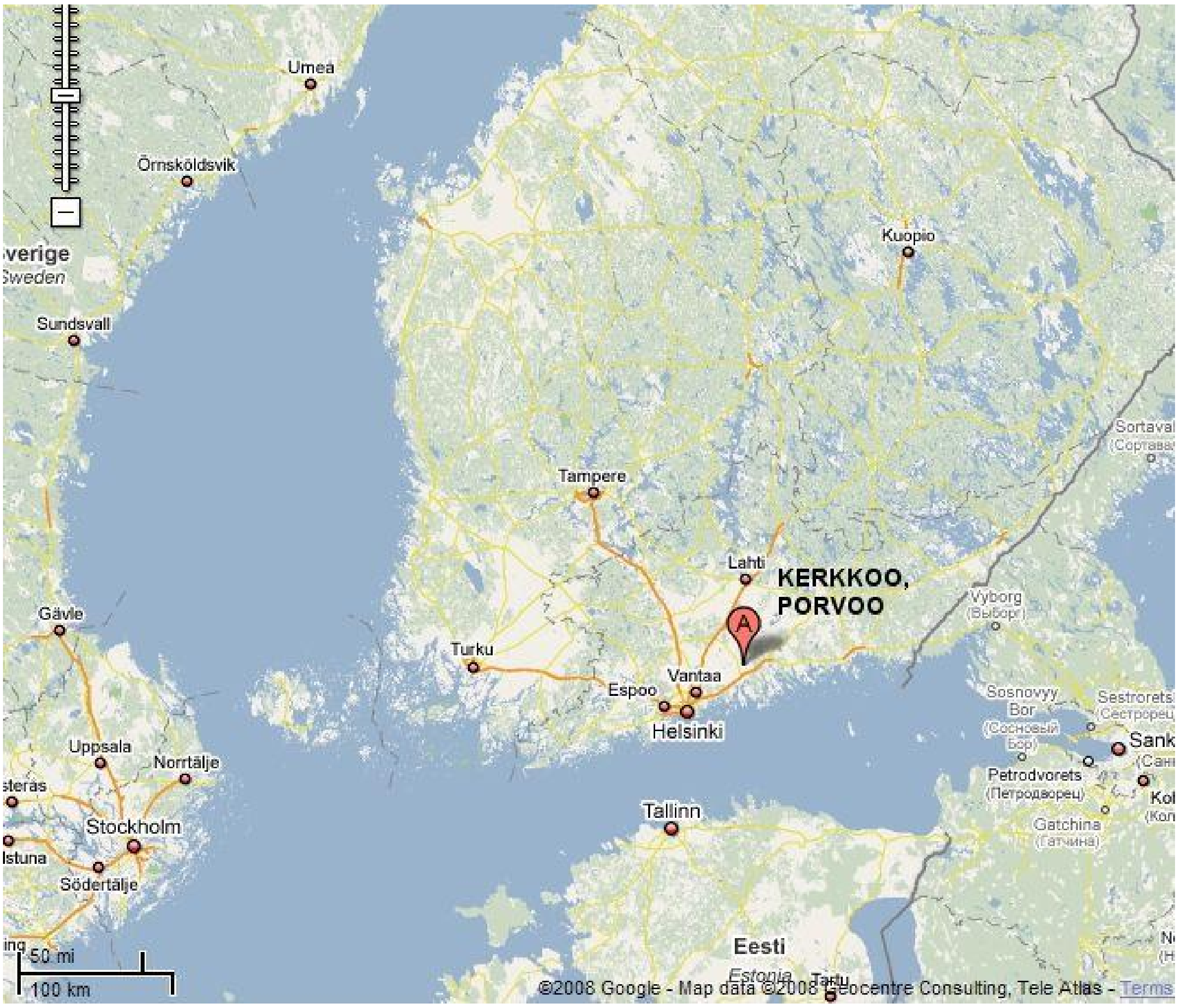

Figure 3. The location of the test line. Figure drawn with Google Maps.

Petrological crust-mantle boundary vs. seismic Moho in the central Fennoscandian Shield: constraints from collocated wide-angle and near-vertical seismic profiles

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We present analysis of the crust-mantle boundary in the Precambrian Fennoscandian shield based on comparison of P- and S-wave 2-D velocity models of wide-angle reflection and refraction profiles (SVEKA'81, SVEKA'91, FENNIA, POLAR) to correspondent collocated new reflection profiles in Finland (FIRE).

Keywords: lithosphere, crust, upper mantle, Fennoscandia, the Moho, seismic, P-wave velocity, S-wave velocity, Vp/Vs

1. Introduction

By definition, the Moho discontinuity is a seismic velocity boundary, where P-wave seismic velocities, as measured by seismic wide-angle reflection and refraction data, increase to values of more than 7.8 km/s (Mooney and Meissner, 1992), while the petrological crust-mantle boundary is defined as transition from felsic-mafic crustal rocks to ultramafic rocks (with high olivine content) typical of the upper mantle. The crust-mantle boundary is dependent on compositional variations in the lower crust and upper mantle which, in turn, are linked to the tectonic/magmatic history of the lithosphere. Therefore, the longer is the tectonic/magmatic history, the more complicated is the structure of the crust-mantle boundary. As a result, the seismic "Moho" do not always coincide with the crust-mantle boundary.

In our study we present analysis of the crust-mantle boundary in the central Fennoscandian shield in Finland. In the 80s-90s this part of the shield was studied by BALTIC, SVEKA'81, SVEKA'91, FENNIA and POLAR wide-angle reflection and refraction profiles (see Luosto, 1997, for review). The profiles crossed the Paleoproterozoic Lapland-Kola orogen (1.94-1.86 Ga) and the composite Svecofennian orogen (1.92-1.79 Ga), that, in turn can be divided into the Lapland-Savo, Fennian, Svecobaltic and Nordic orogens (Lahtinen et al., 2008).

Our study is based on comparison of P- and S-wave 2-D velocity models of wide-angle reflection and refraction profiles to correspondent collocated reflection profiles in Finland (FIRE, Kukkonen et al., 2006). For this we analyse lateral variations of Vp, Vp/Vs and reflectivity in the lower crust and uppermost mantle and compare them to published data about elastic properties of major types of crustal and upper mantle rocks.

2. The crust-mantle boundary beneath the Svekofennian orogen (SVEKA'81, SVEKA'91, FENNIA, FIRE1, FIRE2)

Three main types of the crust-mantle boundary beneath the Svekofennian orogen has been revealed (Janik et al. 2007). Beneath the Lapland-Savo orogen and southern part (terrain?) of the Svekobaltic orogen the eclogitic lower crust overlies peridotitic upper mantle (no magmatic underplating). In this case the wide–angle Moho boundary coincides with the pertological crust-mantle boundary and reflection Moho is unclear. Beneath the Fennian orogen the peridotitic upper mantle is overlaid by lower crust composed of mafic garnet granulites (magmatic underplate). The wide-angle Moho and the petrological crust-mantle boundary coincide, but reflection Moho is unclear. Beneath the Southwestern part (terrain?) of the Svekobaltic orogen the wide-angle Moho corresponds to the contact of mafic garnet granulites and eclogites. The petrological crust-mantle boundary is located deeper than the wide-angle Moho.

3. Crust-mantle boundary beneath the Lapland-Kola orogen (POLAR, FIRE4)

In the southwestern part of the POLAR profile the wide-angle Moho is coincident with the crust-mantle boundary and corresponds to the contact of anorthositic lower crust with the upper mantle composed of mixture of peridotites and pyroxenites. In the central part (Tanaelv belt, southern part of the Lapland Granulite Terrane) the wide-angle Moho marks the top of the eclogitic body in the upper mantle (crustal root), while the petrological crust-mantle boundary can be associated with the bottom of this body (sub-horizontal reflectors in the upper mantle at a depth of 65–75 km). Beneath the northern part of profile (Archean Kola province) the Moho is a boundary between granulitic lower crust and the upper mantle composed of peridotites and pyroxenites (Janik et al., submitted).

4. Conclusions

1) The Moho boundary beneath ancient orogens in the Fennoscandian Shield does not always coincide with the crust-mantle boundary due to presence of eclogites at the base of the crust.
2) Dense eclogitic crustal roots beneath orogens do not necessary delaminate and sink into the mantle. They can preserve in the uppermost mantle for millions and billions of years.
3) Cratonic roots are heterogeneous and can contain large amount of dense eclogitic rocks. This heterogeneity is necessary to take into consideration in geodynamic models.
4) Preservation of dense eclogitic orogenic roots is possible, if the underlying mantle is cold and mechanically strong.

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Interpretation of geoid anomalies in the contact zone between the East European Craton and the Palaeozoic Platform in Poland

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We present analysis of lateral variations of density in the crust and upper mantle in the area of contact of the Precambrian East European Craton (EEC) and the Palaeozoic Platform (PP) in Poland obtained by 3-D forward modelling and inversion of geoid undulations.

Keywords: lithosphere, crust, upper mantle, Trans-European Suture Zone, geoid, density

1. Introduction

Knowledge of 3D density distribution in the Earth crust and upper mantle is a necessary condition for geodynamic modelling. It can be estimated using forward modelling and inversion of the gravity data. As the gravity modelling is generally non-unique, it should be constrained by existing seismic velocity models. In our study we investigate 3D density variations in the crust and upper mantle beneath Poland and investigate their effect of on geoid undulations. The major tectonic feature in the study area is the Trans European Suture Zone (TESZ) separating the Precambrian East European Craton (EEC) from younger tectonic units of Palaeozoic Europe. This zone plays an important role in geodynamic of Europe. For example, Marotta and Sabadini (2004) demonstrated that the TESZ separates the Europe into two areas with fundamentally different regimes of intraplate deformations. Thus the main motivation for our geoid study was to access the density inhomogeneities in the crust and upper mantle beneath this important tectonic suture and adjoining areas. The other motivation was a great number of recently published information about the crustal structure in Poland obtained by deep seismic sounding experiments (for example Grad et al., 2006; Majdański et al., 2007),

2. Geoid for the territory of Poland

The gravimetric geoid for the territory of Poland was elaborated on the basis of satellite measurements (Łyszkowicz and Denker, 1994). The values of the observed differences between the geoid and the reference ellipsoid GRS80 in the study area vary between 23 and 48 meters and in Poland itself between 28 to 43 meters. The area of Palaeozoic Europe is characterized by larger anomalies (N>40m) than the area of East European Platform (N<30m), whereas the gradient zone between them corresponds to the TESZ area. As the size of the area is approximately 8 degrees and 12 degrees in N-S and W-E directions, respectively, the longest wavelength of a geoid signal there is l=30. This suggests that only harmonics with numbers of l>30 should show signals totally inside the study area, while harmonics with smaller numbers would produce a linear trend or a constant shift from the average. Such long-wavelength gravity anomalies are not necessarily caused by deep structures beneath the lithosphere or outside our study area. They may be associated with local factors, like strong variations in crustal structure or areas of glacial isostatic adjustment (Simons and Hager, 1997). In our study area such a local source can be a large contrast in thickness and structure of the crust in the TESZ revealed by seismic studies (c.f. Grad et al., 2006).

3. 3D density distribution in the crust and its effect on geoid undulations

High-resolution seismic models of the crust and upper mantle from experiments POLONAISE'97, CELEBRATION 2000 and SUDETES2003 as well as previous profiles LT and TTZ were interpolated into a 3D P-wave velocity model for the whole Poland. The model, parameterized by a grid defined in geographical coordinates system, was converted to a density model assuming different equations connecting seismic velocities to densities for crustal rocks (5.8 km/s < Vp < 7.9 km/s), sediments (Vp < 5.8 km/s) and the uppermost mantle (Vp > 7.9 km/s). The crustal density model was used to calculate synthetic geoid undulations for the territory of Poland and to estimate influence of separate layers (topography, sediments, crust and uppermost mantle) on the geoid. To calculate the gravity effect of a large-scale 3D density model we developed a code based on a point mass algorithm as well as prisms algorithm that uses some easy to implement optimizations (Majdański et al., submitted).

The shape of the calculated geoid reproduces rather well the main features of the observed geoid, including the long-period ones. The computed geoid undulations vary between 49 m for the Variscan Europe and 22 m in the EEC. The change of the crust structure from a relatively thinner crust for the Palaeozoic Platform and the Carpathians to a much thicker crust in the EEC region results in a gradual change of the geoid height that occurs in the TESZ. In the residual between the observed and calculated geoid one can see two significantly anomalous regions. The area with the largest positive residual (up to +6m) is observed in the Palaeozoic Platform, while the largest negative residual (down to -8 m) is seen within the EEC. However, the main crustal suture in our study area (TESZ) is not seen in the residual, which means that this structure has no continuation in the upper mantle. Having assumed that the 3D velocity model of the crust is close to the true one, we may conclude that we need the assumption of a heterogeneous mantle in order to explain the observed gravity effect.

4. Modelling of density distribution in the lithospheric mantle

To estimate the density inhomogeneities in the lithospheric mantle, we performed inversion of a residual between the observed geoid and undulations caused by the 3D density distribution in the crust (Swieczak et al., submitted). In order to constrain the inversion, we estimated possible variations of density that can be expected in the upper mantle of our study area using results of surface wave tomography in the TESZ (Cotte et al., 2002) as well as published mantle xenoliths data and previous results of gravity modelling in the area. Physical properties of continental lithospheric mantle are relatively well known not only from geophysical studies, but also from direct measurements using mantle rocks that have been overthrust or exhumed to the surface by various tectonic and magmatic processes.

As was shown by Kaban et al. (1999), any compensating mass distribution can be approximated by a thin layer placed above the effective compensation depth. Basing on the assumption of local isostatic compensation and Pratt–Hayford isostasy model, the density distribution in the upper mantle was parameterized as a 40 km thick layer located above the assumed compensation depth of 140 km and subdivided into irregular blocks. The boundaries of the blocks were defined according to boundaries of major tectonic units in the study area and position and shape of the most pronounced anomalies in the residual geoid. A series of sensitivity tests calculated for such density heterogeneities in the upper mantle showed that such density inhomogeneities can produce geoid undulations of the order of several meters.

The density values in each unit were taken as model parameters for the inversion procedure and inverse problem was solved using global optimization with constraints (Kozlovskaya, 2000).

The geoid calculated from the final model has the shape similar to the observed one and the absolute values of the residual are less than 2 m. Further increase of the number of blocks and modification of block boundaries did not result in improvement of the fit to the observed geoid. The density variations in the upper mantle in the final model correlate well with the surface heat flow. This suggests that these variations are partly due to diversity in mantle temperatures. The major suture separating the EEC from the Palaeozoic Platform (the TESZ) is not observed as a distinct unit in the mantle. Instead, our study suggests continuation of the lithosphere of the EEC beneath the PP and confirms subdivision of the TESZ into terranes with distinctly different evolution**.**

5. Analysis of local isostatic compensation

As our density model was obtained under the assumption of local isostatic compensation, we checked whether this condition is satisfied in our final density model. The calculations were performed in similar way as in publication by Ebbing et al. (2006). For each postulated depth of compensation an average density was calculated in a column with respect to a mean density of the whole model. Such an estimate is proportional to the dipole moment of the density distribution above the compensation depth, but it is more convenient for visualization. The result shows clearly that there is no compensation in the uppermost 25 km, because of the load due to topography (Sudetes and Carpathians). Moreover, the variations of density and thickness of the crust between the EEC and younger units are not compensated at the Moho boundary. However, this difference disappears almost completely at the assumed compensation depth of 140 km, except of several units. (Bohemian Massif, Pomerania unit and small unit in the EEC).

6. Conclusions

1. The major part of the observed geoid undulations in the area adjoining the TESZ is due to variations of thickness and density of the crust. Density heterogeneities in the upper mantle cause the undulation of geoid of an order of several metres.
2. Spatial distribution of low densities in the mantle correlates well with the areas of increased heat flow, suggesting that they may be of thermal origin.
3. The upper mantle of the EEC is extended beneath the TESZ up to the Carpathians front. It is indicated by densities of the Kuiavian and Malopolska units that are similar to the density of the EEC. This suggests different tectonothermal evolution for SE and NW parts of the TESZ.
4. The higher densities observed in the northern part of the Palaeozoic Platform correlate well with high P-wave velocities in this area and may be explained by presence of high-density eclogitic rocks in the uppermost mantle. This high density rocks are underlain by low densities (probably, asthenosphere).
5. The low densities below the Sudetes and Carpathians can be interpreted as being due to partially molten material (asthenosphere).
6. Generally, the condition of local isostatic compensation and Pratt-Hayford type of isostasy is fulfilled in our study area. Deviation from the state of local isostatic equilibrium and high density in the mantle is observed in several units. For small-scale units this can be explained by non-precise crustal model. However, for large-scale units (Pomeranian and Sudetes) this deviation can be explained also by larger than assumed depth of compensation.

Acknowledgments:
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Composition of the upper mantle beneath the Lapland-Kola orogen (northern Fennoscandian shield) obtained by 3-D modelling of Bouguer anomaly

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We present evidence for preservation of thick eclogitic grustal root beneath the Lapland-Kola orogen in northern Fennoscandian Shield, obtained by 3-D gravity modelling. The structure of the crust there is well constrained by controlled-source wide-angle and near vertical reflection seismic studies. Using this data as a constraint, we made forward modeling and inversion of the Bouguer anomaly in the area around the orgen. We show that the major source of the regional Bouguer maximum is a well-preserved dense eclogitic root beneath the orogen that continues to a depth of more than 70 km.

Keywords: lithosphere, crust, upper mantle, Fennoscandia, 3-D gravity modelling

1. Introduction

To estimate response of the lithosphere of the Fennoscandian shield to glacial isostatic adjustement, it is important to know differences in density and mechanical properties of rocks in the upper mantle. These properties are usually estimated using seismic velocity models that are interpreted in terms of rock composition and temperature. However, the same velocity anomalies can be explained also by seismic anisotropy, as the upper mantle beneath the shield is generally seismically anisotropic. The anisotropy is caused by large-scale fabric in the upper mantle due to preferred orientation of olivine. As the gravity data is not sensitive to seismic anisotropy, modeling of the gravity data can be applied in order to distinguish between velocity anomalies caused by seismic anisotropy and anomalies caused by variation in rock composition and temperature.

An example is a high velocity anomaly in the upper mantle beneath the wide-angle reflection and refraction POLAR profile that crossed the Proterozoic Lapland-Kola orogen, separating Archaean Karelian craton and Kola province in the northern Fennoscandian Shield), where a regional maximum of the Bouguer anomaly is also observed (Korhonen et al., 2002). Recent velocity modeling along the POLAR profile (Janik et al., submitted) revealed a large body with high Vp and high Vp/Vs ratio high beneath the wide-angle Moho boundary in the area of the orogen. Comparison of Vp and Vp/Vs of this body to published values of Vp and Vp/Vs for the main types of lower crustal and upper mantle rocks (Sobolev and Babeyko, 1994, Janik et al., 2007) suggests that this body may be composed of eclogites. In order to verify this, we made forward modeling and inversion of the Bouguer anomaly in the area of the orogen, using the seismic velocity model of the POLAR profile as a constraint.

2. Gravity modelling along the POLAR profile

In order to construct the 3-D density model and make 3-D gravity modelling and inversion we used interactive Bloxer and Grablox software by Pirttijärvi (2004). The model is 260 km in N-S direction, 230 km in E-W direction, and 100 km deep. It consists of 10x10x2 km regular blocks with constant density. The starting 3-D model was constructed using 2-D velocity model of POLAR profile as a constraint and trial-and-error fit to the observed Bouguer anomaly. After that we applied SVD (singular value decomposition) inversion with 3-D smoothing to three uppermost layers (first 6 km of the model). Results of gravity modeling are presented in Fig. 1.

Error estimation was done for density inhomogenities with most significant density contrast. First, the density of the inhomogeneity was changed by some small amount $\Delta\rho$ and synthetic Bouguer anomaly was calculated for this “error test model”. By comparing the calculated anomaly to the anomaly of the final model, the average difference between the anomalies of two models was found ($\delta g_{average}$). The confidence limit was chosen to be the one that gives the $\delta g_{average}$ of no more than 1 mgal. The confidence limits were calculated for density inhomegeneities in the upper crust corresponding to the Kittilä Greenstone Belt and Lapland Granulite Terraine. The others inhomeogeneities were the low velocity body at the depth of about 20 km, high Vp and Vp/Vs body in the lower crust, and a high Vp and Vp/Vs body in the upper mantle. The average densities and confidence limits are shown in Table 1.

The density of the high-velocity in the upper mantle (3.50 g/cm^3) is much higher than that of upper mantle peridotites (3.32-3.34 g/cm^3), indicating that it is composed of dense eclogitic rocks. Such value of density explains well the observed regional maximum of the Bouguer anomaly in the area. We propose that the body represents a well-preserved crustal root beneath the Lapland-Kola orogen.

3. Discussion of the results

Basing on the assumption of local isostatic compensation and Pratt–Hayford isostasy model, we estimated the state of isostatic equilibrium in the area around the Lapland-Kola orogen, For the postulated depth of compensation of 100 km an average density was calculated in a column with respect to a mean density of the whole model. Such an estimate is proportional to the dipole moment of the density distribution above the compensation depth (Turcotte and Shubert, 2002). The calculation showed that the crust in the area of the POLAR profile is generally in the state of quasi-isostatic equilibrium, with the exception of local-scale inhomogeneities in the upper crust. However, the eclogitic crustal root beneath the Lapland-Kola orogen is not isostatically compensated at the assumed compensation depth. Preservation of dense eclogitic material inside less dense depleted peridotitic cratonic mantle is possible, if the lithosphere under the root is cold and mechanically strong enough to support the root and prevent delamination. In this case the seismic boundaries at a depth of 65–75 km may mark the upper boundary of an Archaean mantle wedge.

Alternatively, the root can be preserved, if the Archaean lithospheric mantle beneath the Lapland-Kola orogen underwent erosion and the root is supported from below by astenospheric material.

Unfortunately, our study cannot distinguish between these two explanations, as seismic velocities (and, consequently, densities) beneath these boundaries are not constrained by our data. Further studies of the upper mantle by passive seismic methods are necessary in order to distinguish between these two hypotheses.

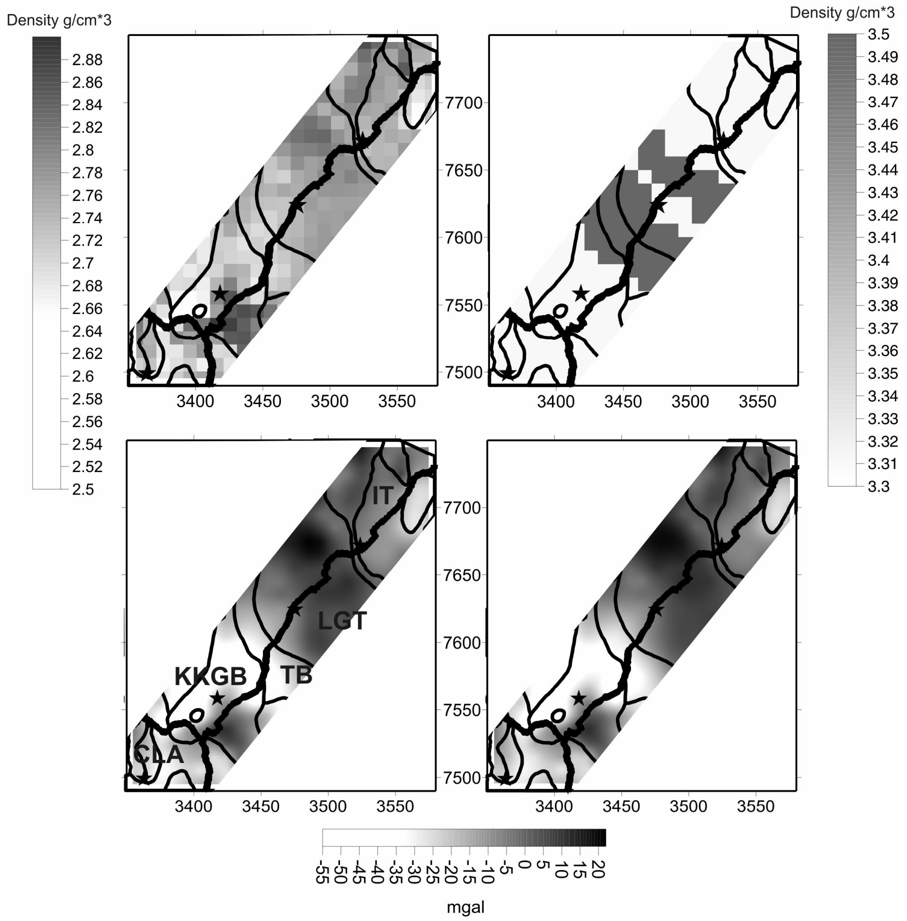

Figure 1. Upper panel: two horizontal sections through uppermost crust (left) and upper mantle at a depth of 50 km (right) of the final 3-D gravity model. Lower panel: observed Bouguer anomaly (left) and synthetic Bouguer anomaly calculated from 3D density model (right). Also the borders of the main geological units from 1:10 000 000 geological map of Finland (GTK, 2003) (thin black lines) are shown together with FIRE4, FIRE4A, and FIRE4B profiles (thick black lines) and the shot points of POLAR profile (black stars). The coordinate system is the National Finnish Coordinate System (KKJ) (Hirvonen, 1949; Ollikainen et al., 2001). Abbreviations: CLA is Central Lapland Area, KKGB is Karasjok-Kittilä Greenstone Belt, TB is Tanaelv Belt, LGC is Lapland Granulite Terraine and IT is Inari Terraine).

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Table 1. Main density inhomogeneities, their average densities, and confidence limits of the 3-D density model POLAR profile.

Density inhomogeneity	**Density (g/cm^3)**	**Confidence (g/cm^3)**
Karasjok-Kittilä Greenstone Belt	**2.864**	**0.003**
Lapland Granulite Terraine	**2.778**	**0.002**
Low velocity body at the depth of about 20 km	**2.740**	**0.005**
high V_p and V_p/V_s body at lower crust	**3.00**	**0.01**
High V_p and V_p/V_s body in the mantle	**3.50**	**0.02**

POLENET/LAPNET - a multidisciplinary seismic array research in northern Fennoscandia

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We present first results of a new multidisciplinary seismic array research in northern Fennoscandia during the International Polar Year 2007-2009.

Keywords: lithosphere, Fennoscandia, broadband seismic array, International Polar Year

POLENET (http://www.ipy.org/development/eoi/proposal-details.php?id=185) - POlar Earth Observing NETwork is a multidisciplinary consortium of activities during the International Polar Year 2007-2009 that aims to dramatically improve the coverage in geodetic, magnetic, and seismic data across the polar regions (both Arctic and Antarctic).

Compared to other continental regions of the Earth, the polar regions are poorly studied by seismic methods. These regions have unique geodynamic environments where the solid Earth, the cryosphere, the oceans, the atmosphere and the global climate system are closely linked. In the high latitudes, the weight of ice-sheets provides an additional force affecting the state of stress and deformation in the lithosphere. In accordance with the scientific program of POLENET, the main targets of seismic observations in polar regions (bi-polar seismology) can be formulated as follows:

1) Studying the deep structure of the Earth (in particular, the Earth's core)
2) Studying the lithosphere structure of polar regions (including structure and evolution of the Archaean lithosphere) and estimation of realistic distribution of mantle viscosity in the areas of glacial isostatic adjustment
3) Studying the cryosphere-lithosphere interaction and glacial seismic events.

One of the sub-projects of POLENET related to seismic studies in the Arctic regions is POLENET/LAPNET –a multidisciplinary seismic array research in northern Fennoscandia. In recent years dense arrays of portable broadband seismic stations have become a major tool for studying the mechanical structure of the Earth on global and regional scales. The POLENET/LAPNET broadband array, with the average spacing between stations of 70 km, was designed to solve specific tasks of polar seismology. The geographic position of the LAPNET array is favourable for registering seismic phases travelling through the Earth's core, because it is located at epicentral distances of 120^0-150^0 from seismically highly active area around Fiji, Tonga, Vanuatu and Kermadec Islands in the Pacific Ocean, where the earthquake with the magnitude of more than M_W =5.5 are quite usual. In addition, it is continuation of the previous SVEKALAPKO seismic array research. The project was a passive seismic array research in southern and central Finland aiming at studying the lithosphere-asthenosphere system in the suture zone of Proterozoic Svecofennian and Archaean Karelian domains of the Fennoscandian Shield. One of the main targets of the LAPNET research is to obtain a 3D seismic model of the crust and upper mantle down to 670 km (P- and S-wave velocity models, position of major boundaries in the crust and upper mantle and estimates of seismic anisotropy strength and orientation) in northern Fennoscandian Shield.

An important part of the LAPNET project is studying of regional and local seismic events. In Fennoscandia, the natural seismicity is of intraplate type, and, in general, is low-to-moderate in magnitude. In the area covered by the LAPNET array, the local seismic events are quarry blasts and earthquakes originating from several re-activated ancient faults and other zones of weakness in the crust. Studying of local events will help to map these zones and improve understanding of local seismicity and seismic hazard in Fennoscandia. Together with teleseismic receiver functions, these events can be used to create a 3-D velocity model of the crust, which is a necessary constraint in all studies using waves from teleseismic events.

Compared to the previous seismic array experiments in Fennoscandia (TOR and SVEKALAPKO), which were oriented primarily on recording and storage of teleseismic events with relatively low sampling rate of 20 Hz, the LAPNET array records high-frequency continuous data (sampling rate from 50 to 100 Hz) which is pre-processed in Oulu, Grenoble and Prague and stored in the data centre of the University of Grenoble. Due to high sampling rate, the LAPNET dataset can be useful not only for such traditional techniques as teleseismic body wave tomography, surface wave studies, receiver functions and seismic anisotropy studies, but also for the methods based on ambient seismic noise analysis, studying of source mechanisms of local events, discrimination of man-made activities and natural events etc.

