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Svalbard
Barents Sea
Atlantic
Ocean
Caledonides
SVEKALAPKO
Pechora
Basin
Timanides
East-European Craton
V a r i s c i d e s
Pericaspian
Basin
Alps
Carpathians
Black Sea
Caspian Sea
Mediterranean

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Evolution of Palaeoproterozoic and Archaean Lithosphere

by Sven-Erik Hjelt (Oulu), Stephen Daly (Dublin) and SVEKALAPKO colleagues

One of the best places on Earth for studying the thermal and mechanical processes controlling the evolution of ancient lithosphere is the Fennoscandian Shield. This well-exposed, composite craton, cored by the Late Archaean granite-greenstone Karelian belt, and flanked to the northeast and southwest by Palaeoproterozoic orogens, is ideal terrain for testing plate tectonic theory and seeking to understand the contrasted signatures of Archaean and Proterozoic lithosphere. Ophiolites, magmatic arcs, fore- and back-arc basins and accretionary wedges are identified with confidence in the Proterozoic; their presence in the Archaean is conjectural. The Svecofennian Orogen, dominating much of Finland and Sweden, resulted in the accretion of vast volumes of thick juvenile crust; by contrast, in Russia north of Karelia, the Lapland-Kola Orogen is predominantly composed of Archaean crust, reworked during the Palaeoproterozoic.

A considerable geological, geochemical and geophysical data base provides the foundation for focused new EUROPROBE investigations. Deep seismic refraction profiles have defined the velocity structure of the shield; shallow CMP reflection profiles in Russia give unique insight into upper crustal structure. Deep and superdeep drillholes (including Kola) provide exceptional opportunities for calibrating further geophysical data.

EUROPROBE'S multidisciplinary investigation of the Fennoscandian Shield SVEKALAPKO: (SVEcofennian-KArelia-LAPland-KOla) focuses on the following key issues:

1) Establishing the character of the deep lithosphere (lower crust and upper mantle) and its relationship to the asthenosphere below the different parts (Lapland-Kola, Karelia and Svecofennia) of the Fennoscandian Shield. The latter provides unusually favourable bedrock conditions for major geophysical experiments aimed at defining lithosphere-asthenosphere relationships, particularly electromagnetic probing and deep tomography studies. An important target is the deep structure of the highly anomalous (c. 60 km thick) juvenile Svecofennian crust, where correlation with gravity data and topographic relief are lacking.
2) Defining the crustal evolution across the Shield to establish the timing of formation of the different major structures and their relationship to the underlying deeper lithosphere; this will provide insight into ore genesis and contribute to further exploration efforts. Particular interest concerns:

a) The Archaean evolution of the Karelian terrane and the extent to which it has been reworked in post-Archaean time.
b) The Proterozoic suturing, with the local preservation of ophiolites and prominent boundaries between reworked Archaean and juvenile Proterozoic rocks.
c) The evidence for subduction-related magmatism and development of Proterozoic fore- and back-arc basins.
d) The analysis of crustal and upper mantle xenoliths.
e) The effects of Palaeozoic (Devonian), potentially plume-related magmatism on lithospheric structure of the Kola-White Sea areas.

The Fennoscandian Shield is a key element in the reconstruction of the Laurussian mega-continent. EUROPROBE studies will promote integration with Canadian Lithoprobe geoscience.

Introduction

Plate tectonic processes, comparable to those operating today, can be inferred to have controlled the evolution of the lithosphere far back through the Phanerozoic and Proterozoic, maybe into the Archaean. Nevertheless, the resulting crust and upper mantle of ancient cratons differ greatly from that of Phanerozoic counterparts. These contrasted signatures of the young and old lithosphere reflect significant differences in mantle heat flow and geochemical evolution. Smaller volumes of craton crust and greater turbulence of hotter mantle during Earth's early history, probably imply less well developed, stable subduction systems and more haphazard interaction of cratons. Collisional thickening and extensional collapse were perhaps less dramatic in the Archaean than in Palaeoproterozoic and Phanerozoic orogens.

The Fennoscandian Shield is one of the best places on Earth for studying the tectonic processes controlling the evolution of Late Archaean and Early Proterozoic lithosphere. Recent geophysical studies have revealed marked contrasts in the crustal thickness and composition across the shield. Structural and geochronological studies have shown that these differences can be correlated with the near surface geology.

The Fennoscandian Shield is dominated by three major provinces. In the north, the crust is largely of Late Archaean age, extensively reworked during the Palaeoproterozoic; it composes the Lapland-Kola Orogen. Collisional thickening was followed by rapid rebound and exhumation of deep crust. In contrast, in the southern Fennoscandian Shield, the Svecofennian Orogen comprises juvenile Palaeoproterozoic crust, distinguished by low-pressure metamorphism and regions underlain by some of the thickest (up to 60 km) crust in Europe. The intervening Archaean Karelian Province, a cratonic buttress against which these two orogens were moulded, apparently experienced little tectonic reworking, except along its margins.