The array consists of 32 temporary stations deployed in northern Fennoscandia and of existing permanent broadband stations in northern Finland (Sodankylä Geophysical Observatory of the University of Oulu and Institute of Seismology of the University of Helsinki), Sweden (Swedish National Seismological Network, University of Uppsala) and Norway (NORSAR and the University of Bergen). The equipment for the temporary array was provided by Sodankylä Geophysical Observatory, University of Grenoble and University of Strasbourg (France),Geophysical Institute of Academy of Sciences, Prague (Czech Republic), Institute of Geodesy and Geophysics, Vienna University of Technology (Austria), Institute of Geophysics ETH Zurich (Switzerland), Institute of Geospheres Dynamics, RAS, Moscow (Russia), University of Leeds (UK). The financial support for operating of the LAPNET array was provided by the University of Oulu and by the Academy of Finland.

Most of the stations of the LAPNET temporary array were deployed in May-September, 2007. In summer, 2008 some of the instruments (mainly short-period) were changed to broadband ones and one more temporary station was deployed in Pyhäjärvi. The array will continue recording of local, regional and teleseismic events in 2009 and partly also in 2010. As most of the stations of the array are located beyond the polar circle, operation of broadband instruments in extreme polar climate conditions is a challenging task.

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Rapakivi granite magmatism in the Fennoscandian Shield: Heat source, palaeotectonic reconstructions and implications to supercontinent development

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We interpret the genesis of Mesoproterozoic rapakivi granites of the Fennoscandian Shield with a new model where the crust has a decisive role in providing the heat source of magmatism without any major mantle input such as plumes or magmatic underplating. Rapakivi granite magmatism is attributed to supercontinent assembly and collisional thickening of crust in the Palaeoproterozoic and subsequent long-term warming of crust in post-orogenic time. The Fennoscandian rapakivi granite province was formed in a plateau already uplifted in the Svecofennian times due to thermal expansion of the thickened crust. Cauldron collapse of the exhausted rapakivi granite magma chambers in the Mesoproterozoic and subsequent cooling together with erosion resulted in formation of the present intra-continental basins in the Baltic Sea area.

Keywords: Rapakivi granite, Fennoscandian Shield, thermal models, radiogenic heat production, collisional orogens, supercontinents

We investigate the genesis of Mesoproterozoic rapakivi granite and associated mafic magmatism in the Fennoscandian shield and adjacent areas. Rapakivi granite intrusions of 1.65-1.47 Ga are hosted by about 250 Ma older Svecofennian orogenic rocks (Fig. 1). We attribute this bimodal magmatism to post-orogenic heating of the late Svecofennian orogenic front formed in the collision (~1.86 Ga) between Fennoscandia and Sarmatia as a part of the formation of supercontinent Hudsonland (Columbia) (Kukkonen and Lauri, 2007).

The heat source of rapakivi granite magmatism was provided by the thick crust itself as radiogenic heat from normal U, Th and K concentrations in rocks. By conductive heat transfer this crust-derived heat increased the lithosphere temperatures and eventually temperatures high enough to generate melts in the lower crust and even in the upper mantle were attained (Fig. 2). No magmatism of mantle origin, such as a magmatic underplate, or increased mantle heat flow is required. The long time difference between the orogenic peak and rapakivi granite magmatism is attributed to the low rate of conductive heat transfer in a thick crust. Thus, there is a causal relationship between rapakivi granite magmatism and Svecofennian orogeny, and rapakivi granite magmatism should not be considered anorogenic but post-orogenic (Kukkonen and Lauri, 2008). The most plausible source for both the granitic as well as the anorthositic magmatism is lower crustal granulite (restitic rock), which was depleted already during the Svecofennian orogeny by extracting orogenic granitoid melts.

High temperatures of the crust and upper mantle of the Svecofennian lithosphere induced thermal expansion and isostatic uplift, which peaked in Mesoproterozoic time and an extensive plateau of about 1.5 km height was formed approximately at the location of the present Baltic Sea, Bothnian Sea, Gulf of Finland and Lake Ladoga. The plateau was characterized by rhyolitic volcanic centers of considerable dimensions at the locations of the present rapakivi granite batholiths. When the magma production ceased due to exhaust of suitable lower crustal source the volcanoes collapsed, generating depressions later filled with Jotnian sediments. Due to slow cooling in the Meso and Neoproterozoic as well as

Phanerozoic times, subsidence continued with further deposition of sediments, which partly fill the present shallow sea basins of Fennoscandia.

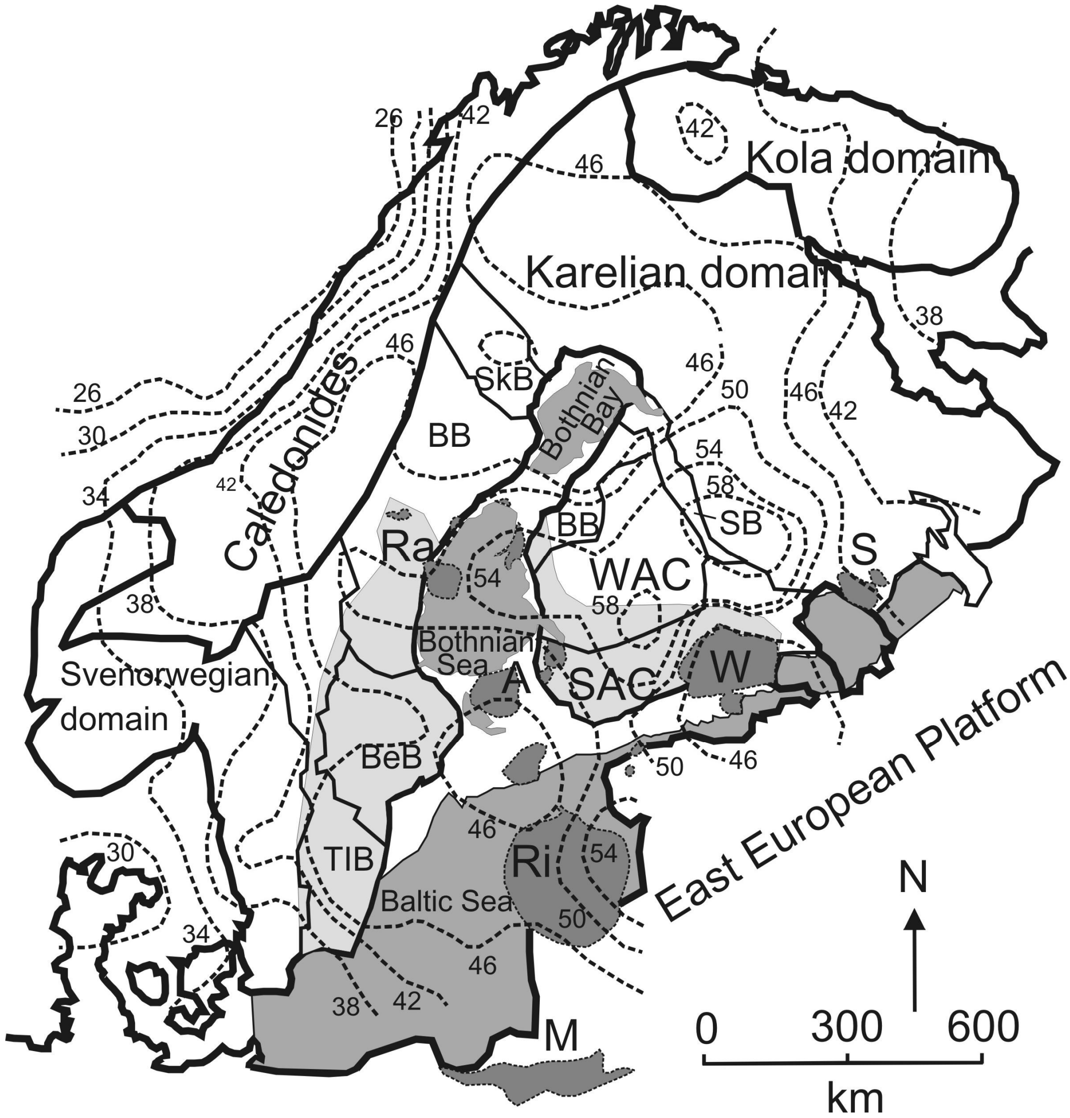

Figure 1. Generalized geologic map of the Fennoscandian Shield and adjacent areas (adapted from Koistinen 1994; Koistinen et al., 2001; Dörr et al., 2002), with depth contours (km) of Moho (Korja et al., 1993; Lahtinen et al., 2005). Locations of Mesoproterozoic rapakivi granite intrusions outcropping or covered by sediments but indicated from drilling or geophysical data are shown in dark grey, whereas areas of elevated heat flow and radiogenic heat production in the Palaeoproterozoic Svecofennian areas hosting rapakivi granite intrusions are indicated with pale grey (modified from Kukkonen, 1989, 1993 and Näslund et al., 2005). Main rapakivi granite complexes: A, Åland (1.645-1.615 Ga); Ra, Ragunda (1.53-1.47 Ga), Ri, Riga (1.584-1.574 Ga); M, Mazursky (1.525-1.499 Ga); S, Salmi (1.547-1.530 Ga). Sedimentary rocks (Precambrian and Phanerozoic) in present sea basins are shown in medium gray. WAC = Arc complex of western Finland, SAC = Arc complex of southern Finland, SB = Savo Belt, BB = Bothnian (Pohjanmaa) belt, SkB = Skellefteå belt, BeB = Bergslagen belt, TIB = Transscandinavian igneous belt.

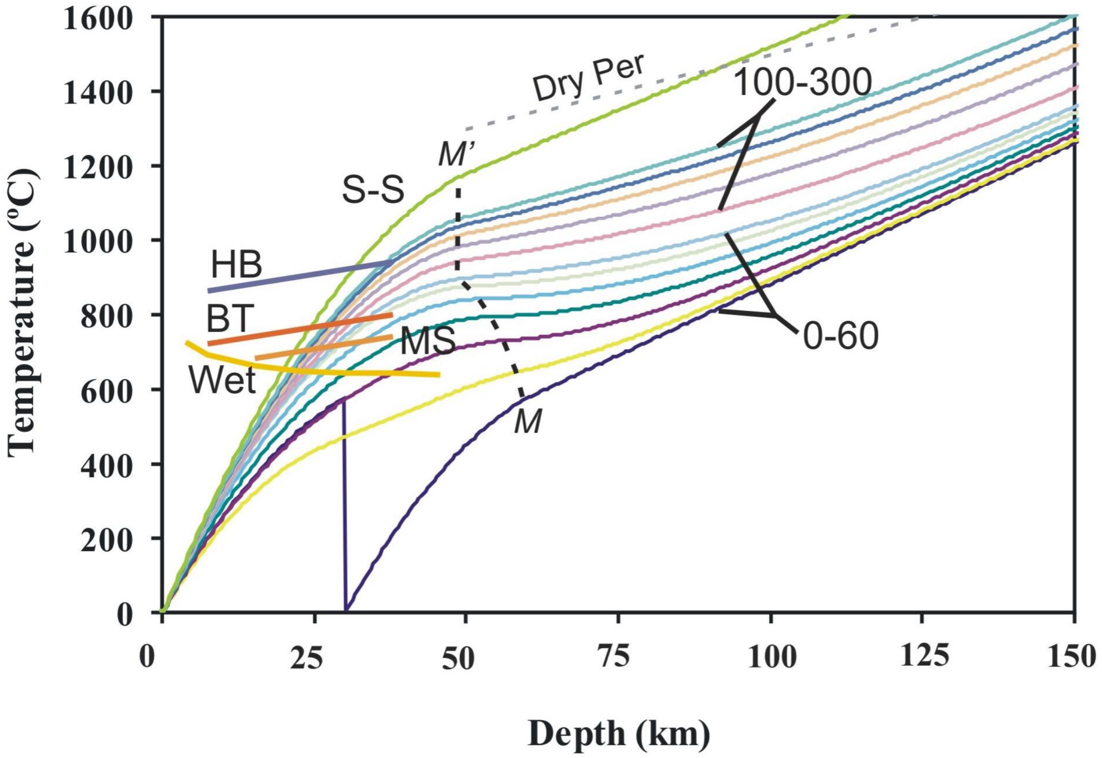

Figure 2. Thermal effects of crustal thickening calculated with a 1D conductive heat transfer model. Crust of original thickness of 30 km is doubled to 60 km thickness at model time 0 Ma. The thickened crust is assumed to erode at a rate of 0.2 km/Ma until the crust has a final thickness of 50 km. Location of Moho is indicated with *M-M'*. Geotherms are shown at 10 Ma intervals for 0-60 Ma and 50 Ma intervals for 100-300 Ma. Line S-S, the final steady-state geotherm; WET, wet solidus of haplogranite; MS, BT and HB, onset of dehydration melting of muscovite, biotite and hornblende (Johannes and Holtz, 1996); Dry PER, solidus of dry peridotite (Takahashi and Kushiro, 1983). Radiogenic heat production is 1.35 $\mu W\ m^{-3}$ in the crust and 0.003 $\mu W\ m^{-3}$ in the mantle. Basal heat flow density is 18 $mW\ m^{-2}$.

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Shear Zones and Fault Rocks in Deeper Parts of the Continental Crust

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Ductile shear zones and fault rocks in the Finnish Archean and Paleoproterozoic crust have often been developed in the conditions of amphibolite to granulite facies metamorphism. Banded blastomylonites and migmatitic rocks have been often found within those, whereas lower-grade fault rocks such as cataclasites and mylonites may lack totally. Various types of blastomylonites and migmatites are genetically associated with shear zones and, thus, shear zone models should be augmented to cover this kind of environments of effective metamorphism. Consequently, shear related migmatite rocks, "shear migmatites", should be treated as one principal subgroup among the fault rocks.

Keywords: fault rock, shear zone model, shear migmatite, melt-bearing shear zone

Concepts dealing with the character of shear zones formed in different levels of ancient and present crust have developed substantially during the last decades but the studies are often concentrated on the characteristics of the objects deformed in a brittle, semi-ductile or ductile manner (e.g. Sylvester 1988) excluding the products from the deepest parts of the shear zones. Well-known scheme of shear zone cross-section presented by R. Sibson (Sibson 1977) showed that cataclasites and mylonitic fault rocks are products of the shear deformation in the upper crust conditions, whereas blastomylonitic fault rocks dominate the deeper parts of the shear zones. Blastomylonites or "striped gneisses" develop in higher grade or at least more effective environment of metamorphism than traditional mylonites.

Descriptive terminology for cataclasites and low-grade mylonitic fault rocks (Higgins 1971, Bell & Etheridge 1973, Lister & Snoke 1984, Wise et al. 1984, Passchier & Trouw 2005) is well-known and universally accepted. During last decades, numerous works are focused on the interaction between shear related ductile deformation, partial melting and migmatization at deep crustal levels (Halden 1982, Hollister & Crawford 1986, Mogk 1992, Esteban et al., 2008) but common approval is lacking in description of these medium- and high-grade shear zone systems and their components.

The bedrock of Finland includes numerous ductile shear zones that have been formed as a consequence of different stages of the Archean and Paleoproterozoic tectonic events. Evolution of each of those zones includes practically always multiple stages of shear deformation, and the sections exposed at the present surface contain products created in various crustal levels and often in different metamorphic environments. The deepest parts or "roots" of the ancient shear zones with "high-grade fault rocks" are also visible in many places. These sections of ductile shear zones are often dominated by various medium-grained, blastomylonitic fault rocks but still migmatitic, shear-related rocks are often more common. Relationship between those rocks resembles the relationship between normal banded gneisses and migmatites, which naturally is better-known but still often misunderstood. Within shear zones, highly permeable subzones or subunits are more common than in other kinds of environments, which may lead to great variation in the partial pressure of a fluid component and further to great variation in the degree of migmatization increasing the complexity of "high grade ductile shear zones". However, augmentation of shear zone concepts to cover the products from the deepest parts of the shear zones is really needed as supported by many Finnish examples. Typical surface section of ductile shear zone comprises an anastomosing system of individual shear structures, the types of which may vary largely. The degree of shear strain varies regionally and the contacts between the most intensely sheared units and the weakly deformed country rock are more or less gradational. Based on that, a schematic vertical cross section of a shear zone is presented in the Figure 1. Detailed characterization of different high-grade fault rocks, blastomylonites and shear migmatites is still missing.

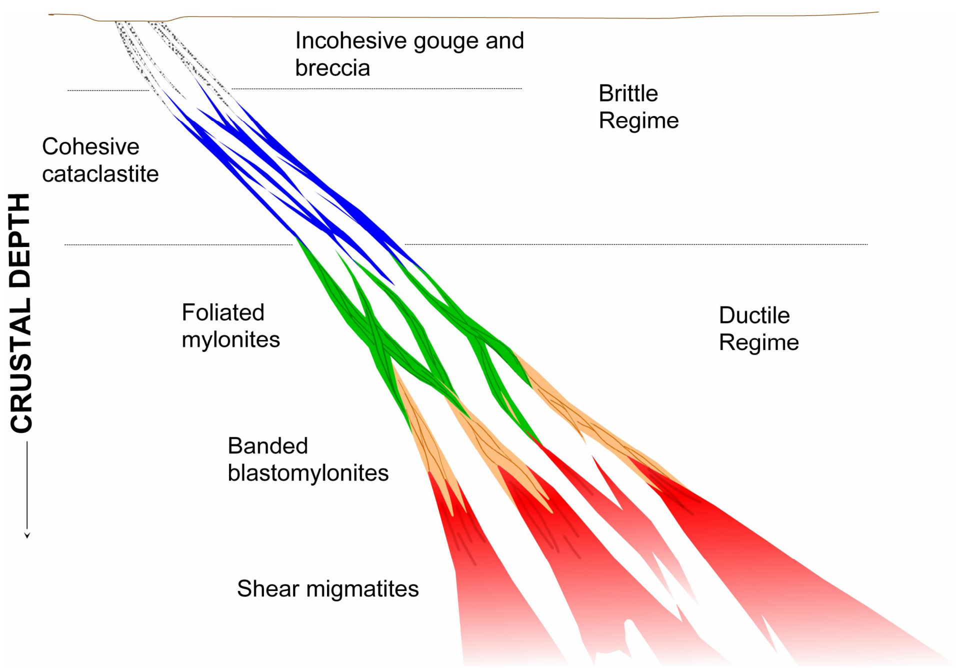

Figure 1. Schematic cross-section of shear zone.

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Palaeoproterozoic tectonics of the Fennoscandian Shield – some key questions

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Palaeoproterozoic is the most important crust-forming era in the Fennoscandian Shield. Most studies favour that subduction-type plate tectonics operated during 2.0–1.8 Ga in the Fennoscandian Shield but in detail it is still under debate how this occurred. We are still unsure where Palaeoproterozoic plate boundaries exist, how many orogens formed or are we seeing only an end product of an 200 My accretion. Some of the key questions in the Palaeoproterozoic tectonic evolution of the Fennoscandian Shield will be addressed and discussed.

Keywords: plate tectonics, rifting, orogen, Svecofennian, Fennoscandia

1. Introduction

The Fennoscandian crustal segment represents the northern part of the East European craton consisting of the Fennoscandian Shield, its southern continuation covered by platform sediments, and the Caledonides in the west. Palaeoproterozoic is the most important crust-forming era in the Fennoscandian Shield and the composite Svecofennian orogen forms the largest Palaeoproterozoic unit. It covers ca. 1 mill. km2 and extends southwards, under the Phanerozoic cover, as far as the Trans-European Suture Zone (TESZ). Numerous tectonic models, from continuous accretion to separate collision stages, have been proposed but most models infer that subduction-type plate tectonics operated during 2.0–1.8 Ga in the Fennoscandian Shield.

2. Questions related to the Palaeoproterozoic evolution

The Palaeoproterozoic evolution of the Fennoscandian Shield can be divided into major rifting and orogenic stages. The main Palaeoproterozoic rifting events of the Archaean comprise stages of intraplate, southwest-prograding rifting between 2505–2100 Ma, and c. 2.06 Ga drifting and separation of the cratonic components by newly-formed oceans; the Kola ocean and the Svecofennian sea. Major questions related to the break-up of craton/cratons are: Laurentia-Kola-Karelia connection, Lapland Sea and Karelia-Norbotten connection. The western margin of the Karelian Province show evidence of rifting and lithosphere thinning from 2.1 Ga to 1.95 Ga but it is still under debate whether the craton breakup occurred at 2.06 Ga in a volcanic (e.g., Siilinjärvi, Väystäjä) or/and later at 1.95 Ga in a non-volcanic (Jormua-Outokumpu) margin setting.

No subduction-related magmatism aged between 2.5 and 2.1 Ga has been found in the Fennoscandian Shield. The 2.02 Ga volcanic rocks in Kittilä, 1.98–1.96 Ga arc magmatism in Kola, 1.95 Ga supracrustal rocks and granitoids in Knaften, and the 1.93–1.92 Ga island arc rocks in the Savo belt are oldest yet defined Palaeoproterozoic arc rocks. However, the existence of still older 2.1–2.0 Ga lithosphere, as microcontinents, in the Svecofennian domain has been proposed. The main Palaeoproterozoic orogenic events in the Fennoscandian Shield are the Lapland-Kola orogen (1.94–1.86 Ga) and the composite Svecofennian orogen (1.92–1.79 Ga). The latter is further divided into the Lapland-Savo, Fennian, Svecobaltic and Nordic orogens.

The Lapland-Kola orogen is a large and wide orogenic root of a mountain belt comprising mainly reworked Archaean crust. It has many similarities to c. 1.9 Ga orogens, like the Trans-Hudson orogen, which are due to a continent-continent collision between two Archaean continents, with only a limited amount of juvenile crust preserved. Main open questions are the number of sutures and colliding systems, the amount and nature of the eroded material and connection of the Lapland-Kola orogen to Laurentia.

The composite Svecofennian orogen forms a large Palaeoproterozoic unit of new crust. It comprises 2.1–2.0 Ga microcontinents with unknown prior evolution histories, juvenile arcs from >2.02 to ~ 1.8 Ga, and Andean-type vertical magmatic additions at 1.9–1.8 Ga. The collision between the Archaean Karelian continent (lower plate) and the Palaeoproterozoic arc-microcontinent assembly, Keitele microcontinent (upper plate) indicates that the Archaean continental edge decoupled from its mantle during initial collision and overrode the arc and its mantle during continued collision. This led to a formation of a thick crustal core of the Lapland-Savo orogen (presently up to 62 km).

One challenge in studying a hot orogen like the composite Svecofennian orogen is to delineate plate boundaries, sutures, within the orogen. One possible example of such suture occurs in the Pirkanmaa belt, interpreted as a combination of a fore-arc and an accretionary wedge that has formed at a rifted continental margin.

Other major questions in the tectonic evolution of the composite Svecofennian orogen are the Sarmatia-Fennoscandia connection, and the 1.85-1.80 Ga evolution in southern Sweden. Also the 1.86-1.85 Ga mature sedimentary rocks (arenites, arkoses and pelites) in southern Finland and central Sweden are problematic as they point out to strong chemical weathering in the source area and to a non-orogenic, or even cratonic environment. The c. 1.8 Ga NE-SW directed Nordic orogen that crosscuts the E-W and SSW-ENE directed Fennian and Svecobaltic orogens, is formed either due to a continent-continent collision between newly established Fennoscandia and another continent or as an advancing Andean-type accretionary orogen.

The Fennoscandian Shield is maybe one of the best-known Precambrian regions in the world but new studies continuously add complexity to its Palaeoproterozoic evolution. We have to remember that only fragmented and selective parts of the evolution are preserved and that with the help of the surface observations and few drillings (normally < 500 m) we can directly observe only << 1% of the crust and all the other interpretations are based on indirect observations.

Geochemical mapping of the Häme dyke swarm, southern Finland

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Geochemical data for 42 dykes belonging to the Mesoproterozoic Häme dyke swarm indicate predominance of low-MgO compositions. The concentrations of incompatible trace elements are relatively high, e.g. Zr varies from 162 ppm up to 449 ppm. Generally, the major, minor, and trace elements correlate well with MgO and the variations are compatible with fractional crystallization of olivine, plagioclase, and clinopyroxene. Ratios of incompatible elements show notable variations, however, suggesting other processes also operated. Comparison between the WNW and NW trending sets of dykes does not lend support to previously suggested compositional dichotomy between the two principal sets. Clustering of the analysed samples into three groups based on relationships between TiO_2, Fe_2O_3tot, and MgO implies different magma batches, but the division needs to be corroborated by high-precision trace element data. Nevertheless, the gradational compositional variations bring forward the possibility of several magmatic pulses between the two presently dated intrusive events at ~1.67 Ga and ~1-65 Ga.

Keywords: mafic, basalt, dolerite, lithosphere, mantle, Fennoscandia

1. Introduction

Continental flood basalts (CFB) typically exhibit pronounced compositional heterogeneity that results from variable magma sources, partial melting, crystallization and contamination processes, and secondary alteration. Understanding of the temporal and spatial evolution of CFB systems requires specification of process- and source-dependent variations; this is frequently hampered by inadequately established relationships between different rock types. Rigorous geochemical grouping of magmatic successions is fundamentally important to identifying co-magmatic lineages and their key characteristics and may facilitate recognition of geochemical tracers of mantle source regions. Geochemical grouping also provides valuable guidelines for geochronological and palaeomagnetic research and, in many cases, facilitates correlation to previously established magmatic events when radiometric dating is not possible.

The Häme dyke swarm extends ~150 km NW of the Wiborg rapakivi batholith. The swarm has been frequently divided into two sets of dykes based on different strikes, compositional features, and geochronological data. One of the sets strikes WNW and is typified by abundant olivine (Laitakari, 1969); a concordant U-Pb baddeleyite age of 1667±9 Ma on zircon from one of the dykes (Virmaila) has been interpreted as the emplacement age of the set as a whole (Vaasjoki and Sakko, 1989). The other set strikes NW and is typified by phenocrysts, megacrysts (up to <20 cm), and fragments of plagioclase (Laitakari, 1969). One of these dykes (Ansio) has been dated at 1646±6 Ma based on U-Pb intercept age on zircon (Laitakari, 1987). The presumably younger NW dykes are considered to be more evolved than the older dykes. The currently available age data thus indicates at least two distinctive magmatic events separated by ~ 6 – 36 Ma. Field evidence for the assumed age relationship is lacking, however (Laitakari, 1987). Here we present preliminary data on a recently launched geochemical mapping project on the Häme swarm.

2. Sampling and analytical methods

Our dataset consists of 59 analyses of 47 samples which represent 42 dyke outcrops, distributed across the swarm. Some of the outcrops probably represent strike-parallel exposures of a single intrusive unit. The geochemical samples were extracted from the bedrock with a hammer.

The sample preparation and analysis were completed in the Geochemical laboratory, University of Helsinki. The samples were divided into smaller pieces using a hydraulic splitter and a jaw crusher (steel surfaces). Clean rock chips were hand picked for the analysis in order to avoid weathered surfaces, large phenocrysts, and other heterogeneities, such as metal chips from the crushing instruments. The chips were pulverized using a swing mill (tungsten carbide surfaces) and glass beads were prepared following the guidelines of Virkanen et al. (2007). The glass beads were analysed using the Philips PW1480 x-ray spectrometer.

3. Results

Geochemically, the analysed samples correspond to relatively evolved basalt with SiO_2 = 46.3–50.0 wt% and MgO = 6.0–3.3 wt% (Fig. 1a). One sample with distinctly higher MgO (11.6 wt%) and lower SiO_2 (43.0 wt%) contents probably contains accumulated olivine. The samples plot within the field of alkali basalts in TAS diagram, but they can be classified as olivine tholeiites (n=33) and quartz-tholeiites (n=11) on the basis of the CIPW normative compositions. Generalizing, the concentrations of SiO_2, TiO_2 (1.4–3.3 wt%), K_2O (1.0–2.4 wt%), and P_2O_5 (0.4–1.1 wt%) increase and those of Al_2O_3 (18.1–12.5 wt%) and CaO (8.1–6.1 wt%) decrease with decreasing MgO. In contrast, Fe_2O_3tot (14.2–19.0 wt%) and Na_2O (2.2–3.3 wt%) do not correlate with MgO. Furthermore, the studied dyke rocks have relatively high contents of incompatible trace elements (e.g. Nb = 14–36 ppm and Zr = 162–449 ppm) and low contents of compatible trace elements (e.g. Ni = 61–11 ppm).

Overall, the major, minor, and trace elements, including alkali and earth alkali metals, correlate well with MgO, demonstrating general compositional uniformity and suggesting minor influence of subsolidus alteration. A closer analysis of the data reveals geochemical variations that indicate significant heterogeneity of magmas. Variations of TiO_2 and Fe_2O_3tot at given MgO content indicate clustering of the data into three suites; Suite A is distinguished by relatively low TiO_2, whereas the two suites with relatively high TiO_2 can be identified based on relatively high (Suite B) and low (Suite C) Fe_2O_3tot. Each suite further exhibits notably variable incompatible element ratios, e.g. Ti/Zr (74–42), Ti/P (6.2–3.7), and Nb/Y (0.43–0.99).

4. Implications and conclusions

Qualitatively, the geochemical trends of major, minor, and trace elements and the positive correlation between CaO/Al_2O_3 and MgO are compatible with fractional crystallization of a gabbroic assemblage of olivine, plagioclase, and clinopyroxene. The apparent immobility of elements and the small amount of phenocrysts and other heterogeneities in the analysed material suggest that the analyses may correspond quite closely to melt compositions. The compositions of relatively coarse-grained parts, however, may have been affected by accumulation of liquidus phases and/or in-situ magmatic differentiation. Given the evolved nature of the magmas, in-situ crystallization of Fe-Ti oxides may have caused at least some of the variations in TiO_2 and Fe_2O_3tot (Fig. 1a).

Geochemical comparison of the WNW and NW trending sets of dykes does not lend support to the previously suggested compositional difference between the two sets (e.g., Laitakari and Leino, 1989); in contrast, both sets show notably similar geochemical ranges

(Fig. 1b). We suspect that the previous estimates have been biased by limited geochemical data and, possibly, overrepresented data for the two dated dykes, Ansio and Virmaila, which are amongst the widest dykes of the swarm (Laitakari, 1969) and thus susceptible to in-situ differentiation. In fact, inspection of geochemical data (P. Peltonen, personal communication, 2005) for these dykes reveals a strong influence of olivine accumulation and Fe-Ti oxide fractionation (Fig. 1a). Based on our data, the Häme swarm is characterised by subtle heterogeneities not correlated with the two principal sets of dykes. Examples of other mafic dyke swarms have revealed strong control of lithospheric structure on the emplacement and distribution of magmas (Jourdan et al., 2004). The same lithospheric discontinuities may be repeatedly reactivated leading to intercalation of multiple dyke phases within a physically defined swarm. In the case of the Häme swarm, the two dated dykes show different geochemical compositions indicating at least two intrusive events of compositionally different magmas (Fig. 1). Given the gradational geochemical variations of the dykes, and the considerable age difference between the dated events, the total number of magmatic pulses could have been higher. High-precision trace element data (ICP-MS) for the dykes will be available in spring 2009; will expect these data to facilitate identification of separate magma batches and provide constraints to the possible number of separate magmatic events in the Häme swarm.

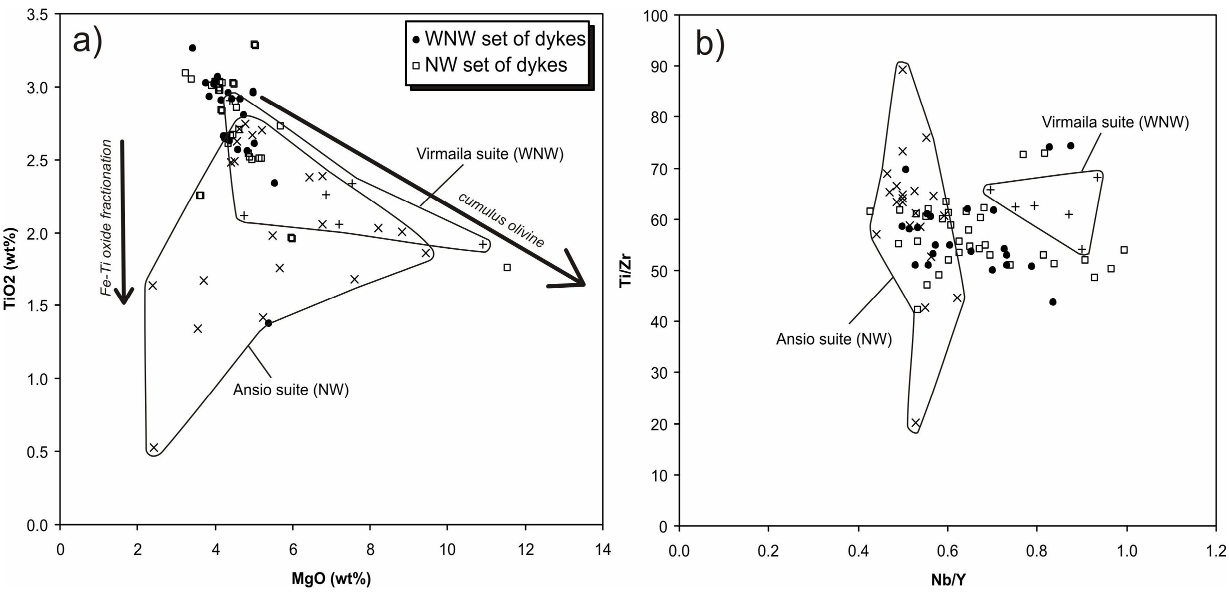

Figure 1. Variations of TiO_2 vs. MgO (a) and Ti/Zr vs. Nb/Y (b) for mafic dykes belonging to the Häme swarm, southern Finland. Compositional fields for two dated suites, Virmaila, 1667±9 Ma; Vaasjoki and Sakko, 1989) and Ansio (1646±6 Ma; Laitakari, 1987), and consequences of olivine accumulation and Fe-Ti oxide fractionation are shown for comparison. Geochemical data for Virmaila and Ansio are from Petri Peltonen (unpublished data).

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Seismic Research of Impact Craters and the Seismic Velocity Analysis of the Keurusselkä Impact Structure, Central Finland

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Impact craters found on Earth's surface can be divided in simple, complex and multiring structures on the grounds of their shape and size. Seismic reflection and refraction soundings can help to determine craters proportions and their surrounding and underlying structures. Seismic methods are excellent tools to detect and study hidden impact structures covered by post-impact sediments. So far seismic or other geophysical results are not sufficient to prove an impact origin, but in the future crater identification using geophysical data without drill core samples might be possible. Seismic reflection and refraction data will be used to study the Keurusselkä impact structure in central Finland.

Keywords: seismic reflection, seismic refraction, impact crater, impact structure, Keurusselkä

1. Introduction

Total amount of impact craters found on Earth's surface is 175 (PASSC – Earth Impact Database, 2008). This is only a small portion of craters which meteoritic bombardment has created on our planet. Some of the impact structures have been formed in the oceans and wait to be discovered, some have been buried under sediments and some have been eroded. The Keurusselkä structure is one of the 11 impact structures found in Finland (Figure 1). This structure was discovered by Hietala and Moilanen in 2003 (Hietala and Moilanen, 2004).

Nearly circular lakes and geological structures found in the field or on maps could indicate an impact. It is important to identify true impacts from other geological processes which also form circular shapes, like kimberlites, magmatic intrusions and volcanic eruptions (Mazur et al., 2000; Stewart, 2003; Plado and Pesonen, 2005). Although the manifestations of meteorite, asteroid and comet impacts are generally of surficial (uppermost crust) features, the Moon-Mercury analogues reveal that gigantic impacts may generate structures deep into the lithosphere. On present erosional level the largest terrestrial impact structures (Sudbury, Chicxulub and Vredefort) may have reached the lower crust or even the Moho boundary.

2. Geophysical methods and other evidence of impacts

Geophysical methods, like gravity, magnetic, electric and electro-magnetic surveys and radiometric measurements have helped in finding new impact craters on Earth (French, 1998). Seismic methods have recently been used to discover buried impact structures. High resolution seismic soundings can visualize the size and shape of an impact structure, its surroundings and subsurface structures including the possible central uplift. Gravimetric measurements often show impacts as negative anomalies, because the density of fractured rock is lower than target rocks and craters are often covered with light sediments. Impact structures do not always create district magnetic anomalies, but can be recognized from magnetic maps due to their circular shape and weak magnetic relief.

Well-developed shatter cones are thought to be products of low to moderate shock waves and have so far been found only in association with impact structures. The discoveries of pseudotachylite breccias, planar deformation features (PDFs) in quartz, impact rocks (such as suevites and melts) and excess of iridium are the best evidences of an impact. It would be important to be able to recognize impacts from other evidences than drill core samples. Drillings of deep buried craters are expensive projects which are seldom done without references of craters economical potential. Stewart (2003) proposes a geometrical identification technique of impact craters due to extensive high quality 3D seismic data.

3. Seismic results of Lake Bosumtwi and Chicxulub

Seismic reflection and refraction soundings have been conducted for example in Lake Bosumtwi and Chicxulub impact craters (Figures 2 and 3). Lake Bosumtwi in Ghana is one of the youngest (1.07 Ma) well-preserved terrestrial craters (Pesonen et al., 2003). The structure is 10,5 km wide and its central part is covered with water and sediments. Karp et al. (2002) have created a four layer model of seismic velocity, where water, post-impact sediments, brecciated rocks and crater floor can be distinguished. The central uplift is clearly visible in the depth migrated reflection profile (Figure 2). According to Morgan et al. (1997), approximately 65 Ma old Chicxulub crater in Mexico is the best remained large (diameter over 150 km) impact structure on Earth. Because the structure is situated partly on land and partly under water, seismic soundings suit well to study the structure. In 1996 BIRPS (The British Institutions Reflection Profiling Syndicate) conducted a large reflection and refraction survey in the Chicxulub area. The results suggest a multiring structure with at least three rings (diameters 80, 130 and 195 km). A 3D velocity model reveals a concave high velocity area around 5 km depth (Figure 3). This is thought to be the central uplift of the Chicxulub crater (Morgan et al., 2002).

4. Seismic investigation of the Keurusselkä impact structure

The impact origin of the Keurusselkä structure is based on shatter cone findings and PDFs in a boulder breccia. The structure is associated with distinct magnetic and gravity anomalies, which, however do not perfectly match with each other (Pesonen et al., 2005). The seismic FIRE2 reflection and FENNIA refraction lines cross the Keurusselkä shatter cone area (Figure 1) and can therefore be used in the seismic investigation of the area. The aim of the MSc-thesis by M. Malm is to process the seismic FIRE2-data near the Keurusselkä impact structure and to make a tomographic velocity model of the area. Other goal is to find out whether the impact structure can be seen in the seismic data of the area. The Keurusselkä structure is probably very old (even Proterozoic) and strongly eroded, so we will not be able to see the original structure anymore, but perhaps the roots of the central uplift or the fractured crater floor. It is feasible that the “impact fractured” floor rocks nevertheless reveal weakened seismic velocities, lower densities and higher porosities which warrants a geophysical scanning of the whole area.

5. Conclusion

Seismic methods can be very useful in impact cratering research, especially in the case of underwater craters and craters buried under sediments. Geophysical results can be used as additional evidences of impacts. The forthcoming seismic research of the Keurusselkä impact structure coupled with other geophysical data (Raiskila et al., 2008) will hopefully reveal some new information of the possible old and eroded impact structure.

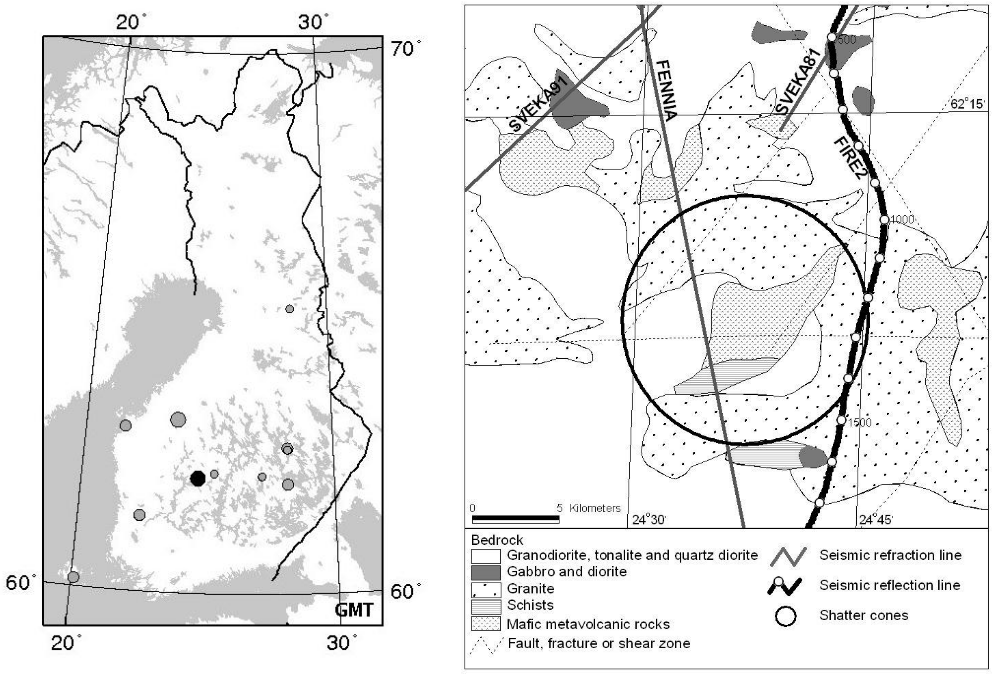


Figure 1. Location of the Keurusselkä impact structure. On the left is a map of Finland's impact structures (coordinates after Dypvik et al., 2008) where the Keurusselkä structure is marked with a black circle. On the right are the seismic reflection and refraction lines around the Keurusselkä area (the bedrock map modified after Korsman et al., 1997).

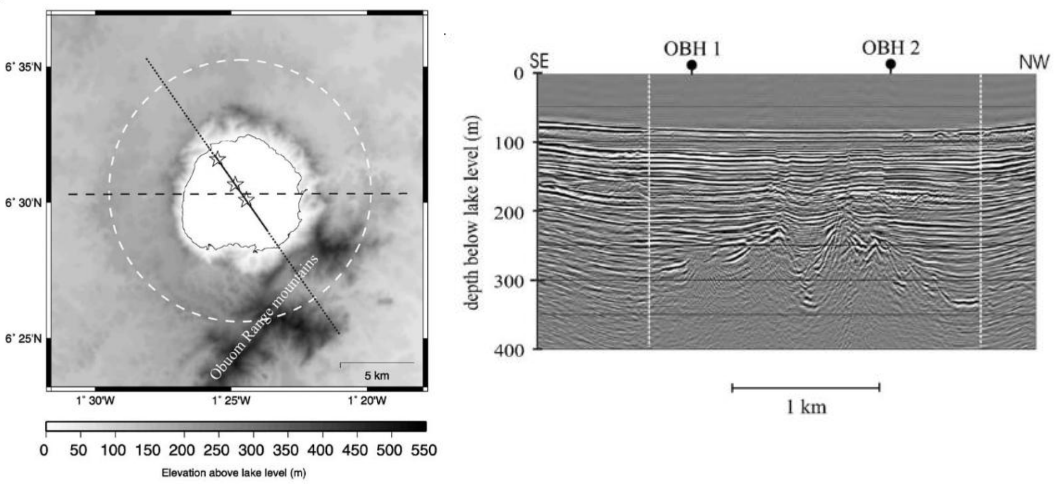
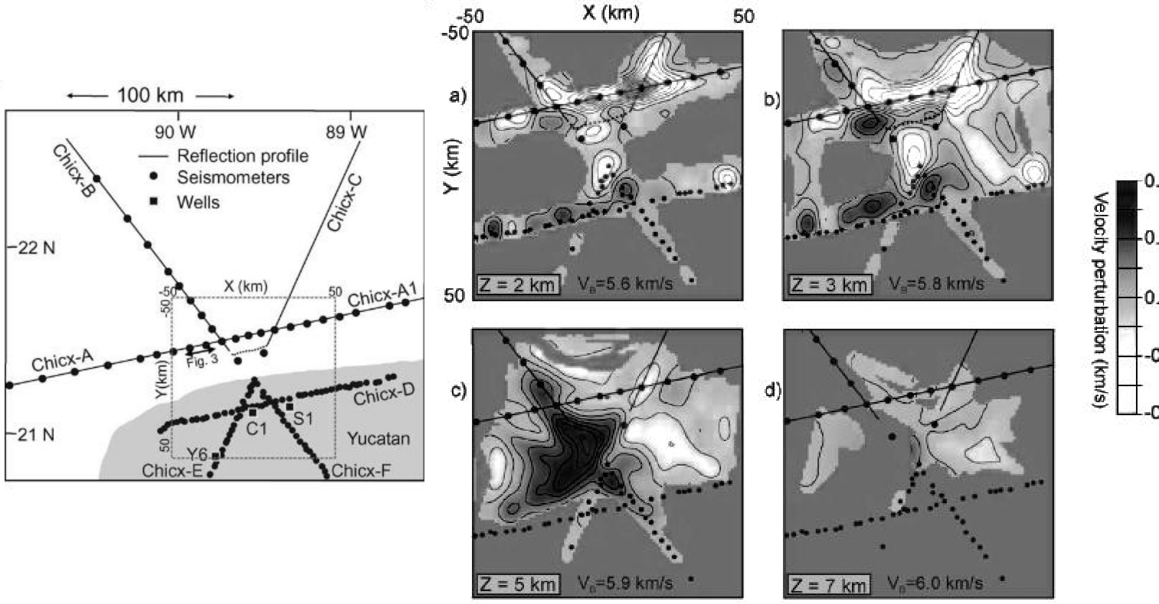


Figure 2. Seismic sounding results of Lake Bosumtwi crater in Ghana. On the left is a digital topography map of the area (Karp et al., 2002). The white dashed line shows the size of the outer ring, the solid black line is the seismic reflection line crossing the lake. Ocean-bottom-hydrophones (OBH) are marked with stars. On the right is a depth migrated seismic reflection profile of the Lake Bosumtwi crater (Karp et al., 2002). The central uplift can be seen in the middle at 220 m depth.

Figure 3 (on the next page). Seismic tomography results of the Chicxulub crater in Yucatan peninsula, Mexico. Seismic survey location is shown on the left (Morgan et al., 2002). On the right are 2D slices of Chicxulub's 3D velocity model at a) 2 km, b) 3 km, c) 5 km and d) 7 km depth (modified after Morgan et al., 2002). The concave high velocity area at 5 km depth is thought to be the central uplift.



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Timing of shearing of two gold-potential formations in southern Finland, based on paleomagnetic and AMS studies

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Results of paleomagnetic, rock magnetic and AMS studies from gold-potential formations in southern Finland are presented. The results imply that strong shear and fault structures of the studied formation were formed after the hydrothermal events which were responsible for the precipitation of sulphides and gold.

Keywords: gold ores, mineralization, shear zones, paleomagnetism, anisotropy of magnetic susceptibility (AMS), Proterozoic, Satulinmäki, Koijärvi, Finland

1. Introduction

Orogenic gold deposits of the Svecofennian domain in southern Finland are delineated by strong fault and shear structures. Aeromagnetic anomaly maps coupled with other geophysical and geological surveys have demonstrated that ferromagnetic minerals like pyrrhotite and magnetite form one of the characteristic features of these structures. Because magnetite and pyrrhotite are one of the main carriers of natural remanent magnetization (NRM), paleomagnetic studies have been carried out in order to test the ability of paleomagnetic method to give some age constraints for the gold forming processes and to investigate the genesis of magnetic minerals that are related to gold. Studies have been carried out in two gold-potential locations in Southern Svecofennian Arc Complex, in Satulinmäki of Somero and Koijärvi of Forssa. Because the gold-mineralized zones are characterized by strong shearing and faulting, studies on anisotropy of magnetic susceptibility (AMS) were carried out in order to define the deformed structures *(Borradaile & Jackson, 2004).*

The first paleomagnetic measurements of the study from Satulinmäki (*Mertanen, 2006*) showed that the direction of the remanent magnetization was not the one expected from Svecofennian ca. 1.9-1.8 Ga aged rocks, and it was therefore considered that the remanence could have been deflected due to later shearing. For studies on magnetic structures which may be responsible for the deflection, AMS gives magnetic orientation of the magnetic minerals. When the knowledge on remanence directions is combined to AMS directions, they can be used in relative timing of shearing versus hydrothermal event in which the ferromagnetic minerals and gold precipitated. The main purpose of the paper is to show the paleomagnetic and AMS results of the study areas in conjuction with rock magnetic studies that can confirm the occurrence of ferromagnetic minerals. Furthermore, the paper aims to demonstrate the possibilities of the used methods in view of forthcoming prospecting.

2. Sampling and measurements

In Satulinmäki, 12 samples were taken from two sites of intermediate metavolcanite that is partly heavily oxidized. Both sites show conspicious NE-SW trending shearing. In Koijärvi, samples were taken from five oriented borehole cores of the Koijärvi fault zone and 46 samples were taken from three outcrops of intermediate metavolcanite at the Koijärvi fault, all showing strong NNE-SSW shearing. In addition, six samples were taken outside the shear zone where no clearly visible structures are seen.

Petrophysical properties, density, magnetic susceptibility, intensity of remanent magnetization and the Königsberger ratio (the ratio of remanent to induced magnetization) was measured for each specimen. Paleomagnetic measurements, comprising gradual demagnetization either by alternating field (AF) or thermally, were made using SQUID magnetometer. AMS measurements were carried out using the Kappabridge KLY-3S equipment. For definition of magnetic minerals, Curie point determinations were done for 11 specimens using Kappabridge KLY-3S combined with the CS-3 apparatus. Three component IRM and subsequent thermal demagnetizations were carried out for 12 specimens by using Molspin pulse magnetizer and SQUID magnetometer.

3. Petrophysics and magnetic mineralogy

All samples from Satulinmäki have magnetic susceptibilities below 10 000 µSI. Two distinct populations were separated, one population with high susceptibility and NRM values and another one with very low magnetization values. The grouping reflects samples where pyrrhotite dominates or samples dominated by paramagnetic minerals, respectively. The samples from Koijärvi also have two major populations. The other population has high susceptibilities of ca. 10 000-100 000 µSI and high NRM values. It is dominated by magnetite with only minor pyrrhotite. The other population has lower susceptibilities ca. 500-1 500 µSI and lower NRMs, and contains purely pyrrhotite. The visibly non-sheared rocks have low magnetization values and contain magnetite and only minor amounts of pyrrhotite.

Curie temperature determinations from the Satulinmäki samples show that ferrimagnetic monocline pyrrhotite is the main magnetic mineral, and only small amounts of hexagonal pyrrhotite are present, even in the most weakly magnetized rocks. In the samples from the Koijärvi outcrop the magnetization is carried either by magnetite or pyrrhotite or by both minerals. The result is confirmed by three component IRM measurements. The Koijärvi drill core samples are dominated by magnetite, but they also contain small amounts of fine grained pyrrhotite.

4. Paleomagnetism

In general, the remanence directions are scattered both in the Satulinmäki and Koijärvi localities, which may be due to very weak intensities in some cases. In most cases it is implied that the scatter of directions is due to later tectonic movements. However, part of the samples from Satulinmäki yield a consistent SW pointing moderate inclination remanence direction, isolated in low coercivities and low unblocking temperatures of ca. 200-330°C, indicating pyrrhotite as remanence carrier. In Koijärvi outcrops the remanence has an overall NE-SW trend, but no consistent remanence direction was obtained as in the sheared rocks the directions vary between sites, and in the unsheared rock the remanence has an anomalous direction. The borehole cores of Koijärvi are different. A consistent NW pointing remanence direction was obtained in high coercivities and in unblocking temperatures of 500-560°C and 300-340°C suggesting both magnetite and pyrrhotite as remanence carriers, respectively.

5. AMS

In Satulinmäki, two major directions of magnetic foliation plane are observed; one that is parallel to the NE-SW shearing and another that slightly cuts the first in the ENE-WSW direction. The ENE-WSW directions lie within the pyrrhotite-rich zone. The mean magnetic foliation of all samples dips steeply to SSE. The anisotropy degree is exceptionally high (P' > 3, corresponding to a 200 % anisotropy) in part of the samples. Magnetic lineations are well defined and dip steeply to SE. The general NE-SW direction of AMS corresponds to the average remanence direction. As there is a causal relationship between AMS and NRM *(McElhinny and McFadden, 2000)*, and because the anisotropy degree is so high, it is evident that the remanence directions have been deflected and do not reflect the ambient magnetic field acquired during cooling of the rocks. In Koijärvi, the average anisotropy degree is about 20% but varies strongly even within sites. The AMS directions from the Koijärvi outcrops show a general NE-SW trend in all locations, including the visually homogeneous site outside the shear zone proper. The AMS directions correspond to the average NRM trend. All Koijärvi borehole cores except one, have relatively low anisotropy degrees below 10 %, and in general, the degree of anisotropy decreases with depth. The AMS has NNW-SSE direction. From these samples, a NW pointing remanence direction was obtained. Figure 1 shows the NRM and AMS results.

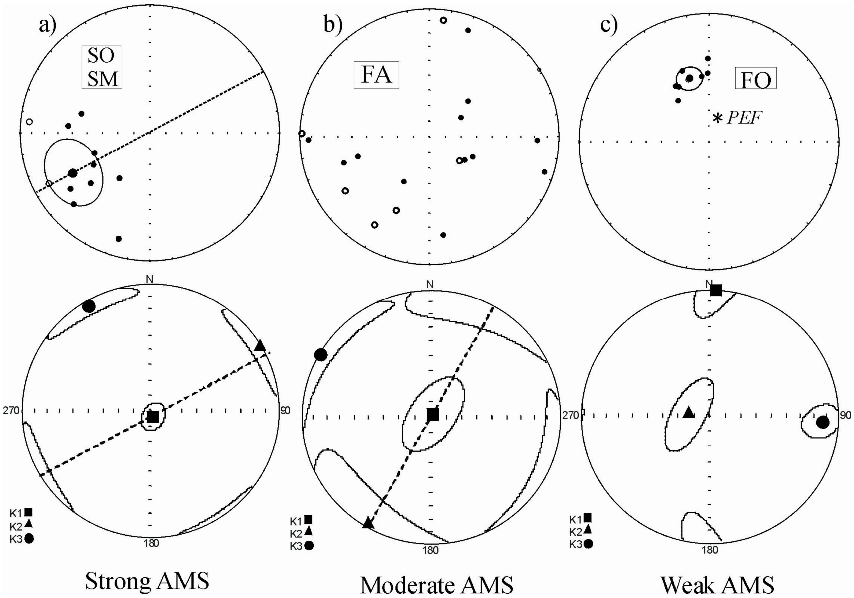

Figure 1. Paleomagnetic and AMS directions from a) Satulinmäki sites SO and SM, b) Koijärvi outcrop FA and c) Koijärvi borehole cores. K1 refers to the magnetic lineation and K3 to the pole perpendicular to the magnetic foliation plane. K2 gives the intermediate susceptibility. The lines define general trends of the shear zones measured from outcrops.

6. Timing of the faulting and shearing versus hydrothermal events

According to rock magnetic studies the main magnetic mineral in Satulinmäki is monoclinic pyrrhotite. It carries the remanence, and the AMS reflects the orientation of the grains. The SW pointing remanence directions in Satulinmäki are in general agreement with the magnetic foliation plane defined by AMS (Fig. 1). The magnetic foliation plane coincides and reflects the general strong SW-NE shearing of the Satulinmäki area *(Saalmann, 2007)*. The main observation of the study is that the SW pointing remanence direction is in conflict with the NW pointing Svecofennian age remanence direction known from undeformed Svecofennian rocks elsewhere in Fennoscandia *(e.g. Buchan et al., 2000)*. Based on geological evidences it is assumed that pyrrhotite was formed in the same hydrothermal system as gold at about 1.83-1.80 Ga *(Saalmann et al., 2008)*. The occurrence of a stable remanent magnetization residing in pyrrhotite indicates that after its formation the temperature has not been above 320°C, the

Curie temperature of pyrrhotite, above which the magnetization vanishes. From that it follows that if the NW pointing Svecofennian remanence was originally blocked below 320°C at ca. 1.83-1.80 Ga in the hydrothermal event, then the deflection of this remanence to its present SW direction must have taken place simultaneously or after that, in temperatures below 320°C. It is suggested that hydrothermal fluid flow and shearing events may have been quite simultaneous, the minimum age of the last faulting and shearing being about 1.79-1.78 Ga (Saalmann, pers. comm., 2008). The present data thus imply that it is not likely that the hydrothermal fluids would have followed pre-existing shear zones (see *Kärkkäinen et al., 2006, Saalmann, 2007*) where the precipitation of gold and sulphides took place after the shear and fault structures were formed.

The overall remanence directions from the Koijärvi outcrop show a corresponding behavior as the remanence in Satulinmäki, although in Koijärvi no consistent remanence direction could be defined. In Koijärvi outcrop the remanence directions are scattered along a general NE-SW trending zone, comparative to the AMS foliation plane. As no Svecofennian remanence has preserved, the most likely reason for the deflection of remanence also at this location is the NNE-SSW shearing that took place after the acquisition of remanence.

Paleomagnetic results from the borehole cores of Koijärvi are different. In the cores the degree of anisotropy of AMS is relatively low, and it is therefore believed that a typical Svecofennian NW pointing remanence direction was able to preserve. The result implies that the rocks have retained their original Svecofennian remanence either due to location in the deeper parts (stable paleomagnetic results were obtained from borehole cores between 10-69 m) or due to survival of some well preserved regions within the zones that are unaffected by shearing. Consequently, contrasting the results from the outcrops, it is possible that in the deeper parts either the already existing, or younger shear and fault structures formed pathways for fluids and the fluids were able to move and precipitate freely without shear stress.

7. Concluding remark

The present study has shown that combination of paleomagnetic and AMS studies can give new insights to the relative timing of the gold-forming hydrothermal and structural processes.

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Diamonds on the Karelian craton: Exploration methods and prospectivity mapping

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Diamondiferous kimberlites have been known now from Finland and European Russia for about 25 years. This review brings together some of the more recent findings on the diamond genesis, the methods used for diamond exploration in Finland and European Russia and an example of diamond prospectivity mapping of the lithospheric mantle from the Kaavi area in eastern Finland.

Keywords: diamond, lithospheric mantle, kimberlites, Karelia, craton, Finland, Russia

1. Introduction

Diamonds are intriguing, not just because of their beauty and value, but also because they are one of the most challenging minerals for which to explore. Additionally, there is practically no other commodity that requires an exploration program that employs so much fundamental science about the geological surroundings in order to have a successful outcome.

The Archean Karelian-Kola megacraton (2.3 10^6 km^2), comprised of the Fennoscandian shield and adjacent Russian platform, contains over 100 kimberlite pipes and associated dykes, sills and stockworks, many of which are diamondiferous (Figure 1). These kimberlites show age clusters of 1800 Ma (Kemozero), 1200 Ma (Lentiira-Kuhmo-Kostamuksha), 760 Ma (Kuusamo), 600 Ma (Kaavi-Kuopio), and 385-365 Ma (Terskii and Arkhangelsk). Despite all of these discoveries, this huge area is still underexplored for diamonds and more kimberlites remain to be discovered.

Diamond exploration in Finland began by chance when a small mining company, Malmikaivos Oy, was exploring for copper in the Kaavi region of eastern Finland and discovered a circular magnetic anomaly that upon drilling turned out to be a very dark, dense rock that could not be identified at the time. Further discoveries of strange rock boulders (so called “almond rocks”, the “almonds” turning out to be highly altered peridotites xenoliths) were the beginnings of a true diamond exploration program when Malmivkaivos turned to Ashton Mining from Australia, which was just beginning operations at Argyle in W. Australia, and immediately identified the rocks discovered in Finland as kimberlites (Tyni, 1997).

2. Diamond Formation

There are three key factors that must be met for a terrane to be prospective for diamonds: it must be Archean in age, it must have low heat flow (less that 40 mW/m^2) and the lithospheric mantle thickness must exceed 200 km. The world over these criteria fit to regions of ancient continental crust called cratons, and no diamond mines (except Argyle) are sited outside of a cratonic area, the so called “Clifford’s rule. Mineral inclusions in diamonds have compositions indicating two main source rocks for diamonds, peridotites and eclogites. Most of the peridotites-derived diamond inclusions (P-type) that have been dated, and in fact only inclusions within diamond can actually be dated, prove that these P-diamonds are generally ancient. For example in southern Africa, P-type diamond ages range from 3.3-3.1 Ga with another population at 1.5 Ga (Richardson et al., 1984, 1990, 1993, 2004) whereas E-Type diamonds from the same kimberlites give ages of 3.2-1.0 Ga (Richardson et al., 2001, Pearson et al., 1998).