The region of thickest crust lacks topographic and gravity expressions or evidence of important post-Svecofennian tectonothermal activity. The deep signatures we register today apparently result from processes that formed the Palaeoproterozoic and Archaean lithosphere.

EUROPROBE'S multidisciplinary SVEKALAPKO project is investigating the deep and shallow structures across the Fennoscandian Shield. Studies are designed to define the upper crustal evolution and correlate this with the evidence from the deep crust and upper mantle, as seen in the geophysical signatures, xenolith studies and geochemistry of intrusions. SVEKALAPKO will throw new light on differences between Phanerozoic and Palaeoproterozoic plate tectonics and the extent to which the Archaean thermomechanical evolution can be interpreted in terms of this global paradigm.

Development of the Research Plan

Research institutes in the Czech Republic, Denmark, Estonia, Finland, France, Germany, Ireland, Netherlands, Norway, Russia, Spain, Sweden, Switzerland, United Kingdom and USA are collaborating in the SVEKALAPKO program. Scientific plans were outlined during EUROPROBE meetings at Bad Herrenalb (1993) and Rastatt (1994). Subsequent workshops at St. Petersburg (1994 and 1995) developed the integrated multidisciplinary programme and the various multinational sub-projects that address specific aspects of the program.

Geoscientific Framework

The Fennoscandian Shield is the major exposure of Precambrian crust in northern Europe and comprises the largest part of Fennoscandia - one of the three crustal segments of the East-European Craton. (Fig. 5.1). The geology and tectonics have been described by many authors (e.g. Balagansky et al., 1995; Boyd et al., 1985; Gaál and Gorbatschev, 1987; Gorbatschev, 1993 and references therein; Haapala and Rämö, 1992; Huhma, 1986; Kontinen, 1987; Korja et al., 1993; Lahtinen, 1994; Lobach-Zhuchenko et al., 1993; Miller, 1987; Mitrofanov, 1995 and references therein; Patchett et al. 1987; Valbracht et al., 1994; Vuollo, 1994). The Shield is dominated by the Svecofennian Orogen (Fig. 5.1), a major development of Palaeoproterozoic juvenile crust. The northern part of the Shield is underlain by late Archaean rocks (Fig. 5.1), extensively reworked during the Palaeoproterozoic in the Lapland-Kola Orogen and to a lesser extent in Karelia. Younger terranes such as the Gothian occur to the west in Sweden and these are partially reworked during Sveconorwegian orogeny (c. 1000 Ma). Models emerging from the European Geotraverse (Blundell et al., 1992), the GGT/SVEKA project (Korsman and Korja, 1996) and IGCP projects 275 (Gorbatschev, 1993) and 371 (Brewer, 1996) suggest that crustal assembly took place during the Palaeoproterozoic, when the Shield was an integral part of a growing megacontinent. The region has important metal resources and prospects, principally of Fe, Cu, Zn, Ni, Pt and Au. Recent discovery of diamonds has led to renewed exploration.

Lapland-Kola Orogen

The Lapland-Kola Orogen, occupying northeastern parts of the Shield (Fig. 5.1), comprises a series of late Archaean terranes variably re-worked during the Palaeoproterozoic. The Murmansk, Central Kola and Belomorian composite terranes (Fig. 5.2a) contain late Archaean orthogneisses and subordinate metasediments and metabasites. The Archaean terranes are bounded by Palaeoproterozoic high strain zones and well-preserved volcanic rift basins, such as the Pechenga and Imandra-Varzuga Belts. Crust formation took place between 2.7 - 2.9 Ga during the Lopian orogeny. Deformation and metamorphism in the Late Archaean (2.7-2.8 Ga) was followed by cooling and uplift before rifting of the Archaean basement began at about 2.45 Ga, e.g. in the Kolvitsa Belt. Palaeoproterozoic deformation and high grade metamorphism at 1.9-2.0 Ga involved southward thrusting along shallow dipping high strain zones towards the Karelian Province and later transcurrent movements. In marked contrast to the Svecofennian, the Lapland-Kola Orogen contains only minor amounts of juvenile crust at the present erosion level. A significant exception is the Lapland Granulite Belt, which contains juvenile Palaeoproterozoic crust, presumably formed in an arc setting. Together with the Kolvitsa Belt and the Umba Granulite Terrane (Fig. 5.2a), it may comprise a major Palaeoproterozoic suture. The entire region constitutes a Palaeoproterozoic collisional orogen with the Murmansk terrane and the Karelian Province making up the opposing margins (Fig. 5.2b).

Karelian Province

The Karelian Province at the southern margin of the Lapland-Kola orogen is a late Archaean granite-greenstone terrane. A few localities have yielded "Saamian" ages, as old as 3.1 Ga, but much of the terrane formed about 2.8 Ga ago and was intruded by 2.74-2.68 Ga granitoids. The Karelian Province appears to have acted as the foreland both during late Archaean deformation in the Belomorian terrane and also when Palaeoproterozoic structures of the Lapland-Kola Orogen formed. The southwestern margin of the Karelian Province is a well-defined NW-SE oriented collisional zone where the margin is over-ridden by the Svecofennian island arc complex to the southwest.