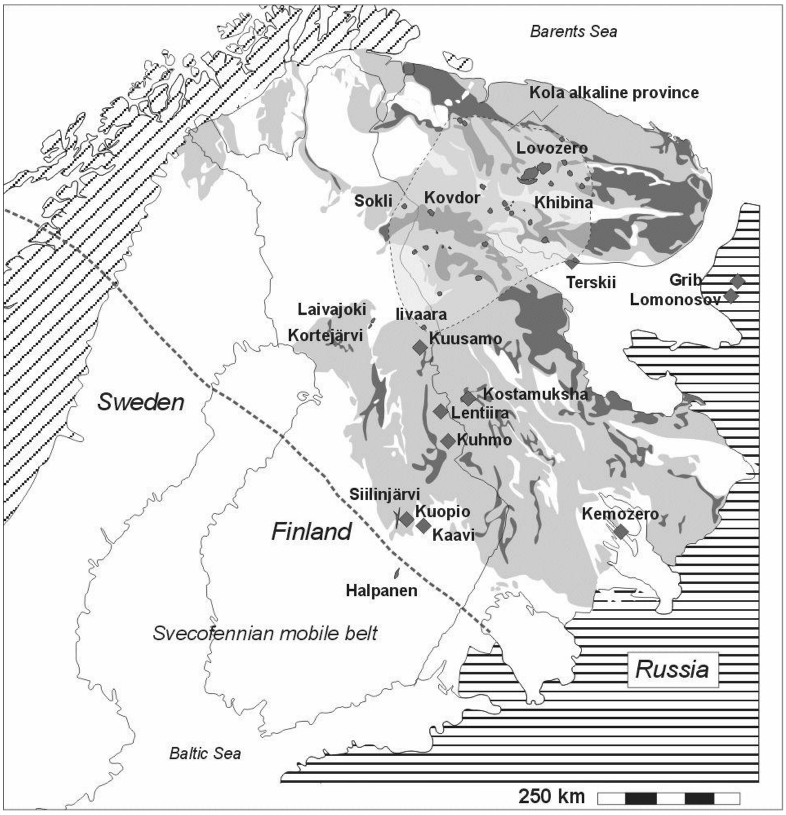


Figure 1. Generalized geological map of Fennoscandia. The Archean/Proterozoic boundary marks the subsurface extent of the Archean craton as determined by Nd isotopes. The black diamonds represent diamond-bearing kimberlites and lamproites, the diamond mines in the Arkhangelsk peninsula are also indicated.

Evidence is building that diamonds are formed in the mantle by the oxidation of asthenosphere-derived CH4 ± H2O fluids as they invade and react with subcontinental mantle peridotites (Stachel et al., 2004, Malchovet et al., 2007). At the same time this reaction produces metasomatic horizons in the mantle with specific types of subcalcic pyropes (G10) and explains the fact that G10 garnets are the dominant silicate inclusion in diamond. Because of this strong association, G10 is the most important pathfinder mineral for diamond exploration (see below). It appears that only Archean lithospheric mantle roots contain sufficiently magnesian (melt-depleted) dunites and harzburgites for this diamond-forming reaction to proceed. This provides the link between the ancient age of diamonds, and their restriction to cratonic areas.

3. Diamond Transport to the surface

Kimberlites and olivine lamproites are the only rock types known thus far that carry sufficient quantities of diamonds to be considered diamond ores. Other associated rock types such as ultramafic lamprophyres (alnöites and aillikites) and carbonatites either lack sufficient propellant or form at too shallow levels in the mantle to carry significant macrodiamonds. As mentioned earlier, the age of most diamonds is ancient, yet the kimberlites and lamproites that contain them are much younger, with the Devonian and Cretaceous being two particularly kimberlite-productive points in time. The age difference between the diamonds and their host kimberlites require that diamonds represent xenocrysts in the kimberlite magma, many of the released from their peridotites and eclogite hosts as the latter disintegrate and disaggregate in the turbulent kimberlite magma as it ascends from >200 km depth.

4. Diamond Exploration methods

It is this fact that such a large quantity of lithospheric mantle is carried by kimberlite magmas that make it possible to trace them in areas covered by glacial sediments. As described above, even though the first kimberlite in Finland was discovered by drilling a geophysical target, all further exploration by Malmikaivos/Ashton was guided by either boulder tracing (the almond rocks) or basal till sampling. The latter requires processing a till sample for kimberlite indicator minerals (pyrope garnet, picroilmenite and Cr-rich diopside) that have been liberated from the kimberlite target and dispersed down-ice (Lehtonen and Marmo, 2002).

In Finland, mapping glacial indicator dispersal trains has been the only effective way of finding kimberlites under such deep and pervasive Quaternary cover. Much of the post-Malmivkaivos kimberlite indicator work on till samples in Finland has been based on a system developed by the Geological Survey of Finland (GTK) and has been used to process over 15,000 samples over the past 10 years. In this system, a modified 3 or 4.5 inch Knelson Concentrator (Chernet et al., 1999) is used to make a preconcentrate of the “semi-heavy” garnets, pyroxenes, oxides, and other silicates. Indicator minerals <1.0 mm in size are then made into final concentrates by heavy media separation ($d = 3.2$ g/cm^3). The 0.25-1.0 mm size indicator grains (pyrope and eclogitic garnet, Cr-diopside, picroilmenite and chromite) were then hand picked under binocular microscope and their identification was confirmed using a Jeol JSM-5900LV scanning electron microscope attached to an EDS-analyzer. Mineral compositions were determined by a Cameca Camebax SX50 electron microprobe.

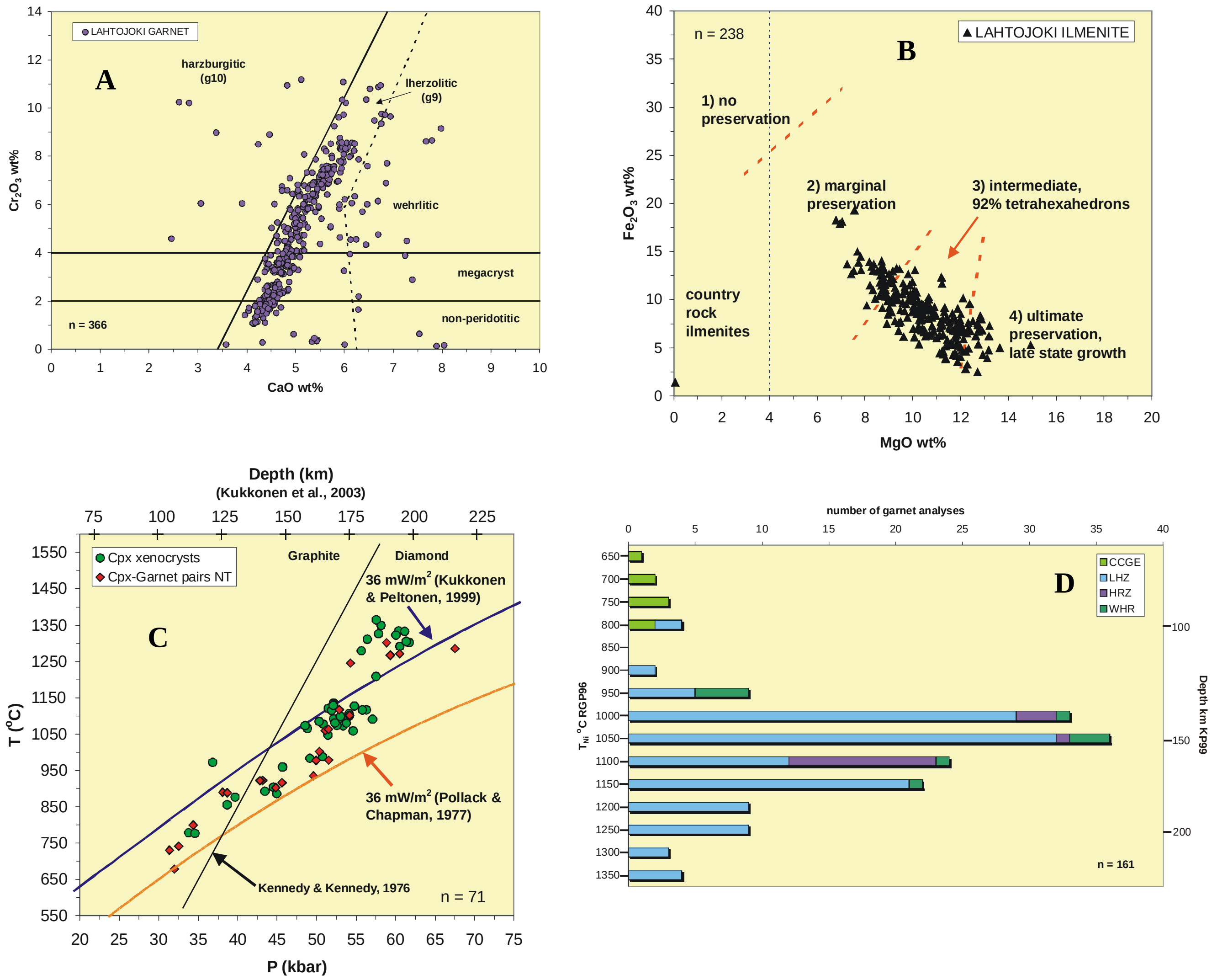
Follow-up after outlining indicator fans usually involves ground geophysical studies, particularly magnetics and em in the area at the “head” of the dispersal train. Ultimately drilling of targets of high interest, or if the till is sufficiently thin, excavating is required to finally test for kimberlite.

In the Arkhangelsk region till sampling has been less useful because most of the pipes, which are Devonian in age, are overlain by younger carboniferous sandstones and limestones. However, these types of overburden typically have very low magnetic backgrounds, and this allows the geophysical signatures of the kimberlites to be seen, even in places where overburden is as much as 60 m and the kimberlites themselves have very weak signatures (e.g., magnetic anomies of 100 nT or less).

5. Mantle Prospectivity Mapping

Major and trace element compositions of pyropes, clinopyroxenes, and ilmenites in indicator samples all provide strong clues as to the mineralogy of the mantle sampled by the kimberlite. Several examples of the various types of diagrams used to interpret a suite of kimberlitic indicator minerals are shown in Figure 2 for the Lahtojoki kimberlite in the Kaavi area. Importantly, even before the kimberlite(s) is discovered, it is possible to get quite a good estimate of the diamond prospectivity both of a particular kimberlite and of a kimberlite province using these methods.

From the plots shown in Figure 2 we can conclude that the mantle under Lahtojoki is lherzolite dominated (2A), has moderate to low oxygen fugacity (2B), contains clinopyroxene and G10 pyropes within the diamond stable field (2C, 2F), consists of 3 distinct mineralogically distinct layers (2E), and has been sampled mostly from deeper than 140 km. Note that the eclogite diamond component, which appears to be the major diamond source at Lahtojoki, is not evaluated in these diagrams.



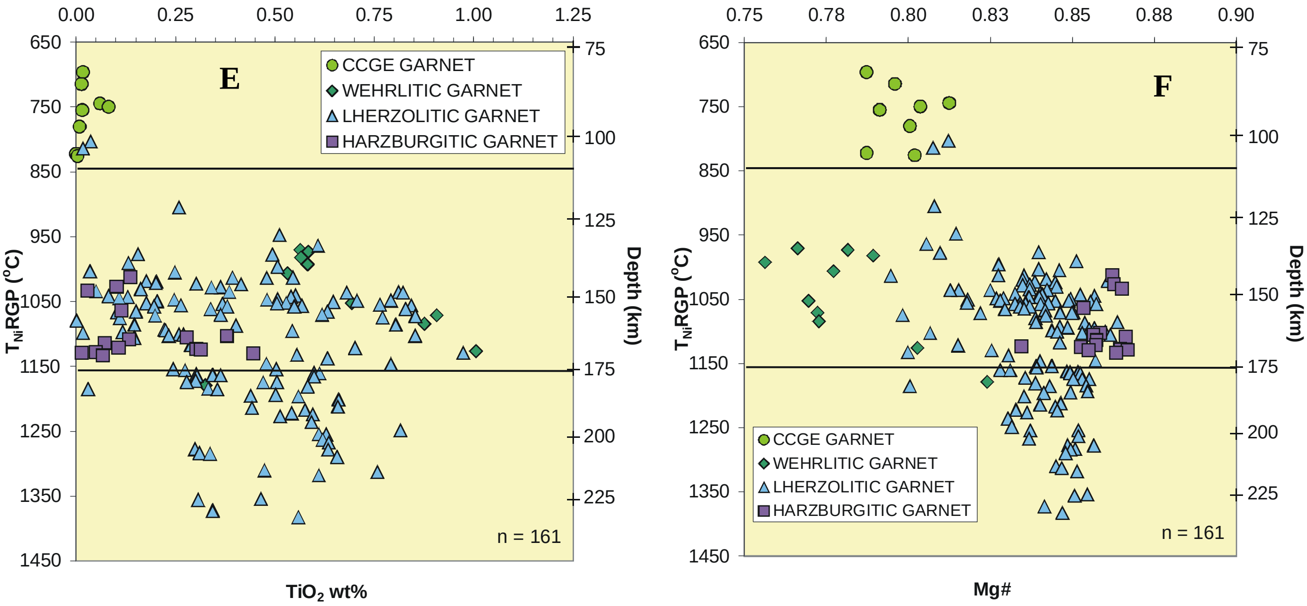


Figure 2. Lahtojoki indicator mineral diagrams. A. Cr_2O_3 vs. CaO of Lahtojoki unsorted garnets. B. Fe_2O_3 (calc.) vs. MgO of Lahtojoki ilmenites. Classification after Gurney & Zweistra (1995). C. CPX P-T data calculated using Nimis and Taylor (2000). Depth in km is converted from pressure according to Kukkonen et al. (2003). The diamond-graphite transition is redrawn after Kennedy & Kennedy (1976). D. Distribution of T_{Ni} for Lahtojoki pyrope xenocrysts using the calibration of Ryan et al. (1996). E. TiO_2 vs. T_{Ni} (Ryan et al., 1996) and depth for the Lahtojoki pyropes showing three distinct layers of the underlying mantle. Depths are calculated by extrapolating the T_{Ni} temperatures of pyropes to the local geotherm of Kukkonen & Peltonen (1999). F. Mg# vs. T_{Ni} (Ryan et al., 1996) and depth for the Lahtojoki pyropes.

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Preliminary reconstruction of the White Sea during the late Younger Dryas

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Several extensive ice lakes existed in front of the Scandinavian palaeo-ice sheet (SIS) in northwestern Russia during the Weichselian Stage. Furthermore, large areas were also inundated by the Barents and Kara Seas as the result of glacioisotatic downwarping. Here we present a preliminary reconstruction of the extent and volume of the waterbody that occupied the White Sea Basin during the late Younger Dryas. The reconstruction is based on ground penetrating radar (GPR) investigations of glaciofluvial deltaic landforms and palaeo-shorelines adjacent to the present White Sea combined with previously presented age determinations and elevation data of ice-contact glaciofluvial deltas. The results show that the waterbody in front of the SIS at around 11500 years ago covered 92890 km^2 and its volume was 6759 km^3.

Keywords: Glacioisostatic uplift, glaciofluvial deltas, ground penetrating radar, Kalevala End Moraine, White Sea Basin, Russia

1. Introduction

The eastern flank of the SIS covered vast areas of NW Russia including the White Sea Basin during the last glacial maximum (LGM) about 18 000 – 17 000 years ago (Demidov et al. 2004). The White Sea Basin from the western shore of Kanin Peninsula to Kalevala end-moraine zone in western Russian Karelia deglaciated between ca. 17 000 – 11 500 years ago. During deglaciation the SIS terminated into a waterbody that existed in the White Sea Basin and adjacent areas onshore (cf. Kvasov, 1979; Ekman and Iljin, 1991; Demidov, 2002). It has been recently postulated that prior to and during the early part of the Younger Dryas chronozone (ca. 15 000 – 12 000 years ago) glacial lake existed in the White Sea area but after a sudden water level drop at around 12 000 years ago the connection between the White Sea and the Barents Sea was established (Lunkka et al. 2008). Subsequently the Kalevala end moraine was formed at the ice margin around 11 500 years ago and thereafter glacioisostatic uplift has caused regression in the White Sea.

Although the general outlines of deglaciation in the White Sea Basin area are reasonably well understood, very little is known about a detailed deglaciation and glacioisostatic uplift history of the White Sea Basin. Therefore, the aim of this paper is to present a preliminary reconstruction of the extent and water volume of the White Sea Basin at the end of the Younger Dryas around 11 500 years ago.

2. Study area and methods

The study area is located in the Kalevala End Moraine zone and adjacent areas to the east (Fig. 1). The glaciofluvial plains studied in the Kalevala End Moraine are lying 125 m above sea level (m asl).

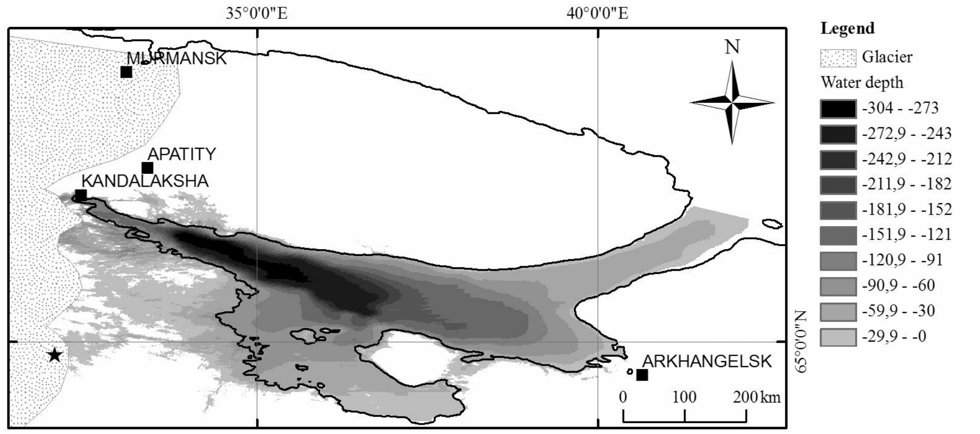

Figure 1. Location map showing the position of the GPR survey (star) and major cities (squares). The map also shows a reconstruction of the White Sea during the late Younger Dryas.

The reconstruction of the water body in the White Sea Basin area was created in ArcGIS 9.3 software using raster layers. A relative rebound surface was created from the elevations of the surfaces of the glaciodeltaic deposits of the same age and the rebound surface was subtracted from the present ground and seafloor elevations similar to the procedure presented in (Mann et al., 1999). The lack of control points did not allow creation of TIN (Triangulated Irregular Network) as in (Mann et al., 1999). Therefore, the relative rebound surface was created by calculating the gradient between the study sites. Determined gradient, 0,46 m/km, was applied in the right angles of the modern glacioisostatic isobases, such that each isobase have the same value for the relative rebound and values for the areas between isobases are interpolated. The present elevation of the ground surface was taken from the GLOBE 1.0 (The Global Land One-km Base Elevation Project), which is a 30 arc-second (1 km) gridded, global digital elevation model (GLOBE Task Team, 1999). The modern bathymetry of the White Sea was taken from IBCAO 2.0 (International Bathymetric Chart of the Arctic Ocean) grid (Jakobsson et al., 2008), which is a 1 arc-minute (2 km) gridded, digital elevation model. In the preliminary reconstruction, the ice margin showed is only giving an estimate of the position of the late Younger Dryas ice margin.

3. Results

Ground penetrating radar

Several radar facies and radar surfaces were identified in the study areas. Only example of radar transect showing radar facies and radar surfaces interpreted to represent glaciodeltaic deposits is presented here. The results of the radar stratigraphy are shown in Fig. 2 and discussed briefly below.

In Fig. 2 four radar facies and four radar surfaces are identified. The interpreted radar facies can be grouped in two sedimentary environments: 1) glaciodeltaic and 2) littoral. Radar facies RF1 is interpreted to represent glaciodeltaic environment. The interpretation is based on clinoform reflections continuing from the top of the radar profile to the bottom interpreted to represent delta foresets. The maximum apparent dip angle is 18°. The radar facies is erosionally truncated by radar surface RS2. Radar surface RS1 is seen between 265-300 m in Fig. 2. It probably shows an erosional top surface of a glaciodeltaic element, possibly representing a change in the direction of the water flow, but no separate radar facies could be determined. Radar facies RF2-RF4 are interpreted to represent littoral sedimentary environment. The clinoform reflections probably show beach faces growing towards the open sea. The maximum calculated apparent dip angle for the clinoforms is 12°. The slightly concave radar surfaces RS2-RS4 are interpreted to represent wave-cut surfaces.

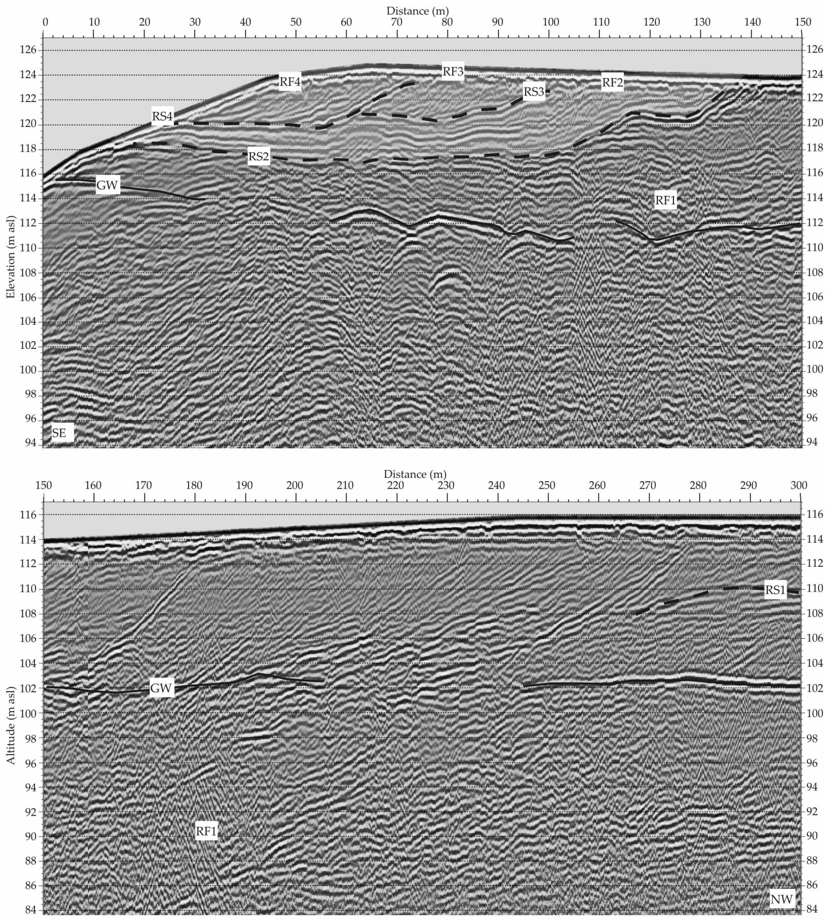

Figure 2. GPR transect from the Kalevala End Moraine showing glaciodeltaic deposits (RF1) and littoral deposits RF2-RF4. Radar surfaces RF2-RF4 represents probably wave-cut surfaces. GW = ground water surface.

Reconstruction of the White Sea

The results of the reconstruction are shown in Fig. 1. The reconstruction shows a connection to the Barents Sea, mentioned above. For the area and volume calculations the connection was demarcated to conform to the northern boundary of the White Sea's Gorlo area (*eg.* Kaitala et al., 2008). The volume and area was calculated using ArcGIS's Surface Volume tool. The calculated volume of the water in the White Sea basin during the late Younger Dryas was 6759 km^3 and the area was 92890 km^2. In the volume calculations the ice margin is assumed to be vertical.

4. Discussion and conclusions

The ground penetrating radar data suggests that the geomorphological interpretation of the flat surfaces is correct and they represent top surfaces of glaciodeltaic deposits, even though the apparent dip angles of the clinoforms calculated from RF1 are slightly too low for the usual delta foresets. As mentioned before, they represent apparent dip angles. The maximum dip angles of interpreted foresets (RF1) are higher than for interpreted beach face (RF2-RF4) suggesting in their part that the radar facies represent separate depositional events. The reconstruction of the White Sea during the late Younger Dryas shows that the transgression occurred mainly at the western and southern side of the sea, whereas at the north-east regression occurred. The calculated volume and the area of the White Sea during the late Younger Dryas was 1,5 times larger than today (Kaitala et al., 2008).

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Seismic velocities of the Outokumpu deep drill core and FIRE profile samples: what do the rocks tell us?

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In order to improve our understanding of the geological evolution of the Paleoproterozoic area near the Outukumpu Deep Drilling site, Central-East Finland, we need seismic velocity data of the rocks as a function of depth. An ultrasonic instrument to estimate the seismic velocities (Vp and Vs) down the core under crustal temperatures and pressures was constructed at the University of Helsinki to obtain the data neccesary to improve the seismic interpretations of the lithosphere under Finland. Seismic velocity data are also used to understand the recent seismic reflection (FIRE) data from the economically important Outokumpu area as well as from the Keuruu-Mänttä corridor, Central-West Finland.

Keywords: P- and S- velocities, reflection seismics, Outokumpu, Keuruu, FIRE, ultrasound

1. Introduction

The Paleoprotorozoic Outokumpu formation is part of the overthrusted nappe, which has suffered multiple tectonic events and metamorphisms since 1.97 Ga. The geology of the area is complex and therefore has been extensively studied; however, the genesis and tectonic evolution of the terrain is not yet fully understood. Geophysically the Outokumpu area is located in a complex network of magnetic and elektromagnetic anomaly patches and distinct gravity highs probably caused by ultramafic rocks of the Outukumpu association (serpentinite) and graphite bearing black schists containing sulphide layers and skarn. The Geological Survey of Finland (GTK) has carried out wide-angle seismic profiles in the framework of the FIRE seismic reflection project and the Outokumpu Deep Drilling Project (ODDP). The Outokumpu Deep Hole (drilled in 2004-05 reaching ~ 2516 m) is located in an antiform revealed by seismic reflection data. In order to better understand the subsurface geophysics and to gain more information of the crustal structures, the knowledge of precise petrophysical properties, notably the seismic velocities of the rocks of this area is required.

Longitudinal (Vp) and shear (Vs) velocities of several ODDC and seismic reflection (FIRE) samples from Keuruu-Mänttä area (middle Finland) were determined. A custom built ultrasonic instrument (*Fig.1*) allowed estimating the velocities encountered under crustal temperatures and pressures. The velocities provide estimates also of the seismic impedances and the reflection coefficients of various rock types. The measurements improve interpretations of crustal structures and are necessary to understand recent seismic reflection profiles in Finland.

2. Instrumentation

The ultrasonic instrument (*Fig. 1*) measures simultaneously Vp and Vs phase velocities in rock samples under varying temperature and uni-axial pressure (0-300 MPa for 25 mm sample diameter (see Elbra et al. 2006a, 2006b, 2007; Lassila et al. 2007). The system comprises two custom-built transducers, a hydraulic cylinder and a load cell residing inside a metal cradle. The transducer housing is made of stainless steel to withstand the high pressure.

Heat and pressure effects on the transducers are subtracted from the Vp and Vs measurements. The longitudinal and shear wave piezos (1,0 MHz and 1,1 MHz respectively) are excited simultaneously with a pulser (5058PR, Panametrics). The signals that traversed the sample are amplified 0-60 dB depending on the sample length and attenuation. The amplified signals are sampled with an oscilloscope. The uniaxial compressional load (max. 25 t) is produced with a hydraulic cylinder.

The loading is monitored with a load cell and the signal from the cell amplifier is recorded with a DAQ card. Samples are heated in an oven and then brought to the transducer setup. This allows heating multiple samples simultaneously to increase throughput. The change in sample height is measured (1 µm resolution) during the compression with a digital gauge 543-250B, Mitutoyo. This change is used not only in correcting the travel times but also in calculating elastic constants (such as Young's modulus, Poisson ratio etc.). All the measured signals, sample temperature and change in height, as well as the applied load are recorded with a PC running a Labview measurement program that controls also the hydraulic pump.

The device is the result of collaboration between the Solid Earth Geophysics Research Laboratory and the Electronics Research Laboratory of the University of Helsinki. (Pesonen 2006).

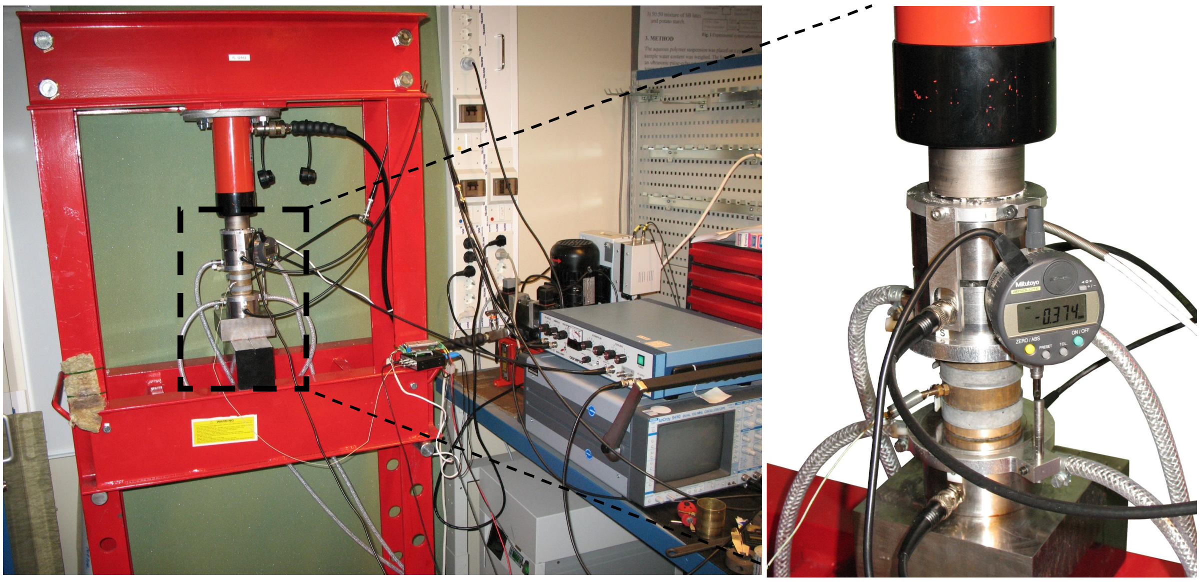

Figure 1. The ultrasonic instrument used to measure and shear wave phase velocities in rock samples under varying temperature and pressure.

3. Results

The Vp and Vs measurements were carried out on several ODDP (Outokumpu) and FIRE (Keuruu) samples. Results (dry samples, ambient T and P) of FIRE samples from Keuruu area indicate values of 3800-5100 m/s for Vp and 1700-2900 m/s for Vs, yielding to Vp/Vs ratio of 1.62-2.7 depending mostly on sample conditions (micro/macro cracks). Under 300ºC / 120MPa Vp and Vs values raised to <5700 m/s and <3100 m/s, and Vp/Vs to 1.68-2.2, respectively.

Results from Outokumpu drill samples (saturated, ambient T and under corresponding lithostatic pressures of each sample) show a small overall raise of Vp as a function of depth *(Figs.2- 4)*. Vp and Vs vary between 4800-6400 m/s and 2300-3700 m/s, respectively, depending on mineralogy as well as on sample conditions. Vp/Vs ratio of the samples is 1.63-2.15 with reflection coefficients -0.06 to 0.2.

Figure 4 reveals occasional peaks down the core at the same depths for Vp and Vs pointing to either fractures (l) (e.g., 350 m, 595 m), or to higher velocity layers (h) (e.g. at 800 m) which can mark black schist or sulphide veins within metasediments. The seismically detected strong reflectors at ~ 1300-1500 m may correspond to increased Vp and Vs at ~ 1350-1500 m.. The notable drop in Vp & Vs with simultaneous increase in Vp/Vs at ~ 1700 m may mark a pegmatite vein, but more data are needed at greater depths to verify this.

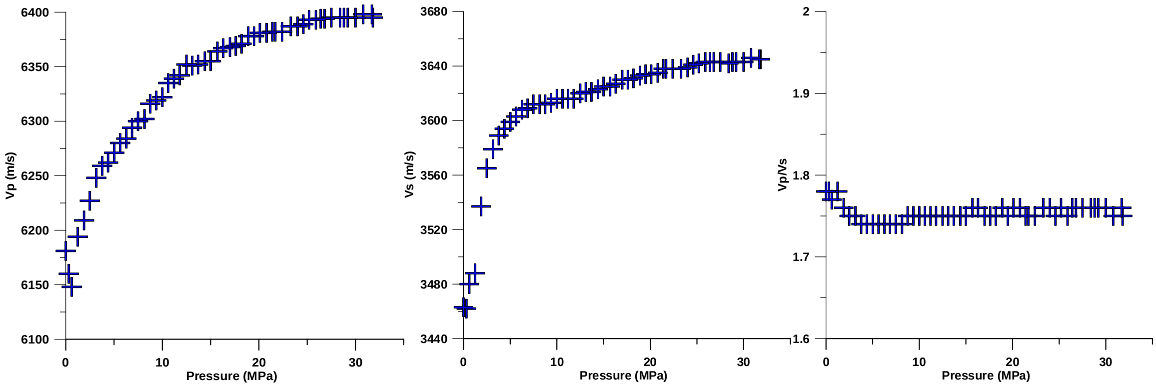

Figure 2. Examples of Vp (left), Vs (middle) and Vp/Vs (right) of the dry Outokumpu mica schist (water saturated) sample under crustal P-conditions. Note that nearly equilibrium conditions are reached at pressures ≥20 MPa for Vp & Vs, but already at ~ 8 MPa for Vp/Vs.

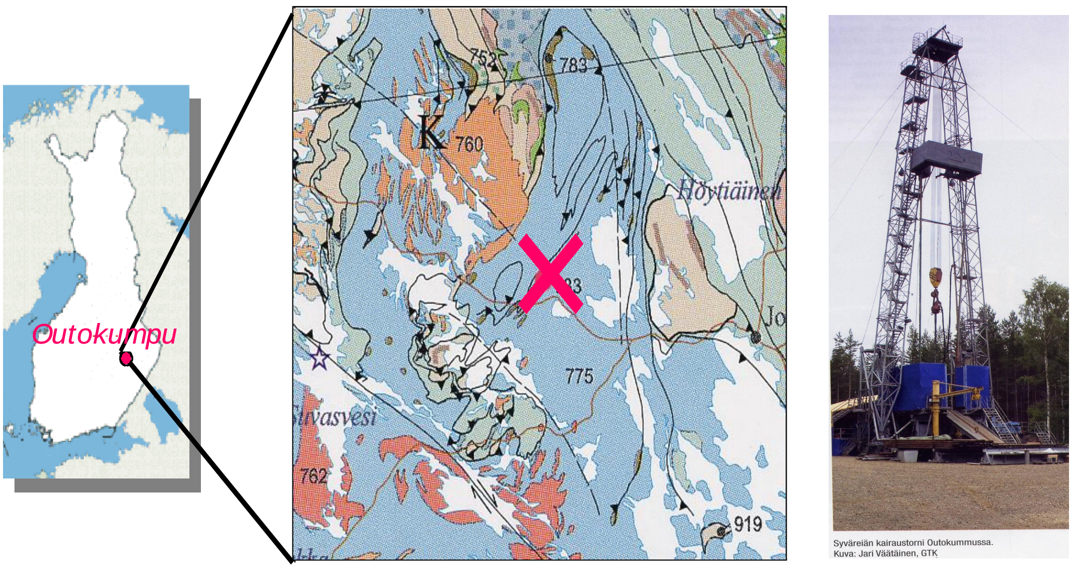

Figure 3. Left: the location of the Outokumpu Deep Drilling Site (ODDP) in Central-East Finland. Middle: geological map of the Outokumpu nappe area where cross denotes the drilling site. Right: the Drilling Shaft in construction.

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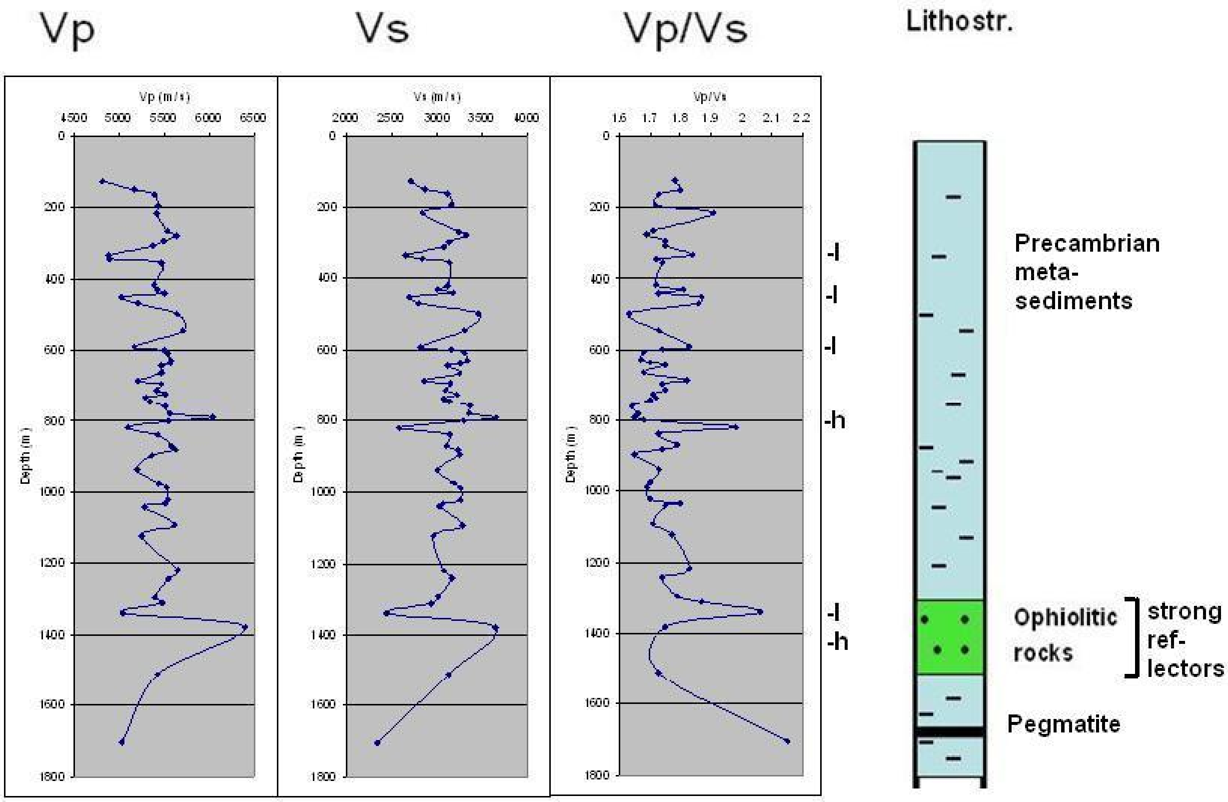

Figure 4. Vp, Vs and Vp/Vs of water saturated samples from Outokumpu deep drill core, indicating a small increasing trend of Vp-values down the core. Precambrian metasediments include mica schists and black schists with sulphide interlayers. The ophiolites (previously Outokumpu association) includes serpentinites, skarn and black schist interlayers, respectively, l (low), h (high), denotes peaks in the Vp& Vs –curves, respectively. See text for discussion.

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Did lithosphere plates move already during the Paleoproterozoic? – paleomagnetic evidence

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Plate tectonics is a convenient model to describe the relative movements of lithospheric blocks over the convecting mantle. Considerable amount of reliable evidence of lithospheric plate movements is available for the past 200 million years. Recently discussion has focused on whether the lithospheric plates moved already during the Precambrian times. Here we show evidence of ancient plate movements during the Paleoproterozoic as based on global paleomagnetic data.

Keywords: lithosphere, plate tectonics, Paleoproterozoic, paleomagnetism, Dharwar, Baltica

1. Introduction

When and why did plate tectonics began? This question is still one of the most important unresolved problems in understanding the geological evolution of planet Earth. Past motions of lithospheric plates can be traced by geologic, seismic, magnetic, isotope chemical and, in particular, paleomagnetic methods. The following observations strongly suggest that plate movements did take place already during the Paleoproterozoic times:

- Proterozoic supercontinent assemblies are different than the last supercontinent Pangaea and present position of continents – the continents must have been moved
- Apparent Polar Wander Paths (APWP) of continents differ for certain periods – the most likely explanation is that continents (lithospheric blocks) have been moved relative to each other
- Analysis of paleoclimatologically sensitive sediments (such as evaporates, reefs, redbeds) support plate movements
- Geological records signalling plate tectonics include ophiolites, arc-type basins, continental riftings, collisional and accretional orogens
- Geophysical data reveal remnants of once occurred subduction processes
- Recent discoveries of detrital zircons call for close association of “exotic” continental blocks, which later have been separated

In this study we show that the reassembly of the continents during the Paleoproterozoic (~2.4 Ga) differs from the preceding Archaean Kenorland assembly and also from the successive Neoproterozoic Rodinia assembly (~1.0 Ga), which strongly favour of existence of plate motions during the Proterozoic.

2. Paleoproterozoic cratons used in this study

Although previous Precambrian supercontinent assemblies do show variations (see above), many of the reconstructions are based on only a few dated paleopoles. Here we focus on re-looking the global assembly of continents at ~2.4 Ga, which probably marks the break-up of the Archaean supercontinent Kenorland (Pesonen et al., 2003). For achieving a reliable reconstruction at ~2.4 Ga we compiled the paleopoles from various databases (e.g. GPDB: Pisarevsky database etc.). We chose cratons, which had data from an age interval 2.3-2.45 Ga. The cratons are: Baltica (Karelia), Dharwar (India), Laurentia (Superior), Congo - Sao Francisco and Yilgarn (Australia) (Figure 1B).

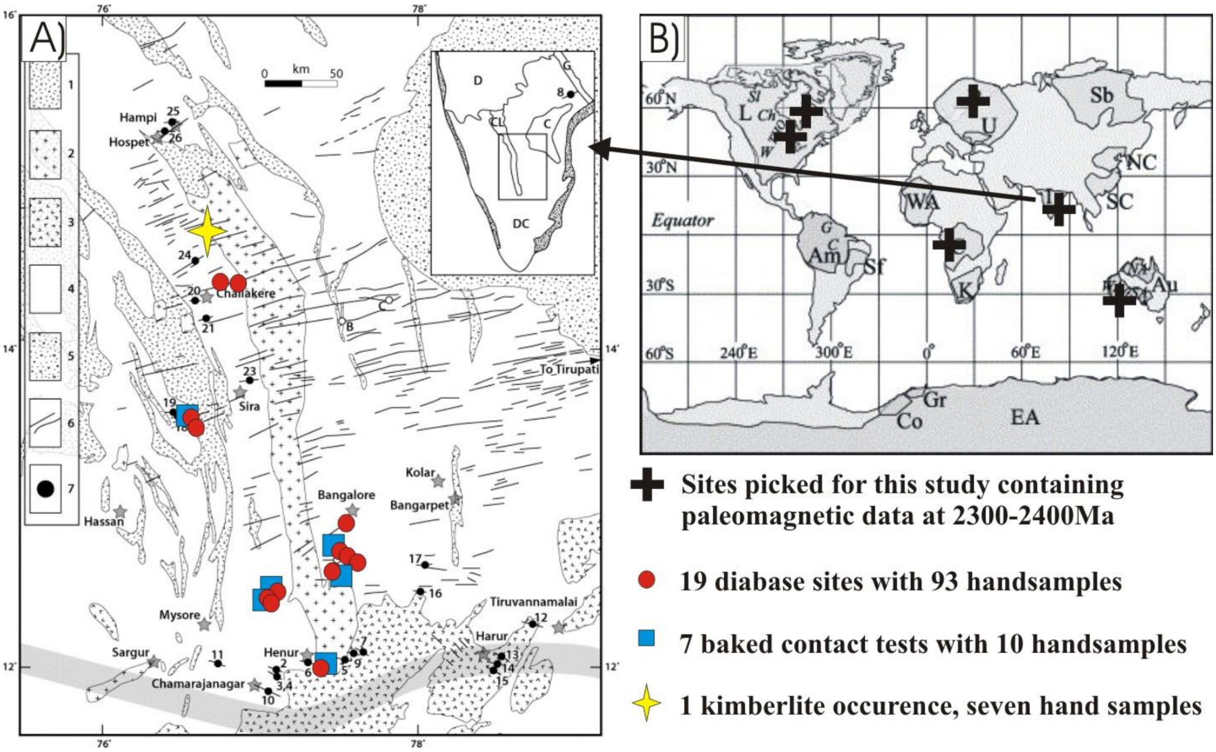

Figure 1. A) Locations of the sample sites in Karnataka, Dharwar craton (India) collected during 2006-2008 on a simplified geological map (modified after Halls et al., 2007). B) Locations of the paleomagnetic data used in this study showing Proterozoic cratons (modified after Pesonen et al., 2003).

3. Dharwar craton of India

In addition to data from the global paleomagnetic database we used our new data from Dharwar craton (India) from more than one hundred oriented hand samples (Piispa et al., 2008). The samples were collected from Paleoproterozoic diabase dykes of the Harohalli area (Karnataka) belonging to the Archaean Dharwar Craton of India (Figure 1A). The area consists of several dyke swarms of different ages with cross-cutting relationships. Of them, the most conspicuous is the ~2.37 Ga (Halls et al., 2007; French et al., 2004) East-West trending quartz dolerite swarm. Other relevant dykes are the possibly older N-S trending dykes and much younger (~0.8-1.0 Ga) alkaline dykes.

Paleomagnetic and rock magnetic investigations of the samples were carried out in the Laboratory for Solid Earth Geophysics of the University of Helsinki. Alternating field and thermal treatments, reveal the presence of two to three remanence components. The characteristic remanent magnetization component (ChRM) in the E-W trending dykes is an upward directed magnetization, which is strikingly similar to that reported by Halls et al. (2007) and Dawson and Hargraves (1994). Some sites reveal antipodal directions thus indicating field reversals and supporting the interpretation that the ChRM is primary. This component places India at high (southern?) paleolatitudes. The Dharwar Craton can be juxtaposed at 2.37 Ga with the Yilgarn Craton of Australia, where nearly coeval dykes (the Widgiemooltha swarm, 2.4 Ga) yield similar dyke trends in the reconstruction. This result may point to a long lived mantle plume under joint Dharwar-Yilgarn cratons.

4. Reconstruction based on paleomagnetic measurements

Mean paleopole positions, used in the Paleoproterotzoic reconstruction, are listed in Table 1.

Table 1. Mean paleopole positions of Proterozoic cratons used in this study for determining the past positions of these cratons in a reconstruction shown in Figure 2C. Plat (Plong) denotes latitude (longitude) of the paleopole and A95 is its error circle.

Craton	Mean Plat (ºN)	Mean Plong (ºE)	A95
Baltica	-24,4±10,3	292,0±11,3	10,3
Dharwar (India)	14,4±5,5	59,3±5,6	5,5
Laurentia (N-America)	-41,1±13,5	234,8±17,8	13,5
Sao Francisco – Congo (Africa)	61,0	211,0	14,7
Yilgarn (Australia)	-8,5	157,0	8,0

Reconstruction based on these data (Figure 2C) is similar to Halls et al. (2007, Figure 2B) although their reconstruction is based on only two continents (Dharwar and Yilgarn). Reconstruction (Figure 2A) of Pesonen et al. (2003) also differs from this new reconstruction (Figure 2C).

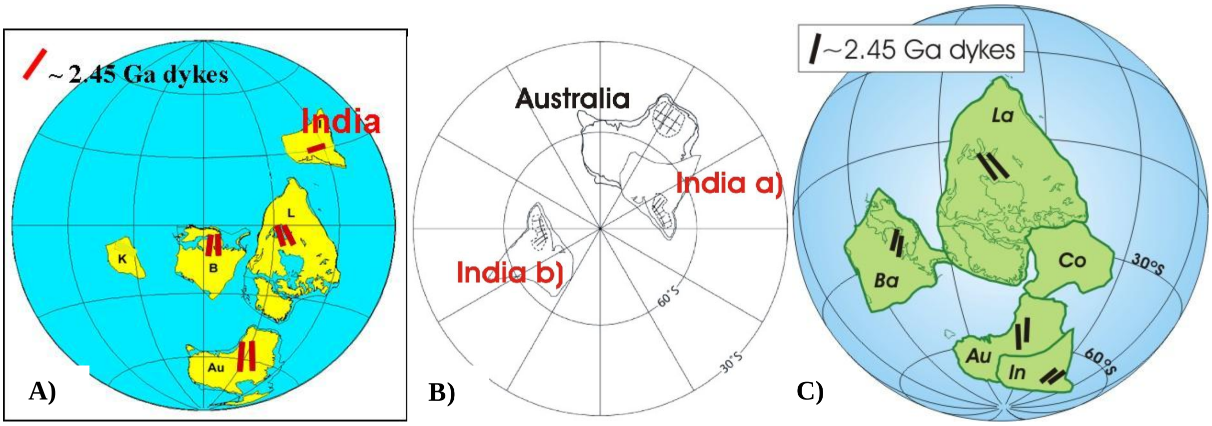

Figure 2. A) Reconstruction after Pesonen et al. (2003). B) reconstruction containing only Dharwar craton of India and W-Australian craton (Halls et al. 2007). C) This study.

The new reconstruction places India and Yilgarn (Australia) onto high southern latitudes whereas Baltica and Laurentia are at more equatorial latitudes. This may indicate that the Kenorland assembly was already broken at 2.36 Ga.

6. Conclusions

1) Lithospheric plates were in relative motion already during Paleoproterozoic
2) Our new data suggest that the Archaean Kenorland assembly was broken already at 2.36 Ga.

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Mapping of surficial deposits and bedrock - the field course in applied geophysics and geology of the University of Oulu

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The fifth field course of applied geophysics and geology was arranged in September 2008. The course is organized together by the Department of Physical Sciences, Geophysics and the Department of Geosciences of the University of Oulu. As a contrast to more theoretical studies the course provides much needed practical "hands on" approach to both geophysical and geological field work. This paper considers the course topics and the actual field work and shows some data and results.

Keywords: field course, applied geophysics, geology, surficial deposits, bedrock, Oulu

1. Introduction

The highly popular "Field course in applied geophysics" was arranged once again in September 2008. In its modern form the course was first arranged in 1997 and since then it has been held every two or three years. The course is organized together by the Department of Physical Sciences, Geophysics and the Department of Geosciences of the University of Oulu. The course aims to provide the students of geology practical knowledge about the methods of applied geophysics. Vice versa, it aims to give the students of geophysics practical information about geological field work and related problems.

The course is of advanced level and it is meant for students with adequate knowledge of geology and geophysics. When compared to the field demonstrations belonging to the basic level course "Geophysical research methods of rock and soil" this course requires more intensive work from the students. For the students of geophysics it is considered a single course of six credit points. For the students of geology it forms two different courses of (a) environmental (surficial) geology and (b) (bedrock) geology and mineralogy. In practice, the course is arranged during two successive weeks that both contain four days of field work and one day of data preparation. Additional homework is still needed to prepare a course report.

This year the total number of students participating the course was 18 (environmental geology) and 14 (bedrock geology). Six students of geophysics attended the course. Because of practical and logistical reasons the number of students had to be limited. Most of the time four teachers (2 + 2) were present supervising the field work. After initial guidance the students carried out the measurements themselves. After the actual field work the students prepared and interpreted their data in groups of three to four persons having usually one geophysicist and two geologists. Finally, the course is approved based on an accepted report elaborated separately by each group.

2. Mappings and measurements

The first part of the course (September 15-19 2008) considered different formations of surficial geology. The targets included Pilpasuo peat bog in Oulu, Kumpuselkä esker and Honkanen hummocky moraine formations in Kiiminki, thick glaciofluvial sand formation of

Polvenkangas in Tyrnävä as well late and postglacial clay deposits of Karvonoja in Lumijoki. The locations of the targets are illustrated in Figure 1.

The Pilpasuo peat bog was drilled for peat samples from top to bottom with twenty meter spacing between the drill holes. Several ground penetrating radar (GPR) lines were also made using GPS and 100 MHz and 250 MHz antennas. The esker formation in Kumpuselkä was investigated with vertical electric soundings (VES) and seismic refraction soundings. The electrical and chemical properties (EC, pH) of the naturally acidified groundwater ponds from a nearby quarry were also analyzed. The hummocky moraine formation of Honkanen was studied with VES and seismic soundings also. Two GPR lines were made but they did not turn out to be very useful. Geoelectric soundings and refraction seismic soundings were also utilized in Karvonoja, where highly conductive clays constitute most of the uppermost sediment layers. Hand drilling was used to identify the layered structure of the clays. In Polvenkangas interpretation of previous time domain electromagnetic (TEM), VES and VLF-R data indicated that the sand layer is over 50 meter thick. This year three GPR lines were measured with 100 MHz antenna to study the more detailed structure of the sands.

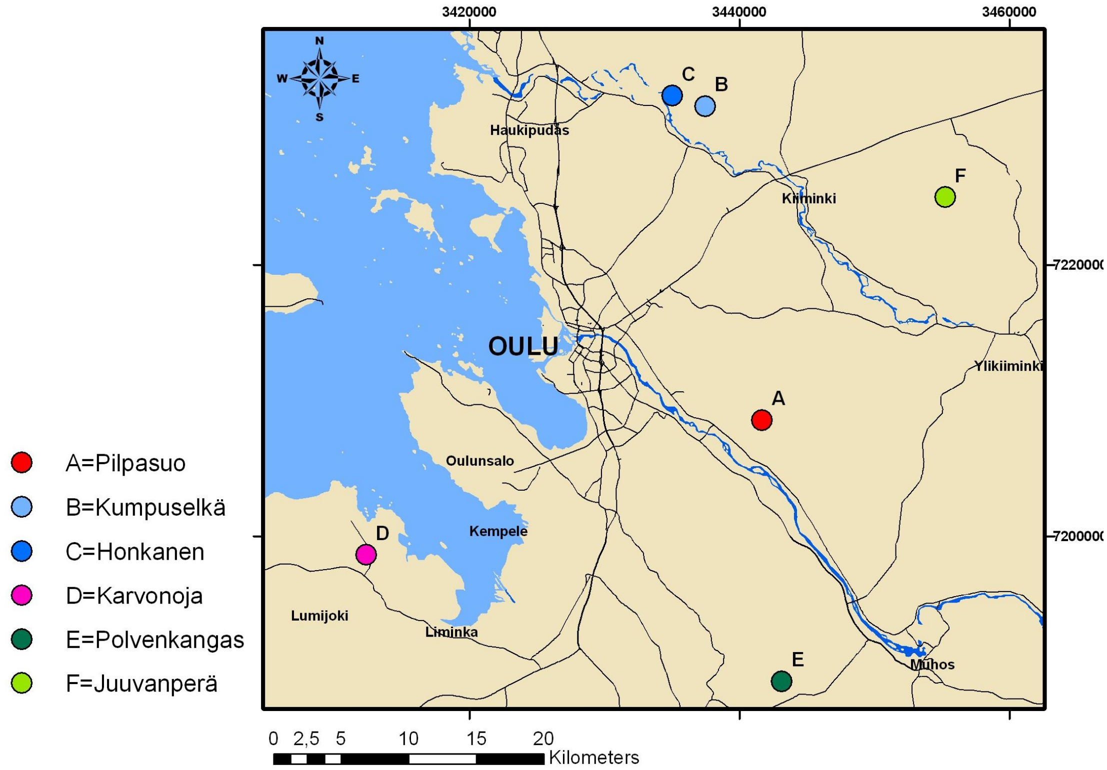

Figure 1. Location of the target areas of the field course. A to E are sites of surficial deposit mapping, F is the bedrock mapping site.

The second part of the course (September 22-26 2008) focused on bedrock mapping in Juuvanperä in Kiiminki (see Figure 1). The detailed study area is illustrated in Figure 2. The objective was to prepare a geological map of the area based on direct geological observations and indirect geophysical measurements. Juuvanperä area is one of the few areas close to Oulu where enough outcrops can be found within a rather small area (c. 1 km^2). Moreover, the area has a wide variety of different types of rocks including metasedimentary rocks, mafic rocks and black schists that give rise to magnetic, electric and electromagnetic and gravimetric anomalies.

In Juuvanperä the principal geophysical mapping method was the measurement of magnetic field (total magnetic induction). Magnetotelluric (MT) measurements in Vaala near Oulujärvi provided a magnetic reference station that was used to account for diurnal variations of the inducing magnetic field. Thanks to the very low present magnetic activity, total field variations during the course were ±50 nT. The magnetic measurements were made with vertical gradient option and a GPS link provided a way to collect data using more or less "random walk" method. In addition to magnetic measurements, self potential (SP) data was collected along three extension profiles. All new data were added to the data from previous years. Figure 2 shows the coverage of various data sets collected in 2004 and 2008. Along the baseline (Figure 2), where Geological Survey of Finland has made gravity measurements, TEM, VLF-R and geoelectric profiling was made to demonstrate their usefulness in geological mapping.

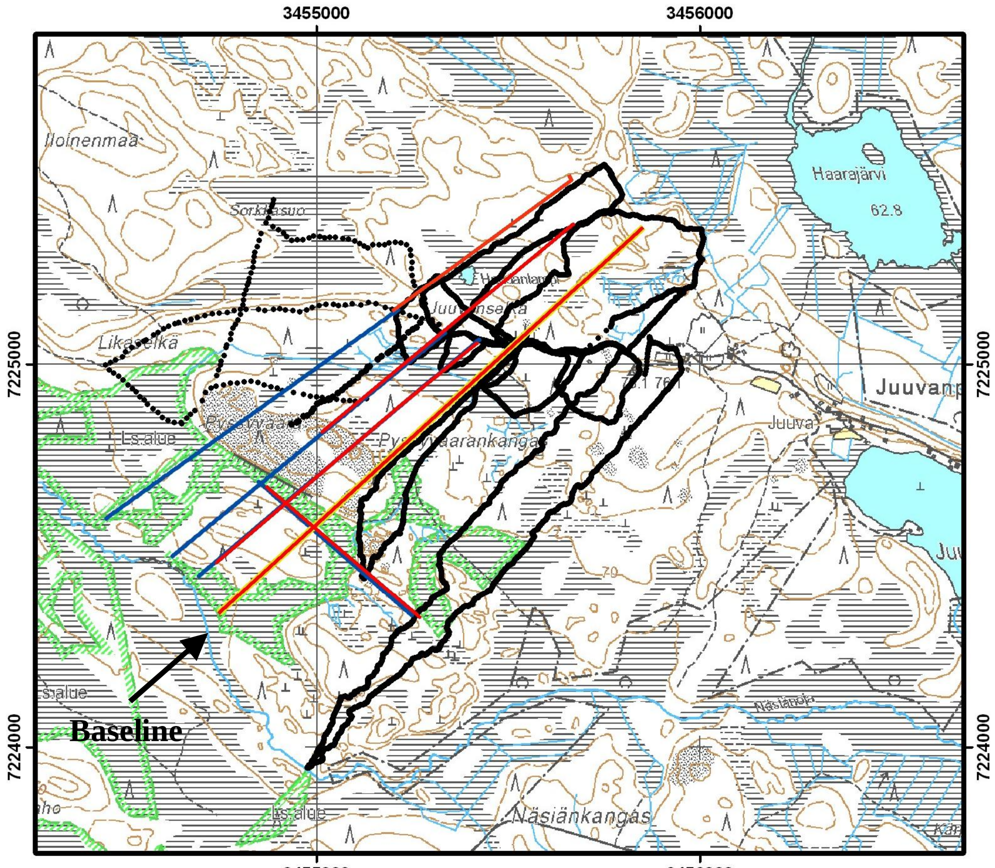

Figure 2. Location of magnetic (blue 2004, black 2008) and SP (red 2004 and 2008) data in Juuvanperä. Along the baseline, in addition to magnetic and SP, also gravimetric, TEM, VLF-R and geoelectric measurements has been made.

3. Summary

The course has proven to be highly useful because of its practical approach to co-operative geological and geophysical field work. The variety of geological investigation problems shows the advantages and disadvantages as well as the limitations of the various geophysical investigation methods. Best results are obtained from combined use of different geophysical methods. For example, joint interpretation of VES and TEM measurements can be used to resolve the thickness of highly conductive clay layers and seismic refraction soundings can be used to improve VES interpretation. The geophysical investigation methods and related geological problems are listed in Table 1. The course also reveals that data collection is only one small part of the job. Careful and time consuming data processing and interpretation by geologists and geophysicists is still required to get the final results.

Table 1. Geophysical investigation methods, instruments and related geological targets in the field course.

Geophysical method	Instrumentation	Surficial deposits	Bedrock mapping
Ground penetrating radar	Malå X3M + 100 & 250 MHz	A,C,E	
Vertical electric sounding	Eda R-plus	B,C,D,E	
Seismic refraction sounding	Geometrics Geode	B,C,D	
TEM measurements	Tem-Fast 48 HPC	D,E	F
VLF-R measurements	Geonics EM16-R	A,D,E	F
Geoelectric profiling	Eda R-plus		F
Self potential profiling	Fluke		F
Magnetic profiling + vertical gradient +base station	Geometrics G858 MTU2005		F

A = peat bogs, B = esker formations, C = hummocky moraines, D = postglacial clays, E = glaciofluvial sands, F = magnetic and electrical properties of the bedrock

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DynaQlim – ILP Regional Coordination Committee[5]

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The inter-disciplinary project DynaQlim (Upper Mantle Dynamics and Quaternary Climate in Cratonic Areas) was accepted as a regional coordination committee of the International Lithosphere Program (ILP) in 2007. The aim of the DynaQlim project is to understand the relations between upper mantle dynamics, mantle composition, its physical properties, temperature and rheology, as well as to study Glacial Isostatic Adjustment (GIA) and ice thickness models, Quaternary climate variations and Weichselian glaciations during the late Quaternary. As a result of the DynaQlim project we expect to have a more comprehensive understanding of the Earth's response to glaciations, improved modelling of crustal and upper mantle dynamics, rheology structure. An important aspect is to construct and improve coupled models of glaciation and land-uplift history and their connection to the climate evolution on the time scale of glacial cycles.

Keywords: Glacial Isostatic Adjustment, mantle dynamics, mantle physics, ice models, quaternary climate

1. Introduction

During the Pleistocene, quasi-periodic variations between glacial and interglacial intervals prevailed, with dominant periods closely related to those present in the Earth-Sun orbit and 25.8 kyr rotational precession of the Earth. These Milankovich variations in the cryosphere have played a key role in shaping the landscape and driving the geodynamic evolution of cratonic regions such as northern Eurasia and North America during the Quaternary.

The process of Glacial Isostatic Adjustment (GIA) with its characteristic temporal signatures is one of the great opportunities in geosciences to retrieve information about the Earth. It contains information about recent climate forcing, being dependent on the geologically recent on- and off-loading of ice sheets. It gives a unique chance to study the dynamics and rheology of the lithosphere and asthenosphere, and it is of fundamental importance in geodesy, since Earth rotation, polar motion and crustal deformation, and therefore the global reference frames are influenced by it.

In spite of long and accurate time series and extensive data sets on GIA, there still exist many open questions related to upper mantle dynamics and composition, rebound mechanism and uplift models, including the role of tectonic forces as well as cryospheric climate and ice thickness during the late Quaternary. DynaQlim aims to integrate existing data and models on GIA processes, including both geological and geodetic observations. The themes of DynaQlim include Quaternary climate and glaciation history, post-glacial uplift and contemporary movements, ice-sheets dynamics and **glaciology, post-glacial faulting, rock**

[5] This paper is based on an article prepared for an ILP book to be appear in 2009 by Springer Verlag. (Poutanen *et al.*, 2009)

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rheology, mantle xenoliths, past and present thermal regime of the lithosphere, seismic structure of the lithosphere, and gravity field modelling.

2. Observational basis

Extensive and diverse sets of observations can be applied to study and understand the key processes involved. Abundant data have been collected in various cratonic regions, including Antarctica, Laurentia and Fennoscandia. Laurentia and Fennoscandia have a similar glaciation history during the Quaternary, though their tectonic evolutions are different. In Antarctica the glaciation history is distinctly different.

Geodetic methods provide accurate measurements of contemporary deformation and gravity change. There are systematic postglacial uplift observations for the last 100 years based on repeated precise levelling, geodetic high-resolution observations of recent movements, gravity change and monitoring of postglacial faults. Until recently, horizontal motions could not be observed accurately. However, current GPS observations are accurate enough to observe even minor horizontal motions over distances of several hundreds of kilometres.

The gravitational uplift signal can be detected by absolute and relative gravimetry. The gravity satellites GRACE and GOCE are providing, or will provide, additional global and regional constraints on the gravity field. Recent studies have demonstrated that the GRACE data clearly show temporal gravity variations both in Fennoscandia and North America.

Continuous GPS observations of plate-wide strain, accompanied by seismological investigations, and followed by continuum mechanical modelling of GIA, studies of seismic source and wave propagation, and studies of the post-glacial faults offer new insights into properties of the lithosphere. Observations and models of glacial and post-glacial faulting can help to illuminate crustal stress fields and therefore crustal rheology issues.

Inversion of deep temperature data in boreholes provides direct access to ground temperature histories during glaciation times. Kimberlite facies in crustal rocks contain mantle xenoliths and these provide a basis for extrapolating temperature and composition to larger depths using seismology.

For GIA two further aspects are important: First, the surface heat flow will constrain the dynamics of the ice sheet and thus the deglaciation history. Second, the viscoelastic response of the solid earth is influenced by the rheological behaviour of the lithosphere. Lateral variations play a crucial role in the inference of the regional palaeotopography.

The present-day seismicity in Fennoscandia as a whole is in general low to moderate in magnitude. This situation differs drastically from that at late-glacial times (i.e. 11 to 9 ky B.P.), when powerful earthquakes created impressive ground surface ruptures. The present-day seismicity in Fennoscandia is of intraplate type. The epicentres of these intraplate seismic events tend to be concentrated along ancient tectonic deformation zones.

The stress state responsible for the observed seismicity appears to be the result of various stress-generating mechanisms. In-situ stress measurements argue for relatively high magnitudes at shallow depths below the ground surface. Post-glacial rebound has often been advanced as a secondary source of stress modifying the tectonic stress. However, no clear radial pattern can be observed in the present-day stress compilations. This suggests that, in contrast with the situation that prevailed just after deglaciation, rebound stresses are nowadays in Fennoscandia, surpassed by plate motion forces or local stress sources.

Some of the largest fault scarps in northern Fennoscandia were formed at the end of the last glaciation. These faults have lengths ranging from a few kilometres to 160 km and generally strike NNE, with maximum vertical offsets of 10-15 m. These glacially induced faults mostly ruptured through old zones of weakness (shear zones), not necessarily following one zone but instead jumping to another to comply with the restraints set by the causative stress field.

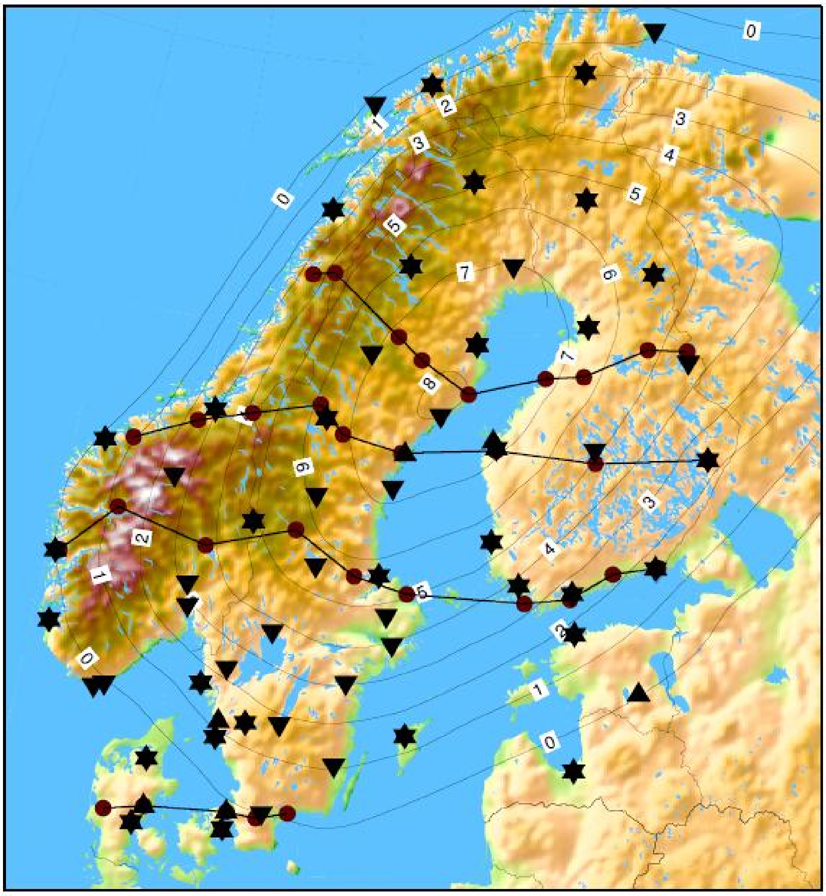

Figure 1. GIA in Fennoscandia. The upside-down triangles on the map are permanent GNSS stations, triangles stations where regular absolute gravity is measured as a part of the NGOS project, and dots with joining lines are the land uplift gravity lines, measured since the mid-1960's. Uplift contour lines are from the Nordic land uplift model NKG2005LU.

3. Future tasks

The observations mentioned above can be used to constrain geophysical models of the GIA using the observational evidence or to provide, e.g., GIA-induced uplift velocities for prespecified rheology. Current GIA models, however, suffer from regional deviations up to 0.2-0.5 mm/yr compared to the observed values. This will degrade the resolution of the past behaviour of the uplift, interpretation of the rheology, and therefore also the ice history.

Current GIA models are mostly based on radially stratified (3D) Earth models with linear rheology. During the last few years progress has been made in the development of global, 3D-stratified earth modelling.

Another task is to couple existing GIA uplift data, uplift models and the most recent geological and palaeoclimatological data on glaciation history. Northern Europe and Russia provide a study area with several recent contributions. Using land uplift models, the sensitivity of uplift data on variations in ice thickness and duration should be quantified, at least for the period of the last deglaciation, i.e. from the last glacial maximum at about 22 ka B.P. to the present time. Inverse modelling of the glaciation history may be a promising new approach previously not applied.

An important step toward a better understanding of GIA in terms of the viscoelastic structure of the earth's lithosphere and mantle has been the joint inversion of different types of geodetic and gravimetric data related to GIA – preferentially connected with geological relative sea-level evidence of the earth' rebound during the last ten thousand years.

Past and present changes in the mass balance of ice sheets and glaciers induce present-day deformation of the solid earth on spatial scales ranging from local to global. The Earth's deformational response to cryospheric change is complex due to a number of factors including complexities in the viscoelastic structure of the earth, the spatial and temporal variability of the ice mass changes and the interaction between the cryosphere and the ocean. Both short and long term physical changes give important boundary conditions for the ice cap variations and their ablation. An example is provided by Greenland, where the ice sheet retreated after the last glacial without disappearing. The associated sea level changes supply important geophysical constraints together with those provided by GPS and gravity studies.

Recent advances in studies of the glacial history of northern Europe and Eurasia have significantly improved our understanding of the glaciation and deglaciation histories during the Weichselian and Holocene epochs over the past 100 ka. In addition, the development of numerical modelling of glaciations has shed new light on the processes involved as well as their mutual couplings. As a result, the latest generation of ice sheet models is significantly better constrained and more realistic than previously.

One of the objectives of the DynaQlim initiative is to produce better models both of the glacial history and of the earth response in order to enhance our understanding of the phenomenon of glacially induced faulting and to better predict where and when it occurs. Not a purely academic exercise, as glacially induced faults are of utmost importance in the safety assessment for future nuclear waste repositories at northerly latitudes.

Another important societal issue is to investigate how much post-glacial rebound stresses contribute to the triggering of seismicity that would eventually threaten human infrastructures. The largest historical earthquakes in Fennoscandia occurred in the Rana region of northern Norway in 1819 with a magnitude of M = 5.8.

The tasks in DynaQlim have been divided into the following broad categories comprising the fields of

1) Geodesy, geodynamics, ocean dynamics;
2) Post-glacial uplift, contemporary movements and gravity;
3) Dynamic ice sheets, glaciology;
4) Quaternary palaeoenvironments and climate;
5) Neotectonics and seismotectonics;
6) Dynamics, structure, properties and composition of the lithosphere;
7) IT, data management and outreach.

For multidisciplinary projects conceptual challenges need to be tackled in order to make the data seamlessly accessible and portable for all users. Different disciplines (domains) describe the same datasets in their specific vocabulary, use their own data formats and organize them according to their requirements. In order to make a certain dataset originating from one domain usable to people from another discipline, the data need to be transformed and mapped between different profiles.

Acknowledgements:
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Poutanen, Markku., Doris Dransch, Søren Gregersen, Sören Haubrock, Erik R. Ivins, Volker Klemann, Elena Kozlovskaya, Ilmo Kukkonen, Björn Lund, Juha-Pekka Lunkka, Glenn Milne, Jürgen Müller, Christophe Pascal, Bjørn R. Pettersen, Hans-Georg Scherneck, Holger Steffen, Bert Vermeersen, Detlef Wolf (2009): DynaQlim – Upper Mantle Dynamics and Quaternary Climate in Cratonic Areas. Submitted for: *New Frontiers in Integrated Solid Earth Sciences* (Eds:.S. Cloetingh, S and J. Negendank). Springer.

Recording deformations of the Earth by using an interferometric water level tilt meter

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Global and local deformations of the Earth are recorded with a new intererometrical water level tilt meter at the Lohja2 geodynamical laboratory. Earth tides, earthquakes, free oscillation events, ocean and the Baltic sea loading are observed. Special interest is the dynamic response of the Fennoscandian crust under the surface load of the Baltic Sea. The new interferometrical tilt meter is a third generation water level tilt meter designed and built at the Finnish Geodetic Institute (FGI) since 1965, when Kukkamäki initiated instrument development for the Fennoscandian land uplift research. This paper describes some details of the new instrument and phenomena recorded with it.

Keywords: interferometric tilt meter, geodynamics

1. A new Michelson-Gale type tilt meter

The new tilt meter is a Michelson-Gale type (1919) instrument. In the design there have been used experiences from the old film based interferometric water level tilt meters and recordings studied in 1977 - 1998 (Kääriäinen, 1979, Kääriäinen & Ruotsalainen, 1989).

In the tilt meter design modern fiberoptics with HeNe lasers are used. Computer controlled digital cameras record interferograms with 15 Hz sampling rate at each end of the tube and those interferogram are interpreted into phase values on-the-fly with 2D adjustment routine.

Test recordings were carried out in 2005-2006 in the laboratory of the FGI, before instrument installation in the Tytyri mine, Lohja, Finland. In those tests we found out how to carry out recordings during microseismic and seismic events. Thermal and air pressure influence on the instrument were studied in details.

With the new instrument (NSWT) we get ~5 nm level sensing at each end of the 50.4m long half filled tube and thus we can achieve tilt resolution of ~0.1 nanoradian. To avoid thermal effects near Fizeau type level sensing interferometers we located recording computers 200m and 260m away from the tilt meter tunnel by using fibre-optic extension (IEEE1394) bus to Basler A502f CMOS-cameras in recording interferometer. We have now a decade better resolution in level sensing than with the old water level tilt meters of the FGI. With this resolution we may have now ability to record reliably e.g. core resonance signal in the diurnal wave groups of the tidal potential development and get information on the character of earth core. To get this resonance signal reliably, we must record continuosly one year or more with the new tilt meter. N end of the NSWT in Tytyri mine, Lohja is shown in Fig. 1.

Figure 1. Northern end of the NSWT tilt meter in Tytyri mine, Lohja

2. Geodynamical signals in the water level tilt meter recording

Raw interferogram is interpreted into phase values between 0 – 1, which indicate level height change 0 – 204 nm. Recordings are downloaded from the recording computer on separate hard disk during laboratory visits and detailed data analyse is carried out at the Institute. One example of phase recordings during China earthquake 12.5.2008 is shown in Fig. 2a. Level change in the recordings before and after the earthquake is caused by earth tides containing a lot microseismic background noise with periods around 4, 6, and 12 seconds. After big earthquakes there exist also free oscillation events. In Fig. 2b there is an earth tide tilt recording of the northern part of NSWT. Upper dark curve is observation and lower curve is theoretical tidal model (Heikkinen, 1978). Downward drift in the recording has nothing to do with earthquake, but is the loading signal of the Baltic Sea.

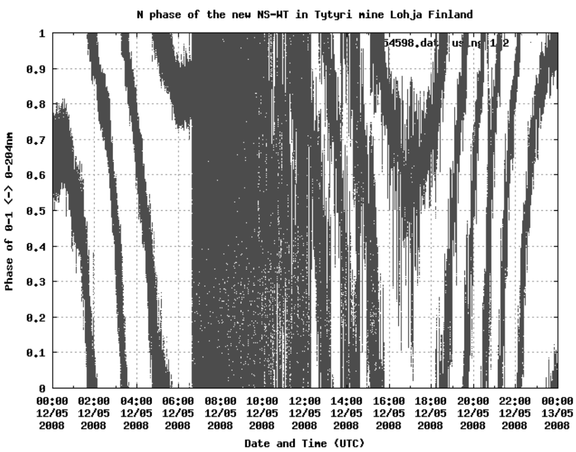

Figure 2a. Phase recording of the level sensing interferometer during earthquake 12.5.2008 in China.

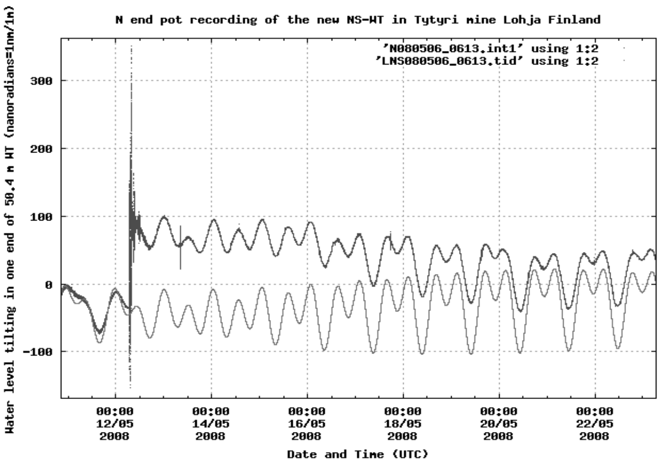

Figure 2b. Recording of N-end of NSWT tilt meter and tidal model tilt.

3. Loading of the Baltic Sea

M. Nordman (2008) modelled loading effects (gravity, tilt, displacements) of the Baltic Sea by using Agnew's (1997) NLOADF program package for different geodetic purposes at the FGI in spring 2008. In one model she determined crustal loading tilt signal for Lohja2 laboratory too. By tidal tilt analyse (Wenzel, 1996) the tidal tilt waves were removed from the NSWT recordings and residual tilt obtained seems to have correlation with loading signal calculated. It was a surprising result, that the amplitude of loading tilt (non-tidal) signal of the Baltic Sea has the similar size as the tidal tilt signal in NS-direction. Geodynamical laboratory Lohja2 in Tytyri mine, Lohja locates 30 km inland away from the coast line of the Gulf of Finland. Is the amplitude of the loading tilt signal even larger more near the coast line? The correlation between calculated loading tilt of the Baltic Sea and observed non-tidal tilt residual of NSWT at Lohja2 in February-March 2008 is shown in Figure 3. There is a lake Lohjanjärvi in the immediate vicinity of the Lohja 2 geodynamical laboratory and whether this lake level variation causes also a different loading signal into the tilt meter recording is not yet known.

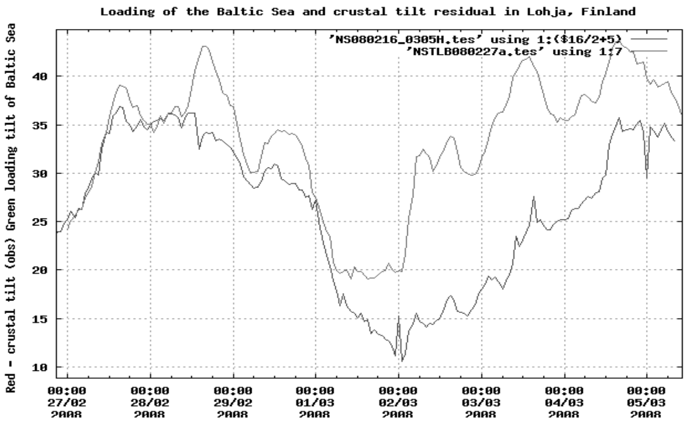

Figure 3. Upper curve: loading tilt model of the Baltic Sea. Lower curve: NSWT non-tidal tilt residual.

4. Conclusion

An interferometrical water level tilt meter is a simple tool for studies relating to the deformations of the Earth. Loading tilt signal caused by the Baltic Sea can give new information on the dynamical character of the Fennoscandian crust.

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~1635-Ma bimodal rapakivi volcanism of the Island of Suursaari, Gulf of Finland, Russia

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The Proterozoic *locus classicus* rapakivi granites of southeastern Finland and vicinity (the Wiborg batholith and its satellite intrusions) are relatively high-level, epizonal plutons that were emplaced in an extensional tectonic setting. Quite probably, these plutons represent the magma chamber system of a complex, rather long-lived caldera event; observations of coeval volcanic rocks are very scarce, however. We describe the lithology, stratiraphy, U-Pb geochronology, and Nd isotope geology of a bimodal (silicic-basic) volcanic rapakivi suite that has been preserved in a down-faulted crustal block on the Island of Suursaari, Gulf of Finland, Russia.

Keywords: rapakivi granite, volcanism, Paleoproterozoic, Fennoscandia, Russia

1. Introduction

The classic Wiborg rapakivi granite batholith in SE Finland and adjacent Russia is a roughly circular multiple pluton with a diameter of ~200 km (Fig. 1). It comprises A-type syeno- and monzogranites as well as minor quartz monzonite, topaz granite, mafic and silicic dikes, and massif-type anorthosite. The batholith was emplaced into the ~1.9 Ga Svecofennian orogenic crust at 1.65-1.62 Ga (Vaasjoki et al., 1991), concomitantly with crustal extension and thinning associated with thermal disturbances in the subcontinental mantle (e.g., Rämö and Haapala, 2005). The current erosional level corresponds to a depth of 1-5 kbar (Elliott, 2001; Lukkari, 2007).

2. Lithology

The Island of Suursaari (or Hogland) on the southern flank of the Wiborg batholith (Fig. 1) hosts a supracrustal sequence with a spectacular record of extruded silicic and basic magmas associated with the rapakivi granites, preserved in a downfolded crustal block. The central and eastern parts of the island are covered by this supracrustal sequence, which dips 10-15^{o} to the ENE (Fig. 1). The western part of the island is typical Svecofennian Paleoproterozoic metamorphic bedrock with mafic to felsic gneisses and schists and a variety of orogenic plutonic rocks.

The lowermost unit in the Suursaari supracrustal sequence is a quartz conglomerate (maximum thickness 30 m) with some quartz arenite interbeds. This is overlain by a discontinuous ~3-m-thick quartz-feldspar porphyritic rhyolitic unit and two discontinuous plagioclase-porphyritic amygdaloidal basaltic units (~15 m and 25 m). The basaltic units are locally separated by a 2-m-thick thinly laminated stratum including siltstone. Atop the basalts is a ~150-m-thick quartz-feldspar porphyritic rhyolitic unit that forms the bulk of the eastern half of the island (Fig. 1). The rhyolitic units, always conspicuously porphyritic, include crystal tuffs and felsitic lavas. Their volcanic stratigraphy is yet to be determined in detail.

3. Geochronology

Early U-Pb zircon work (Vaasjoki, 1977) on the Suursaari porphyries implied an age similar to those of the granites of the Wiborg batholith. Levchenkov et al. (1998) presented a U-Pb zircon age of 1638 ± 4 Ma for the upper rhyolitic unit; for the lower rhyolitic unit a poorly defined age of 1640 ± 11 Ma is available (Bogdanov et al., 1999). We have analyzed two new abraded zircon fractions from the lower rhyolitic unit. These yield a concordia age of 1633 ± 2 Ma (Fig. 2). Combined with the age of the upper rhyolitic unit, our data show that the volcanic succession of Suursaari was extruded at ~1635 Ma.

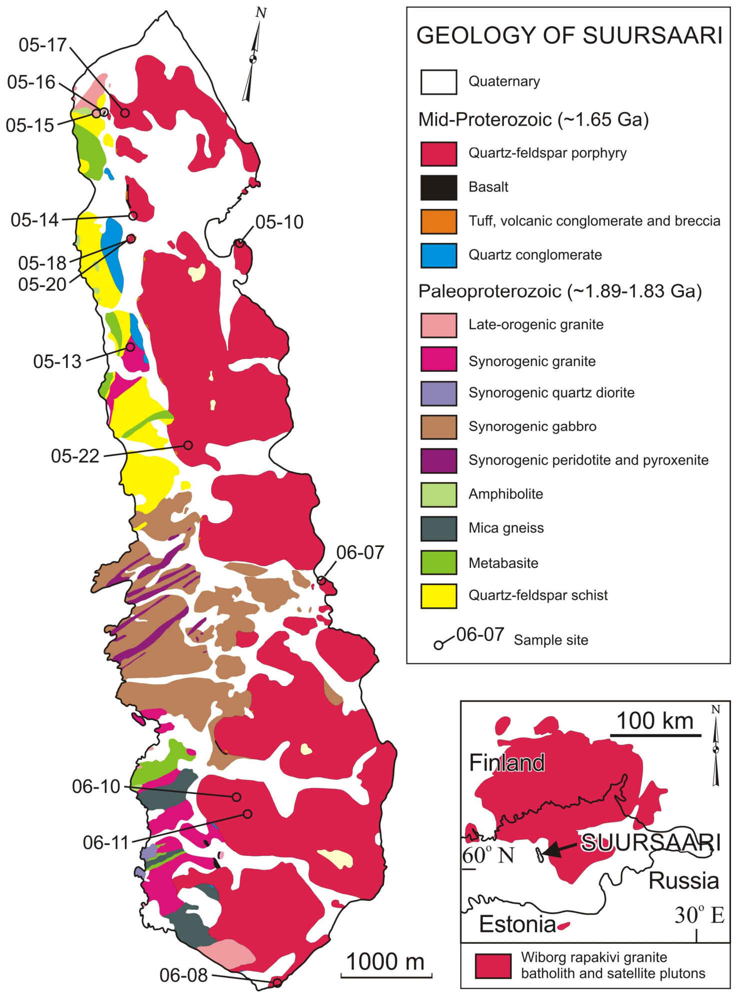

Figure 1. Geological map of the Island of Suursaari, based on mapping performed by the Geological Survey of Estonia in the 1970's. Inset shows the location of Suursaari relative to the Wiborg batholith in SE Finland and adjacent Russia.

4. Nd isotope geochemistry

We have also determined the Nd isotope composition of the lower rhyolitic unit, two basalts from the mafic units, a siltstone between the basalts, seven rhyolitic porphyries from the upper silicic unit, and two basement granitoids. The rhyolitic samples are marginally peraluminous, dacitic to rhyolitic, and show elevated Ga/Al. The Nd isotope data (Table 1) on these volcanic rocks imply quite homogeneous initial compositions with ε_{Nd} (at 1635 Ma) values within the -2.8 to -1.6 range [average -2.2 ± 0.4 (1σ); Table 1, Fig. 3]. This is only slightly in excess of the experimental error (± 0.4 ε-units) and points to subtle isotopic heterogeneity in the magmas from which the porphyries crystallized. The ε_{Nd} (at 1635 Ma) values of the basalts are slightly, yet significantly, higher (-0.6, -0.5). The siltstone between the basalts has a less radiogenic initial ε_{Nd} (at 1635 Ma) value (-3.6), impying a Paleoproterozoic supracrustal provenance. The basement granitoids have depleted mantle model ages of 2.23 Ga and 2.03 Ga and thus comply with the overall evolution of the Svecofennian crust in southern Finland (cf. Huhma, 1986).

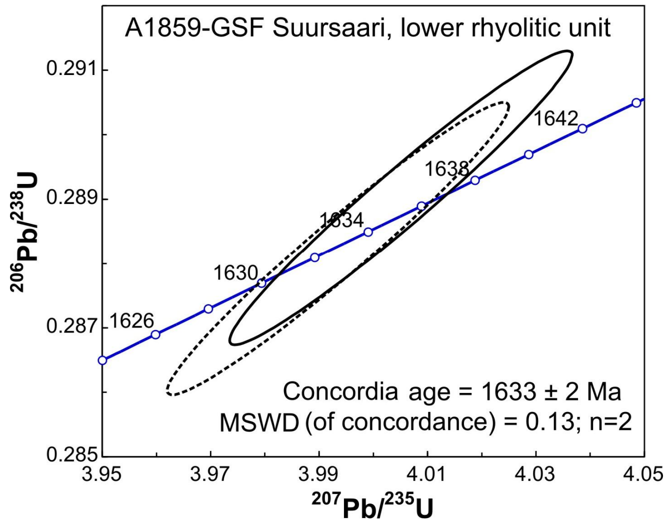

Figure 2. Concordia plot for multi-grain ID-TIMS U-Pb isotope data on two zircon fractions (sample A1859-GSF, 05-18 in Fig. 1) from the Island of Suursaari. Error ellipses are 2σ.

Table 1. Whole-rock ID-TIMS Nd isotope data on 13 samples from the Island of Suursaari.

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$*	$^{143}Nd/^{144}Nd$†	ε_{Nd}§ (initial)	T_{DM}** (Ma)
Quartz-feldspar porphyries (initial ε_{Nd} @ 1635 Ma)						
OTR-05-10	16.03	90.50	0.1071	0.511592 ± 9	-1.6	2067
OTR-05-17	13.24	71.67	0.1117	0.511610 ± 7	-2.3	2134
OTR-05-18	15.70	84.94	0.1117	0.511612 ± 6	-2.2	2132
OTR-05-22	16.25	87.94	0.1117	0.511588 ± 9	-2.7	2167
OTR-06-07	21.69	121.9	0.1076	0.511538 ± 11	-2.8	2155
OTR-06-08	22.35	126.1	0.1071	0.511569 ± 8	-2.1	2101
OTR-06-10	15.51	84.73	0.1107	0.511603 ± 7	-2.2	2124
OTR-06-11	19.50	106.0	0.1113	0.511641 ± 8	-1.6	2079
Basalts (initial ε_{Nd} @ 1635 Ma)						
OTR-05-16	11.82	57.22	0.1248	0.511834 ± 7	-0.6	2066
OTR-05-20	12.56	59.33	0.1280	0.511875 ± 5	-0.5	2069
Siltstone (initial ε_{Nd} @ 1635 Ma)						
OTR-05-14	5.38	28.10	0.1156	0.511583 ± 15	-3.6	2267
Late orogenic granite (initial ε_{Nd} @ 1830 Ma)						
OTR-05-15	6.27	25.95	0.1460	0.512035 ± 9	+0.1	2267
Synorogenic granite (initial ε_{Nd} @ 1880 Ma)						
OTR-05-13	5.51	35.21	0.0946	0.511453 ± 15	+1.5	2030

* Estimated error for $^{147}Sm/^{144}Nd$ is less than 0.5 %.
† $^{143}Nd/^{144}Nd$ normalized to $^{146}Nd/^{144}Nd$ = 0.7219. Within-run error expressed as $2\sigma_m$ in the last significant digits.
§ Initial ε_{Nd} values, calculated using $^{143}Nd/^{144}Nd$ = 0.512638 and $^{147}Sm/^{144}Nd$ = 0.1966. Maximum error is ± 0.4 ε-units.
** Depleted mantle model ages according to the model of DePaolo (1981)

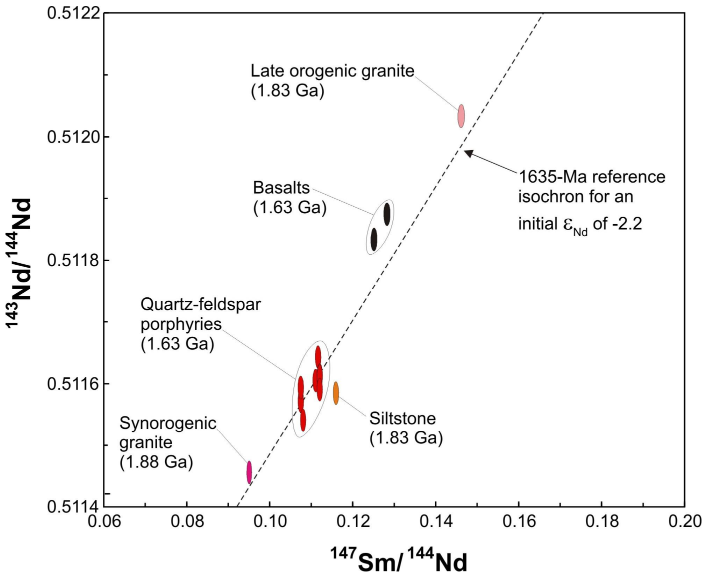

Figure 3. ^{143}Nd/^{144}Nd vs. ^{147}Sm/^{144}Nd diagram for 13 whole-rock samples (Fig. 1, Table 1) from the Island of Suursaari. A reference isochron (based on the U-Pb age and the average initial Nd isotope composition of the silicic porphyries) is also shown. Error ellipses are 2σ.

5. Conclusion

Our new data and field observations show that the bimodal volcanic unit of Suursaari was extruded at about 1635 Ma and is thus coeval with the plutonic rapakivis exposed on the adjacent Finnish mainland. There is no indication of an Archean source for the silicic lavas and the difference in the initial Nd isotope composition of the silicic and mafic lavas implies a more radiogenic signature for the latter. The preservation of the Suursaari volcanic succession probably reflects major block movements at the waning stage of the Wiborg magmatic system that developed within an overall extensional tectonic setting for at least 30-40 m.y.

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Interpretation of wide-angle reflection and refraction recordings of Vibroseis signals and 3D gravity modelling along FIRE4 profile, northern Finland

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This study presents results of interpretation of wide-angle measurement of Vibroseis signals along the southern part of the FIRE4 profile located in the northern Finland. The study was complemented by 3D density modelling of the area around the profile.

Keywords: crust, Fennoscandia, seismic refraction modelling, gravity modelling

1. FIRE experiment in northern Fennoscandian Shield

The Finnish Reflection Experiment (FIRE) was a reflection seismic survey in which data along four profiles was acquired in 2001-2003. Vibroseis sources were used in the measurements. The seismic signals were produced with five vibrator trucks. The applied signal was a linear sweep ranging from 12 to 80 Hz with duration 30 s. The distance between vibration points along line was 100 m. The data quality of the CMP was good (Kukkonen and Lahtinen, 2006).

Along FIRE4 profile also wide angle reflection and refraction survey was made using the same sources as in reflection seismic study. The profile is situated in the northern Finland and it is 235 km long. During this experiment thirteen mobile seismic stations were used. The distance between the stations varied from 12 km to 37 km with average of 21 km. The measurements were carried out during the winter conditions, which made it difficult to find the good places for seismic stations. Therefore only two stations were on the rock. The sampling rate of the mobile stations (Reftek 72A) was 100 samples/s. The seismometers used were Lennartz LE-3D (1 Hz) and of Mark L-4A (2 Hz). The recorded data was stacked, correlated with the sweep signal and processed into recording sections for each recording station. Horizontal stacking in 1 km windows was done to improve signal to noise ratio. At most recording sites first arrivals of P-waves could be observed up to 20-60 km offset distances. Also some secondary arrivals of reflected and refracted P-waves were observed. The quality of S-waves was poor in most recording points.

2. Geology of the study area

The study area is located in northern Fennoscandian Shield with both Archean and early Proterozoic units. It stretches from south to north and crosses Archaean Pudasjärvi Complex, early Proterozoic Peräpohja Schists Belt and Central Lapland Granitoid Complex. The Pudasjärvi Complex is part of Archaean Karelian craton with ages from 3.5 Ga to 2.8 Ga. It is mainly composed of granitoids, migmatites and grey gneisses. The Peräpohja Schist Belt formed about 2.5-1.9 Ga ago. It is a sedimentary basin with terrestrial metasediments and tholeiites (2.5-2.1 Ga) and younger metasediments (2.0-1.9 Ga). The Central Lapland

Granotoid Complex is 2.1-1.8 Ga old and it is mainly composed of granites and pegmatites (Patison et al., 2006).

3. Seismic data interpretation

The first step of the interpretation was picking of phases corresponding to first and second arrivals. Estimated uncertainty of picked times is 0.05-0.1 s. In our study we obtained the P-wave velocity model of the uppermost crust along FIRE4 profile using both travel times of reflected and refracted waves with both forward raytracing, using SEIS83 package (Cerveny and Psencik, 1983) and with graphical interfaces by Komminaho (1998) and Zelt (1994), and inversion using Rayinvr code by Zelt and Smith (1992). The inversion grid was composed of with inversion shell with 10 km horizontal size. The vertical size of shells was distance between upper and lower layer boundary. In the inversion the vertical gradients inside the layers were defined constant while P-wave velocities and layer thicknesses were optimized. Layer boundary smoothing was used.

4. 3D gravity inversion and modelling

The most interesting feature in the velocity model is a zone of high P-wave velocity (about 6.30 km/s) at a depth of about 2-3 km in the middle of the Central Lapland Granitoid Complex. A large-scale maximum of the Bouguer anomaly is also observed above this area. In order to constrain the depth of this feature and explain it in terms of rock composition, modelling and inversion of Bouguer anomaly was applied and a 3D density model of the uppermost crust was calculated for the area around the profile. Interactive Bloxer and Grablox softwares by Pirttijärvi (2004) were used.

The initial model had constant density of 2670 kg/m3 in all but surface layer. In the surface density values were approximated from the petrophysical data of Geological Survey of Finland. First an Occam inversion was used to find a model. In this model main surface geological units can be seen to as well as density maximum inside Central Lapland Granitoid Complex at the same depth as in P-wave velocity model. This body was also modelled with constant densities 2780 kg/m3 and 2800 kg/m3 which have in samples from northern Finland corresponded to P-wave velocity 6.3 km/s (Kern et al. 1993).

5. Results

The maximum model depth of the P-wave velocity is about 5 km (3 km from refractions). The velocity model obtained by forward raytrace model is shown in Fig. 1 (a) and the velocity model obtained by inversion is shown in Fig. 1 (c). Both models demonstrate similar features of velocity distribution within the upper crust and differ only in details.

There are three main layers in the model with near horizontal layer boundaries that can be traced through whole model. The depth of the first boundary is about 0.8 km, while second layer is about 2.5 km deep. There is also one reflector found from some receiver points in the depth of 5-6 km. The major geological units can be seen in the model as horizontal variations in the P-wave velocity. The near surface velocity in the Archaean granitoids, Peräpohja Schist Belt, and Central Lapland Granitoid Complex, are about 6.0 km/s, 5.8 km/s, and 5.9 km/s respectively. Similar horizontal velocity variations were detected also in the second and third layers. There is also a high velocity body inside the Central Lapland Granitoid Complex with P-wave velocity of 6.3 km/s starting at the depth of about 2.5 km and extending all the way to the bottom of the model.

Reflectors detected by the wide-angle data are partly coincident with the reflectors seen in the near-vertical reflection sections. Good coincidence was reached for the central part of the profile, where quality of wide-angle data is better (in particular, for the Central Lapland Granotoid Belt).

The gravity inversion found the same geological units as seismic modelling including the high velocity (density) body inside CLGC. Because Occam inversion is always smoothed also forward modelling was tested with densities corresponding to the P-wave velocity found. The body was located to the depth of 3-6 km.

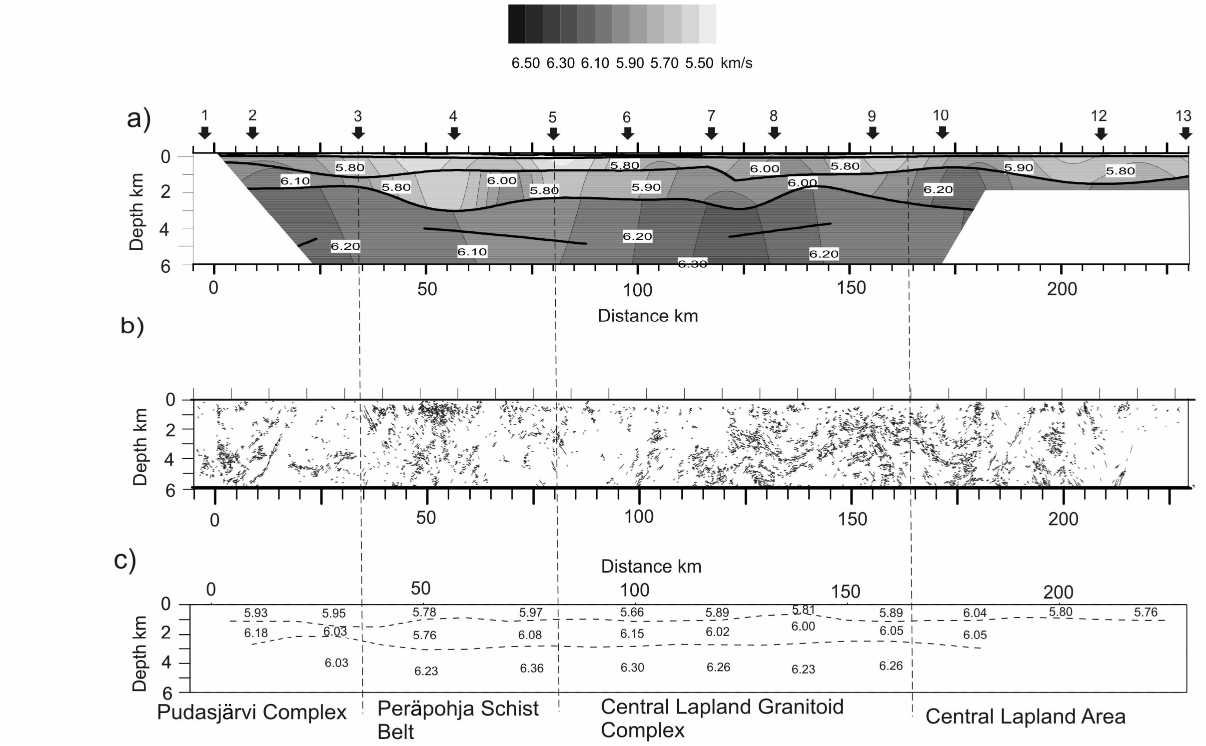

Figure 1. The P-wave velocity models. (a) The ray tracing model of the FIRE4. The receiver points are marked with arrows. (b) The FIRE4 reflection profile on the same area as in wide-angle reflection and refraction model (Patisson et al., 2006). (c) The Rayinvr inversion model of FIRE4. The main geological units are marked below the figures and their boundaries are marked with dashed line throughout all models.

6. Conclusions

1. Recordings of Vibroseis sources registered by 1 Hz and 2 Hz geophones can be effectively used for the purpose of velocity modelling in the uppermost crust.
2. Horizontal stacking of recordings of several Vibroseis sources improves significantly signal- to noise ratios. That makes it possible to recognise not only first arrivals, but also secondary arrivals of reflected and refracted waves.
3. Modelling of reflected and refracted waves makes it possible to obtain P-wave velocity inhomogeneities in the upper crust down to 5 km that correlate well with surface geological units.
4. The method can be used for investigating the velocity structure in the uppermost crust and also as a basis for further research.

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Application of magnetotelluric mini arrays (EMMA project) to study electrical conductivity of the lithosphere

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Two electromagnetic mini arrays (EMMAs) have been employed to investigate electrical conductivity properties of crust and upper mantle of the Fennoscandian Shield in Finland. Arrays consisted of 13 magnetotelluric stations that recorded simultaneously time variations of the Earth's electromagnetic field for nearly 11 months in the EMMA I array in Northern Karelia and for four months in EMMA II array in Kuusamo-Pudasjärvi region in Finland. Site distance was c. 30 km and the period range of measurements extended from 1/300 s to 100.000 s. We use time series data from EMMA I array for (i) horizontal spatial gradient (HSG) analysis and for (ii) examining temporal variations of magnetotelluric transfer functions. HSG analysis use only magnetic data and therefore provides estimates of electromagnetic responses that are not distorted by galvanic effects (static shift). Analysis of temporal variations of magnetotelluric transfer functions shows that one day measurements at any arbitrary time of the year will provide reliable results for periods of 1000 s or shorter. For longer periods recording time must several days or weeks. The results of HSG analysis indicate that upper/middle crust in the Archaean Karelia in the research area has enhanced electrical conductivity on contrary to previous results from other regions of the Archaean crust. Data suggest also the presence of a conducting region at the depth of c.100 km and another below the depth of 250-350 km. The last finding suggests that the base of lithosphere is very deep beneath the eastern part of the cratonic Fennoscandia.

Keywords: Lithosphere, electrical conductivity, magnetotellurics, arrays, HSG, time variations, Fennoscandia

1. Introduction

The EMMA project applies electromagnetic arrays for studying conductivity structure of the Archaean lithosphere in Fennoscandia. Array measurements with simultaneous recordings at several sites allow the application of horizontal spatial gradient (HSG) method for deriving, in addition to magnetotelluric transfer functions, magnetic transfer functions that contain information on subsurface conductivity structure. Magnetic methods have an advantage that they do not use electric field and are therefore free of galvanic distortions (static shift). Hence HSG responses can be used to constrain static shift distorted magnetotelluric responses (apparent resistivities), which makes it possible to provide better estimates on the conductivity structure.

Long duration of recordings (in EMMA case nearly one year) allows the monitoring of the temporal behaviour of electromagnetic transfer functions. Temporal variations might be e.g. due to changes in geomagnetic activity.

We have carried out two long period magnetotelluric surveys situated in the Archaean part of the Fennoscandian Shield (Figure 1). The first array was operated during almost one year, while the second one was running only during summer time. Twelve magnetotelluric instruments, utilizing fluxgate magnetometers, were recording simultaneously five components of Earth's natural electromagnetic field at sites separated by c. 30 km.

In this paper we focus to describe the results of the first HSG-analysis of the EMMA I data set. We also describe the effect of temporal variation in magnetotelluric transfer functions. Yet the analysis of any possible periodic variations will be done in future.

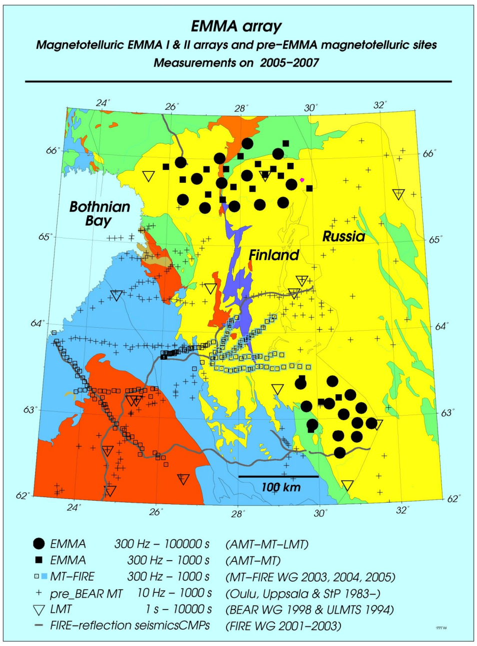

Figure 1. Magnetotelluric EMMA I and II arrays. Array I in North Karelia was operating from Aug 2005 to Jun 2006 and array II in Pudasjärvi-Kuusamo region from Jun 2007 to Sep 2007 consisting of 13 long period measurements (period range 10 - 100000 s). Each site was measured also with AMT-MT instruments (period range 1/300 - 1000 s). Together the two recordings yield data covering a period range from 1/300 s to 100000 s. In array II, additional AMT-MT measurements were carried between long period sites to increase spatial sampling of crustal conductivity. Long period sites are shown by large black dots and AMT-MT sites with smaller black squares. Other sites in the map are other magnetotelluric measurements in the area (e.g. MT-FIRE sites; Vaittinen et al., 2006).

2. Temporal variations of magnetotelluric transfer functions

We have studied temporal variations of magnetotelluric transfer functions for the period of one year by dividing the entire record into one-day-long recordings. The results obtained from one day recordings for the site M02 are presented in Figure 2. We have derived the minimum duration of the recording time to obtain unbiased result at any period of measurements. The bias of the results is estimated relative to final multi-site robust remote reference estimation (red curve in Figure 2). The later one is considered to be unbiased in this case. The results are very close to unbiased estimate, especially phase data. Apparent resistivities seem to be less stable in time. Thus one day measurements at any arbitrary time of the year can be trusted for period shorter than 1000 s. For longer periods recording time must be several days or weeks depending on the longest period that is needed.

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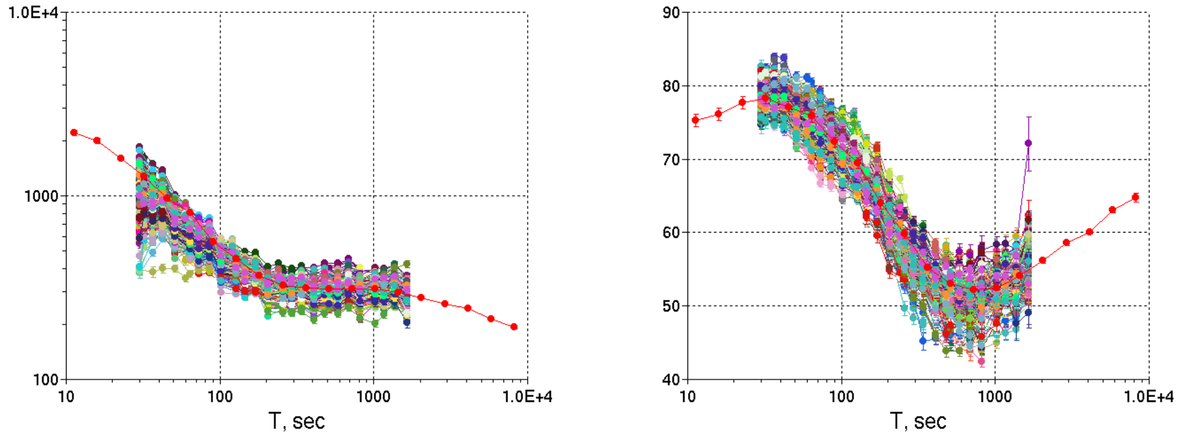

Figure 2. Temporal variations of apparent resistivity and phase during approximately one year. Each of the estimations (shown with different colours) is obtained after processing of one-day -long segment of the entire one year recording. 320 response curves are overlapped in figure. Variations of apparent resistivities and phases can be observed, which can be caused by changes in geomagnetic activity, industrial noise level and statistical variability. Curve with red dots and red solid line denote the final estimate of the entire data set from robust remote reference processing (Smirnov, 2003).

3. Horizontal spatial gradient -method

To better control the source field and to obtain galvanic distortion free responses we have applied horizontal spatial gradient (HSG) method, where only magnetic data (*Hx*, *Hy*, and *Hz*) are used to derive transfer functions. The study area is highly inhomogeneous, thus classical HSG might give erroneous results. The method was extended to include anomalous field effects by implementing multivariate analysis.

Classical univariate HSG-method relates vertical magnetic field *Hz* to the spatial gradients of horizontal magnetic field components as:

$$Hz = C *\{dHx/dx+dHy/dy\},$$

where *C* is TE mode transfer function related to impedance (*Z*=*iwC*). This formulation is valid only for horizontally layered Earth. An extension of the method was proposed by Schmucker (2003) to include anomalous part of electromagnetic field. Thus the complete formulation, which is implemented in this study, is:

$$Hz = C1*\{dHx/dx+dHy/dy\} + C2*\{dHx/dx-dHy/dy\}+C3\{dHx/dy\}+Tx*Hx+Ty*Hy.$$

The system of linear equations may be ill-conditioned; hence we have used SVD technique to estimate *C* transfer function.

3. Conclusions

Analysis of temporal variations of magnetotelluric transfer functions shows that individual estimates from one-day-long recordings are very close to unbiased estimate derived from the entire data set (320 days), especially the phase data. Thus one day measurements at any arbitrary time of the year will provide reliable results for periods of 1000 s or shorter. For longer periods recording time must several days or weeks.

The results of HSG (Figure 3) and 1D analysis of magnetotelluric data (not shown here) indicate that upper/middle crust in the Archaean Karelia in the research area has enhanced electrical conductivity on contrary to previous results from other regions of the Archaean crust. Data suggest also the presence of a conducting region at the depth of c.100 km and another below the depth of 250-350 km (Figure. 3). The last finding suggests that the base of lithosphere is very deep beneath the eastern part of the cratonic Fennoscandia.

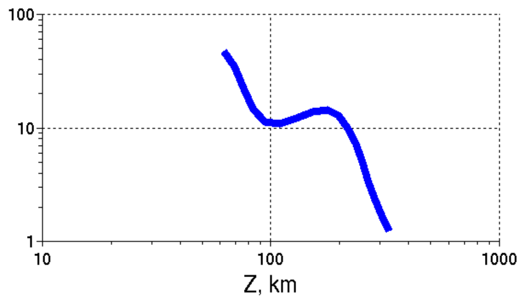

Figure 3. Preliminary resistivity model from 1D inversion of HSG response for the site M02. The HSG response is obtained by solving multivariate problem. Note logarithmic depth scale. Note also that shallower structures (crust) are not show because HSG-analysis has been carried only for periods longer than 1000 s to avoid crustal structures.

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Phase amplitude ratio method in constraining the source parameters of a small earthquake

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On December 13th, 2007 a shallow mining induced earthquake of magnitude M_L=2.1 occurred in the Pyhäsalmi mine, central Finland. The event was recorded by a network of 18 sensors operating inside the mine and also by the Finnish national seismic network, at distances ranging from 90 to 700 km. In this study, we test the reliability of phase amplitude ratio method in constraining the source mechanism and depth of this earthquake. The solution of the local network is used as a "ground truth" data.

Keywords: focal mechanism, amplitude ratio method, mining-induced earthquake, Finland

1. Introduction

The Pyhäsalmi mine in central Finland (Fig. 1) is the deepest underground mine in Europe. The massive sulphide deposits are hosted by hydrothermally altered volcanic rocks (VMS). The volcanic units have tectonic contacts with their surroundings and the area is transected by several sets of faults, which are mainly oriented in NE/SW direction.

On December 13th, 2007 a shallow mining-induced earthquake of magnitude M_L=2.1 occurred in the mine. It was recorded by a mine-wide network of 18 geophones operating within 250 m from the source. The hypocentre was located with an accuracy better than few tens of meters and a well-constrained focal mechanism was determined based solely on first motion polarities of the local sensors. The event was also recorded by the Finnish national seismic network (FNSN), at epicentral distances ranging from 90 to 700 km (Fig. 1). The standard FNSN location placed the epicentre 2.3 km away from the true location, at a depth of 2.1(+/-1.4) km.

In this work, the "ground truth" data from the Pyhäsalmi network is used for testing the reliability of phase amplitude ratios in constraining source mechanism and depth.

2. Phase amplitude ratio method

In Finland, focal mechanisms of micro earthquakes are determined using P-wave polarities together with SV/P and SH/P amplitude ratios (Uski et al., 2003). The FOCMEC code (Snoke et al., 1984) is applied to calculate the set of fault-plane solutions that match both the impulsive polarity and the amplitude ratio data. Among the acceptable solutions, the best-fitting mechanism is the one that minimizes the misfit between observed and calculated amplitude ratios. In addition, synthetic waveform modelling of Rg/S amplitude ratios is used to verify and constrain shallow focal depths (Uski et al., 2006).

3. Results and conclusions

Rg/S amplitude ratios place the focus of the Pyhäsalmi earthquake 1-2 km below the surface. The estimate is in good agreement with the true value. Strong Rg-wave attenuation however limits the use of Rg/S to distances below about 150 km.

Combined use of S/P amplitude ratios and sparse polarity data has significantly constrained the range of possible focal mechanisms. The best-fitting mechanism is consistent with the "ground truth" solution (Fig. 1).

The S/P method is not sensitive to errors of few kilometres in hypocentre parameters. However, the use of refracted phases requires that local velocity distribution is well determined. At critical distances, large differences in take-off angles translate to a scatter of S/P ratios. If possible, S/P measurements close to those distances should be avoided.

The source mechanisms (Fig. 1) imply that the Pyhäsalmi earthquake was caused by downward sliding of talc rich side rock along an older tectonic contact. The faulting was restricted to an area of 100 m x 50 m at a depth of 1.03 km and the displacement was few millimetres. Activation of the fault was initiated by prior mining in vicinity of the northern contact.

Both determinations assume a pure double couple mechanism, which may not be valid for mining induced seismic events. Our next step is to apply full moment tensor inversion to the local waveforms to check whether significant non-double couple component is present.

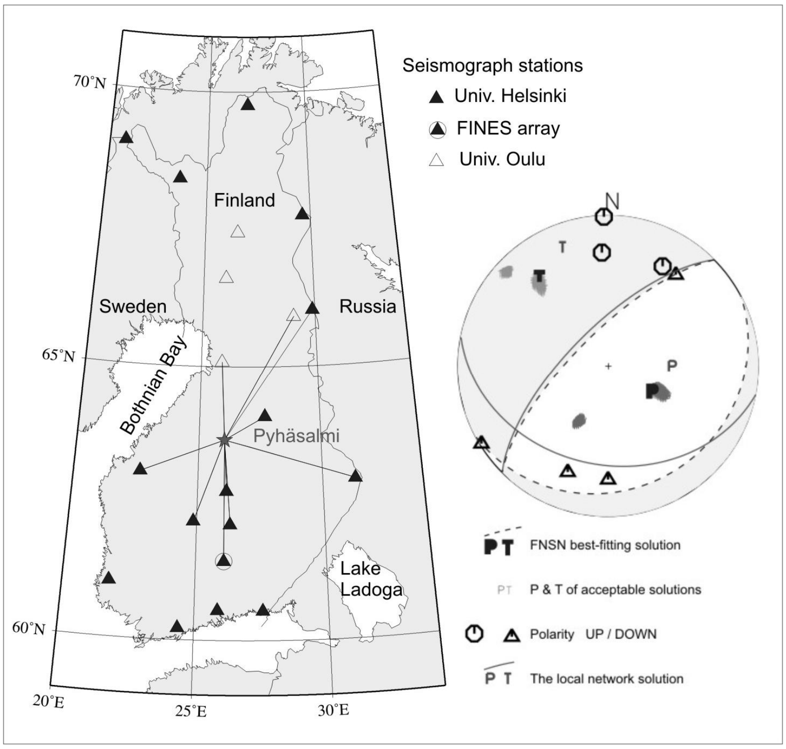

Figure 1. The best-fitting fault plane solution of FNSN (Strike/Dip/Rake = 225/72/-95) in a lower hemisphere stereographic projection. SV/P & SH/P amplitude ratios from 8 stations and 7 clear polarities were used. Take-off angles were computed using a local velocity model. Letter symbols indicate the position of compressional (P) and tensional (T) axes. The local network solution is superimposed. Location of FNSN and the Pyhäsalmi mine is shown on the map; straight lines connect the epicentre to the stations used for event location.

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Electrical conductivity profile of the Central Finland Granitoid Complex western margin by 2D-inversion of magnetotelluric data

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We present conductivity models obtained using 2D-inversion of two magnetotelluric profiles across the Pohjanmaa Belt – Central Finland Granitoid Complex boundary. Main features from the models include SE-dipping conductors in the upper crust, which represent collisional structures of the Pohjanmaa Belt. These conductors are abruptly cut by a large resistive region under the Granitoid Complex. This may indicate that originally conductive graphite- and sulfide-bearing upper crustal metasediments and lower crustal rocks have been deformed by later processes (extensional collapse and intrusion of granites). These processes destroyed the connectivity of conductive phase and made the rocks resistive.

Keywords: magnetotellurics, electrical conductivity, crust, Fennoscandia

1. Introduction

Magnetotellurics is one of the prime methods for acquiring geophysical information at crustal depths. Especially combination of magnetotelluric and reflection seismic methods has proven to be effective in crustal studies (Jones, 1997). Encouraged by this we started the MT-FIRE project with collocated high resolution magnetotelluric soundings with reflection seismic profilings (FIRE project, e.g. Kukkonen et al., 2006). In this paper we focus on the surroundings of the FIRE 3A transect. Previously the area has been studied by magnetometer arrays (Pajunpää, 1987) and magnetotellurics along OULU IV (Vaaraniemi, 1989) and GGT/SVEKA profiles (Lahti et al., 2002). Several conductors have been found by these studies. Crustal conductors in tectonically stable regions, such as the Fennoscandian Shield, often represent ancient collision zones. Enhanced electrical conductivity is caused by for example graphitic or sulphidic metasedimentary rocks (e.g. Korja et al., 1996). Lower crustal conductivity anomalies have been explained mostly by interconnected carbon/graphite or saline fluids (e.g. Haak and Hutton, 1986; Jödicke, 1993; Hyndman et al., 1993).

2. Dataset and Inversion

We have measured 62 new broadband magnetotelluric sites (Fig. 1) across the boundary between the Pohjanmaa Belt (PoB) and the Central Finland Granitoid Complex (CFGC). The measurements form a 230 km long, NW-SE aligned profile (MTF E) along the reflection seismic FIRE 3A transect (Sorjonen-Ward, 2006) and a shorter E-W aligned profile (MTF G). The data covers periods from 0.001 to 1000 s, which corresponds to the depth of investigation ranging from surface to lower crust or even upper mantle. However, due to the fast attenuation of electromagnetic waves in conductive matter, the prominent upper crustal conductors significantly lower the resolution underneath. Thus in very conductive areas we might only be able to determine the top of the conductor and the thickness is left uncertain.

Strike analyses (Bahr, 1988) at most of the sites indicate that the strike is perpendicular to the profile E, which is partly confirmed by surface geology. However, the induction arrows suggest that the strike is perpendicular to MTF E only in the CFGC area where the vectors point to NW. Underneath the PoB – CFGC boundary they turn to SW revealing that the area is generally more 3D than 2D. Thus the model created by 2D inversion is more reliable in the CFGC part of the profile.

Due to lack of consistent geoelectric strike direction along the whole profile we inverted the determinant average of the impedance tensor (Berdichevsky and Dmitriev, 1976) and tipper. In order to reduce possible static distortions phase and tipper were weighted over the apparent resistivity. We used Occam-type inversion code REBOCC (Siripunvaraporn and Egbert, 2000) modified for determinant inversion by Pedersen and Engels (2005).

3. Models and Discussion

The models obtained are shown in Figure 2. Data points are marked with inverted triangles. The two profiles cross each other shortly after the surface boundary of PoB and CFGC, about 80 km from profile E start. The uppermost crust in CFGC area is generally very resistive. There are middle to lower crustal conductors (c. 100 Ωm, marked with A in Fig 2) seen under CFGC in both profiles. The conductive lower crust (B in Fig 2) seems to be present also under the PoB, but due to the smooth nature of Occam inversion it is not clearly distinguishable from the upper crustal conductors (C1-C4). In profile E we see that conductive structures are cut abruptly at about 130 km, and there is about 50 km wide resistive block (D) extending from surface to lower crust.

PoB is characterized by good upper crustal conductors (C1-C4) that dip southeast. It seems that the dip angle as well as depth to the top of these conductors increase towards the end of the profile. The westernmost conductor (C1) flattens at the depth of about 10 km while the conductors at the lithological boundary and under the CFGC (C2-C4) dip to the depth of almost 20 km. These conductors roughly coincide with strong listric reflectors seen in FIRE 3A (Sorjonen-Ward, 2006). Kosunen et al. (2006) interpret these reflectors and the features intersecting them at FIRE 1 as evidence of post-collisional extension related to gravitational collapse of the over-thickened Svecofennian crust. These processes may have destroyed the connectivity of conductive phase and made the rocks resistive (D).

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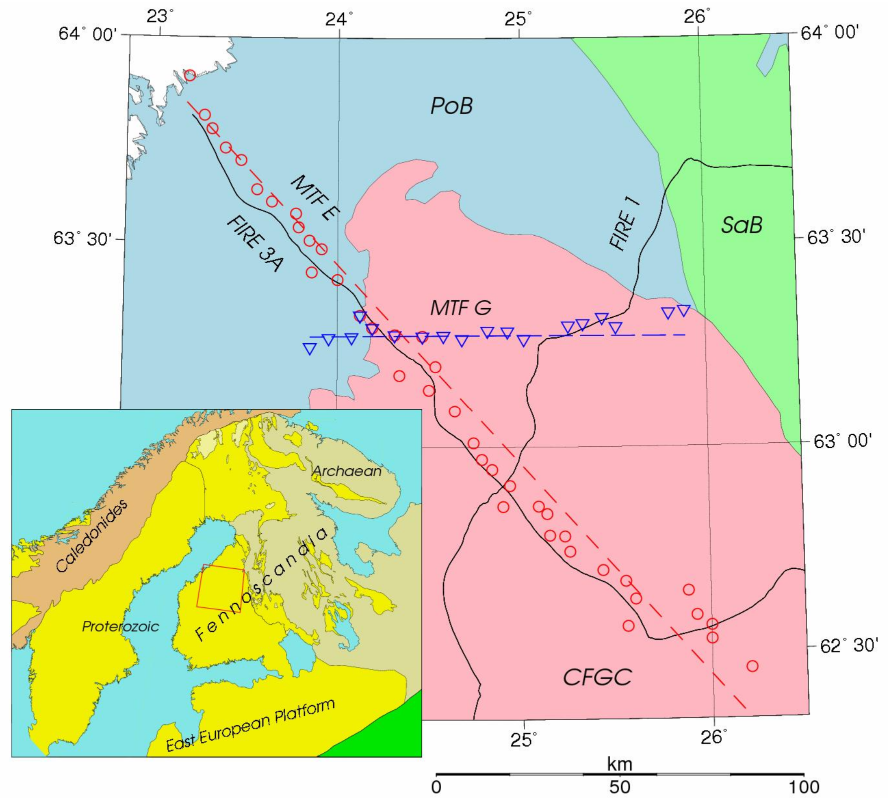
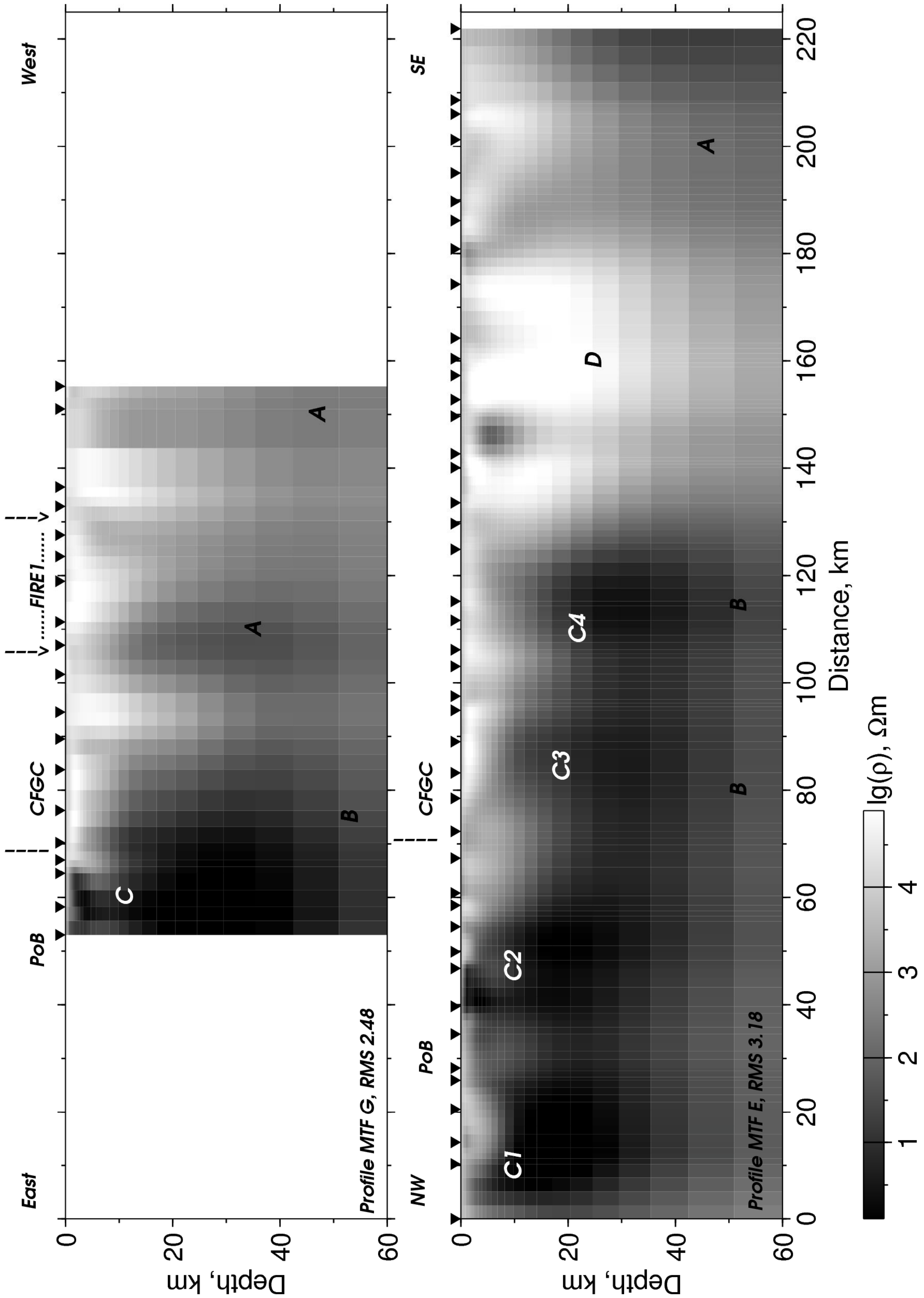


Figure 1. Simplified geology of the study area after Koistinen et al. (2001). PoB = Pohjanmaa Belt, SaB = Savo Belt and CFGC = Central Finland Granitoid Complex. Magnetotelluric sites are marked with circles (MTF E) and inverted triangles (MTF G). Dashed lines represent projected profile along which the inversion was carried out. Locations of reflection seismic FIRE 1 and FIRE 3A profiles are shown with lines.

Figure 2 (next page). Electrical conductivity models acquired by 2D inversion. Above is profile MTF G (west to east) and below profile MTF E (northwest to southeast). Profiles cross each other at about 80 km, and vertical to horizontal scale is 1:1.


East
West
PoB
CFGC
FIRE1
C
A
B
Profile MTF G, RMS 2.48
NW
SE
C1
C2
C3
C4
D
Profile MTF E, RMS 3.18
Depth, km
Distance, km
lg(ρ), Ωm

Time-series analysis of Plio-Pleistocene Prydz Bay sediments for indicating dynamic East Antarctic Ice Sheet behaviour

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The East Antarctic Ice Sheet (EAIS) has existed for more than 34 Ma. During that time it has fluctuated considerably and it has been one of the considerable driving forces of climate and global sea level throughout the Cenozoic era. Warm past climatic optimum e.g. warm middle Pliocene time that was warmer than Present, should be better recognised in Antarctic margin sediments including Prydz Bay. To answer these objectives in this research time-series analysis and cross-validation of physical and clay mineralogical proxies were applied for Plio-Pleistocene continental rise sediments in Prydz Bay, Antactica.

Keywords: Antarctica, physical properties, clay minerals, ice sheet dynamics, climate change

1. Introduction

The East Antarctic Ice sheet (EAIS) has existed for more than 34 Ma. During that time it has fluctuated considerably and also it has been one of the considerable driving forces of climate and global sea level throughout the Cenozoic era (Ehrmann and Mackenzen, 1992; Barret, 1999).

It is well known that polar ice is an important component of the modern climate system, affecting global sea level, ocean circulation and heat transport and marine productivity among other things. Since their inception, the Antarctic ice sheets appear to have been dynamic; waxing and waning in response to global climate change over intermediate and even short (orbital) timescales (e.g., Wise et al.,1991; Zachos et al., 2001; Barker, Camerlenghi, Acton, et al., 1999; DeConto and Pollard, 2003).

Warm past climatic optimum e.g. warm middle Pliocene time that was warmer than Present, should be better recognised in Antarctic margin sediments including Prydz Bay. To answer these objectives in this research time-series analysis and cross-validation of physical and clay mineralogical proxies were applied for Plio-Pleistocene continental rise sediments in Prydz Bay, Antactica. We will present examples of using spectral analysis related to sediment magnetic susceptibility and gamma-ray attenuation porosity/density evaluation (GRAPE) and clay mineral distribution of Ocean Drilling Program Site 1165 on the continental rise, proximal to EAIS of the Prydz Bay.

2. Regional settings and study material

Site 1165 was drilled on the Wild Drift (66°E and 79°E) on the Continental Rise off Prydz Bay, East Antarctica. The site records the number and timing of late Neogene glacier ice expansions to the shelf edge, extending back to the earliest Miocene times (c.a. 22 Ma) (Shipboard Scientific Party, 2001). This study examines existing data on the sediment column (the first 50 metres) which consist of a well-preserved section of Pliocene- to Pleistocene-age (~5Ma) sediments. Time-scale for these sediments is applied from Florindo et al. (2003).

3. Methods

X-ray diffraction (XRD) was performed on oriented clay samples (Junttila et al, 2005) as described by Hardy and Tucker (1988). Magnetic susceptibility was measured from the same discrete samples. Wavelet spectral analysis was performed to smectite content, GRAPE density and magnetic susceptibility to detect possible cyclic behaviour. Analyseries spectral analysis will be used to confirm significant cyclicity.

4. Clay mineral occurrence

In the Early Pliocene the content of smectite mineral tends to dominate the clay fraction frequently suggesting intervals of more open, warmer water than today. In the Middle Pliocene the increasing smectite and decreasing illite content suggest that the ice sheet at that time may have been more dynamic probably warm based. During the Pleistocene low smectite values indicate more polar type of ice sheet conditions.

5. Discussion

There is clear connection to global climate evolution but also active tectonism might have influenced formation of early glaciers in Antarctica. Preliminary ice sheet and climate models suggest that also the elevated topography of the Gamburtsev Subglacial Mountains may play important roles in the evolution of the early ice sheet, and thus, climate.

There is further need to do discussion for interplay with tectonic processes, glacier dynamics and climate change in Prydz Bay margin and hinterland. Preliminary ice sheet and climate models suggest that the elevated topographies and the episodic uplifts might also play an important role in the evolution of the ice sheet.

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Ore forming processes in relation to the tectonic evolution of the Fennoscandian Shield

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Archaean and Palaeoproterozoic plate tectonics probably involved faster moving, hotter plates that accumulated less sediment and contained a thinner section of lithospheric mantle compared to modern processes. This scenario also fits with the complex geodynamic evolution of the Fennoscandian Shield from 2.06 to 1.78 Ga when rapid accretion of island arcs and several microcontinent–continent collisions in a complex array of orogens was manifested in short-lived but intense orogenies involving voluminous magmatism. With a few exceptions, all major ore deposits formed in specific tectonic settings between 2.1 and 1.8 Ga (Weihed et al. 2005).

In the Fennoscandian Shield the Neoarchaean is different. Globally the formation of major Neoarchaean VMS, orogenic gold, and Ni–PGE mineralization seems to be restricted to the period ca. 2.74 to 2.69 Ga and to corresponds to a period of intense intrabasinal mantle plumes and a subsequent global plume-breakout event (Barley et al. 1998). The obvious lack of major Neoarchaean mineralization in the Fennoscandian Shield could possibly be explained by the age of Neoarchaean greenstone belts. Most of the Fennoscandian greenstone belts seem to be slightly older than the global Neoarchaean peak in mineralization and mantle plume activity (e.g., Huhma et al. 1999) and, hence, magmatism and hydrothermal activity might have been less intense and unable to form major metal deposits. This could also explain the lack of major lode gold deposits related to subsequent accretion during peak orogeny. Hence, although there is evidence for Neoarchaean greenstone belts formed through the accretion of oceanic crust, oceanic plateaux and island arcs and those formed through flood volcanism on an older continental basement, they apparently do not contain major ore deposits in the Fennoscandian Shield, or they remain to be discovered.

Orogenic gold deposits in the Fennoscandian Shield formed syn- to post-peak metamorphism. The age of the deposits reflects orogenic younging towards the SW and west. Most orogenic gold deposits formed during periods of crustal shortening with peaks at 2.72 to 2.67 Ga, 1.90 to 1.86 Ga, and 1.85 to 1.79 Ga (Weihed et al. 2005).

2.5 to 2.4 Ga Ni–Cu±PGE deposits formed both as part of layered igneous complexes and associated with mafic volcanism, in basins formed during rifting of the Archaean craton. Svecokarelian ca.1.89 to 1.88 Ga Ni–Cu deposits are related to mafic–ultramafic rocks intruded along linear belts at the accretionary margins of microcratons.

All major VMS deposits in the Fennoscandian Shield formed between 1.97 and 1.88 Ga, in extensional settings, prior to basin inversion and accretion (Weihed et al. 2005). The oldest massive sulphide accumulations, the Outokumpu type, seems not to be exhalative but rather represent deep levels of subseafloor hydrothermal convection in the subcontinental lithospheric mantle (Sorjonen-Ward et al. 2004). The Pyhäsalmi VMS deposits formed at 1.93 to 1.91 Ga in primitive, bimodal arc complexes during extension of the arc. In contrast, the

Skellefte VMS deposits are 20 to 30 million years younger and formed in a strongly extensional intra-arc region that developed on continental or mature arc crust. Deposits in the Bergslagen–Uusimaa belt are similar in age to the Skellefte deposits and formed in a microcraton that collided with the Karelian craton at ca. 1.88 to 1.87 Ga. The Bergslagen–Uusimaa belt is interpreted as an intra-continental, or continental margin back-arc, extensional region developed on older continental crust.

Iron oxide-copper-gold (IOCG) deposits are diverse in style. At least the oldest mineralizing stages, at ca. 1.88 Ga, are coeval with calc-alkaline to monzonitic magmatism and coeval and possibly cogenetic subaerial volcanism more akin to continental arcs or to magmatic arcs inboard of the active subduction zone. Younger mineralization of similar style took place when S-type magmatism occurred at ca. 1.80 to 1.77 Ga during cratonization distal to the active N–S-trending subduction zone in the west. Possibly, interaction of magmatic fluids with evaporitic sequences in older rift sequences was important for ore formation (Martinsson & Weihed, 1999).

Large volumes of anorthositic magmas that characterize the Sveconorwegian Orogeny formed a major concentration of Ti in the SW part of the Sveconorwegian orogenic belt under granulite facies conditions, about 40 million years after the last regional deformation of the Sveconorwegian Orogeny, between ca. 930 and 920 Ma (Weihed et al. 2005 and references therein).

In summary the metallogeny of the Fennoscandian Shield is characterized by intense mineralization in the Palaeoproterozoic and less so in the Archaean. The concentration of metals by various processes is ultimately related to plate tectonic processes that in the Proterozoic were similar to modern day plate tectonics.

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Biotite and fluorapatite macrocrysts in Paleoproterozoic lamprophyres in Fennoscandia: xenocrysts from the subcontinental lithospheric mantle?

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We have analysed biotite and fluorapatite from Paleoproterozoic lamprophyres in Fennoscandia with the electron microprobe. The mineral chemistry of biotite macrocryst cores implies that they did not crystallise from the lamprophyric magma. Geothermobarometric results indicate that they crystallised at upper mantle temperatures and pressures. Matrix biotite/phlogopite is both Al-poor and Ti- and Ba-rich, typical of lamprophyric micas worldwide. Fluorapatite macrocrysts are typically euhedral, REE-enriched with positive Eu anomalies. Matrix grains have similar REE enrichment, but are skeletal and lack Eu anomalies. We suggest that the biotite and fluorapatite macrocrysts are in fact xenocrysts from the subcontinental lithospheric mantle.

Keywords: apatite, biotite, Fennoscandia, lamprophyre, xenocryst

1. Introduction

Lamprophyres are mafic to ultramafic dyke rocks, which commonly contain macrocrystic grains of mica (biotite or phlogopite) together with olivine, clinopyroxene, amphibole or apatite. Rock (1991) outlined a six-tier hierarchy of lamprophyre mineralogy from fully cognate groundmass grains to fully xenocrystic grains. Zoned grains are common, representing overgrowth crystallisation from the magma onto xenocrystic or earlier-formed phenocrystic cores.

Paleoproterozoic shoshonitic lamprophyres occur in several locations in Fennoscandia. They occur both in direct association with shoshonitic granitoids or as isolated dyke swarms (Konopelko 1997, Eklund et al. 1998). For this study, we have examined samples from the Lake Syväri region of eastern Finland and the northwest Ladoga region of Russian Karelia.

2. Analytical method

Mineral analyses were performed at the Institut für Mineralogie, TU-Clausthal on a Cameca SX-100 electron microprobe equipped with four wavelength dispersive spectrometers. A 5µm beam diameter was used with an accelerating voltage of 15 kV and a beam current of 15 nA. The lower beam energy minimizes uncertainties arising from non-reversible excitation of F x-rays (Stormer et al. 1993) as well as interferences from lower order L- and M-lines, which are particularly problematic for the REE analyses (Pyle et al. 2002, 2005). Peak counting times were 10-20 s for major elements and up to 540 s for trace elements. Elements subject to volatilisation (e.g. F, Na, K, Cl) were measured at the beginning of each analysis. Each element was calibrated using a selection of natural and synthetic standards, and the Cameca PAP correction procedure (Pouchou and Pichoir 1985) was used for data reduction. The Durango apatite standard was also measured in order to test the external precision of the calibrations and analytical routine, with good reproducibility and agreement with published values.

3. Results and discussion

Biotite macrocrysts typically exhibit core-to-rim zoning, appearing progressively brighter towards the rims in BSE images. The cores have low Mg# (65-75) and are relatively enriched in Si, K and F. A gradational increase outwards in Mg#, Ti, Al and Ba is observed near the rims. Matrix biotite/phlogopite has the same composition as the outer rims of the macrocrysts. Lamprophyric micas typically have much higher Mg#, decreasing from core to rim in zoned grains (e.g. Rock 1991, Sheppard and Taylor 1992, Meyer et al. 1994). However, mica of similar composition (Mg# 65-75, low Al) has been reported as representing the earliest stage of crystallisation from carbonatite melt (McCormick and Le Bas 1996). Similar biotite could crystallise in the mantle as a result of carbonatite metasomatism. We propose that the mica macrocrysts are xenocrysts, which have been entrained by and equilibrated with the lamprophyric magma in the source region.

We have used the TiO_2-liquid geothermometer and the BaO geobarometer of Righter and Carmichael (1996) to estimate *P-T* conditions of biotite crystallisation (Figure 1). Our pressure calculations for the Ladoga region assume a low $a(H_2O)$, as Andersson et al. (2006) have suggested that these fluids were CO_2-dominated. Assuming a CO_2/H_2O ratio of 0.8 results in emplacement pressures of 1-2 kbar from matrix grains, which is in accordance with previous barometric results from this area (Niiranen 2000). For the Lake Syväri region, our calculations assume $a(H_2O) = 1$, as this results in minimum pressures.

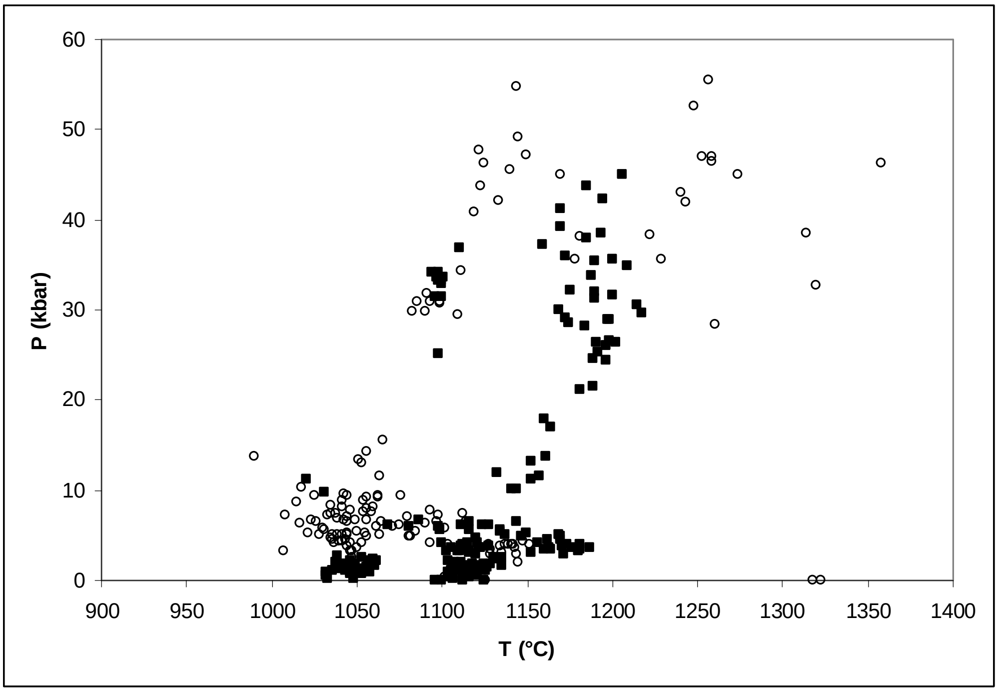

Figure 1. *P-T* diagram for the lamprophyre biotite/phlogopite. Open circles: Lake Syväri region, eastern Finland; solid squares: NW Ladoga region, Russian Karelia.

Two distinct generations of fluorapatite may be identified petrographically. Although there is no distinct difference in grain size between the two generations, we refer to one as macrocrysts and the other as matrix grains, based on their morphological and chemical properties. Macrocrysts appear as euhedral to partially rounded subhedral grains. They are distinctly REE-enriched, with REE curves having a slight negative slope and a positive Eu anomaly (Figure 2a). Analytical totals for these grains are consistently below 100%, indicating the presence of a volatile component that could not be measured with the microprobe, which we suspect to be CO_3^{2-}. Belousova et al. (2002) examined apatites from a wide range of parageneses, and reported positive Eu anomalies only from samples of mantle lherzolite. O'Reilly and Griffin (2000), describing the same apatite samples, reported the presence of CO_3^{2-} substituting for PO_4^{3-}. These apatites crystallised as a result of mantle metasomatism by a hydrous (~10% H_2O) carbonatite melt (O'Reilly and Griffin 2000).

The fluorapatite macrocrysts also commonly contain small (> 5μm), elongate inclusions of monazite and possible bastnäsite, typically oriented crystallographically along the c axis. Similar fluorapatite, with inclusion assemblages of monazite, bastnäsite, quartz, calcite and magnetite, is also found in Fennoscandian carbonatites (Woodard and Hetherington 2006). These inclusion assemblages probably formed via autometasomatitic reaction with the magmatic fluid. Dissolution of a primary phase coupled with the reprecipitation of a new phase or phase assemblage is the primary mechanism for fluid induced mineral replacement reactions (Putnis 2002). Experimental results (Harlov et al. 2002, Harlov and Förster 2003, Harlov et al. 2003) show that nucleation of monazite inclusions in apatite may be induced metasomatically.

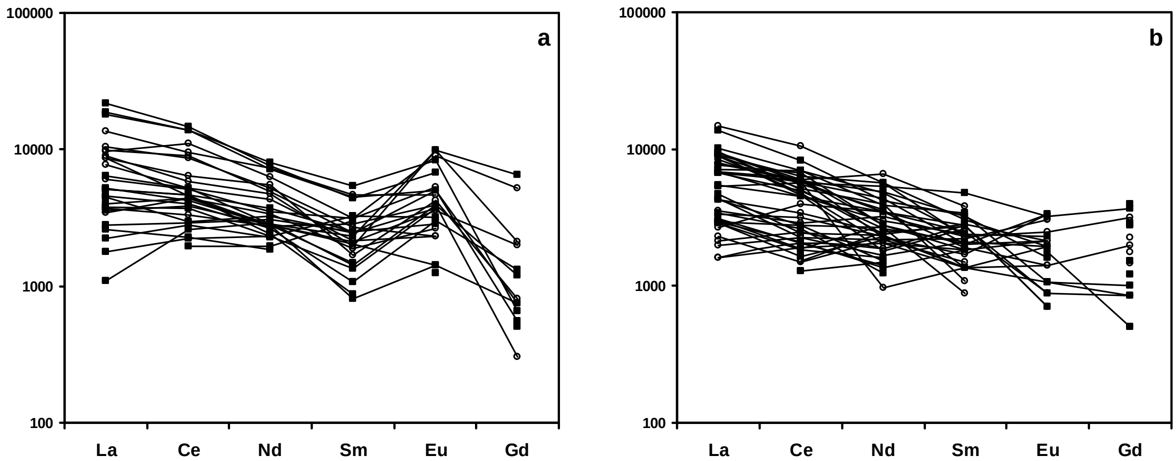

Figure 2. Chondrite-normalised (McDonough and Sun 1995) REE curves for a. fluorapatite macrocrysts and b. matrix fluorapatites.

Matrix grains are long, needle-shaped and skeletal, which is the result of rapid crystallisation at emplacement. During fractional crystallisation, it may be expected that late apatite would have lower concentrations of REE, as well as flatter REE curves. Instead, the matrix grains exhibit similar a degree of REE enrichment; the most noticeable difference is the lack of Eu anomalies (Figure 2b). In addition, unlike the macrocrysts, analysis totals for these grains are consistently around 100%. These data imply that the fluorapatite macrocrysts are also xenocrystic with respect to the lamprophyric magma.

4. Conclusions

The textural and chemical characteristics of the biotite and fluorapatite macrocrysts indicate that they did not likely crystallise from the lamprophyric magma. Instead, comparison with the literature indicates that they likely crystallised as a result of carbonatite metasomatism in the subcontinental lithospheric mantle. The grains were then entrained as xenocrysts withiin the lamprophyric magma and emplaced into the upper crust.

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