Svecofennian Orogen

Rifting of both the Karelian and Kola Archaean continents took place in two phases at c. 2.45 and 2.2-2.0 Ga leading to the development of a passive margin with shelf sediments and tholeiitic magmatism. Formation of oceanic crust is manifested by 1.97 Ga ophiolites (Fig. 5.1), although their tectonic setting is unclear.

The earliest events associated with the Svecofennian orogeny are poorly known, but detrital zircon ages and Sm-Nd data suggest the existence of continental crust 2.1-1.93 Ga ago. A complex, 1.93 - 1.91 Ga old, arc system collided at 1.9 Ga with the Archaean craton margin, leading to thickening of the crust and reactivation of the Archaean craton margin (the Ladoga-Bothnian Bay zone, Fig. 5.3). The main phase of Svecofennian magmatism (1.89-1.88 Ga) was associated with high T - low P metamorphism possibly accompanied by delamination of the lithosphere and magmatic underplating.

A younger high T - low P collisional belt, extending from southeastern Finland to central Sweden, is associated with 1.84-1.81 Ga late-Svecofennian potassic granites, produced in part by crustal melting. Large volumes of slightly younger potassic granitoids (1.80 Ga) occur in northern Sweden. Minor post-orogenic granites (1.81-1.77 Ga) and lamprophyre dykes (1.84-

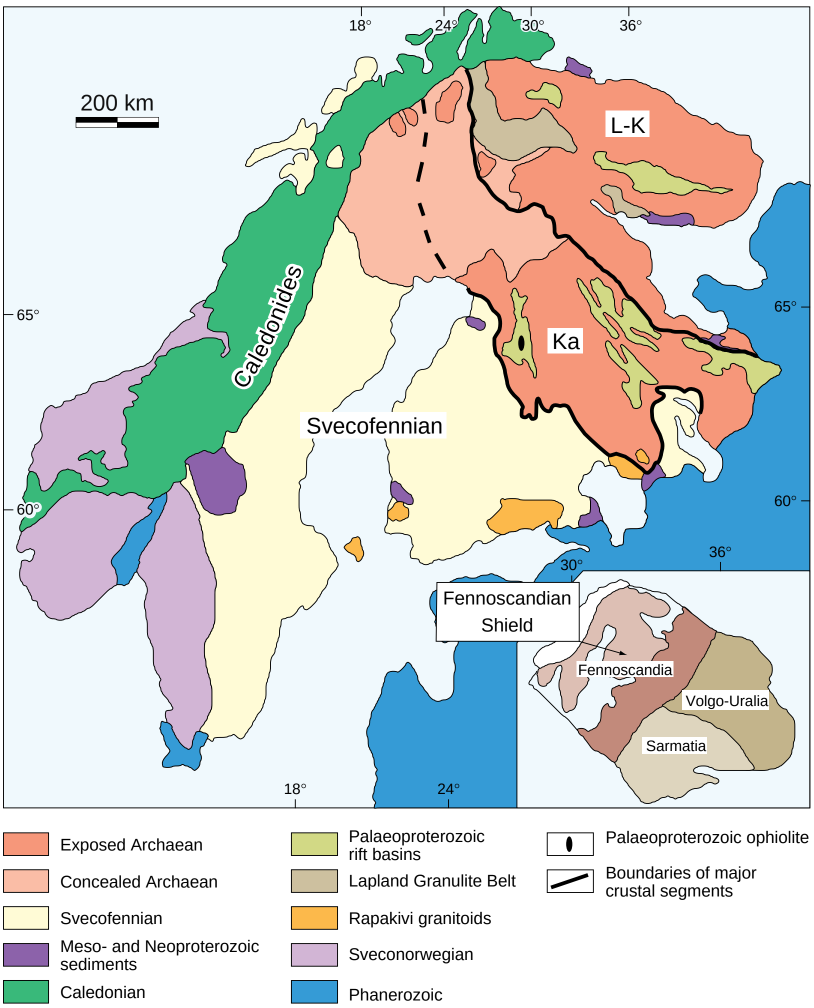

Figure 5.1: Simplified geological map of the Baltic Shield and surroundings (modified from Boyd et al., 1985 and Öhlander et al., in Gorbatschev, 1993; inset showing the subdivision of the East-European Craton from Gorbatschev and Bogdanova, in Gorbatschev, 1993). Generalized tectonic boundaries between the Lapland-Kola Orogen (L-K) and the Karelian Province (Ka) and between the latter and the Svecofennian Orogen are shown as heavy lines, dashed to indicate greater uncertainty. Proterozoic rift basins are omitted in the region labelled 'concealed Archaean'.

1.80 Ga) in southern Finland may have been associated with incipient rifting.
Anorogenic Rapakivi magmatism and coeval mafic dykes (1.65-1.54 Ga) probably represent incipient rifting of the Svecofennian crust that was followed by deposition of the Jotnian sandstone in continental extensional basins. Intrusion of post-Jotnian diabases at c. 1.26 Ga is related to the final major tectonic event to have affected the orogen. Subsequently, only sporadic dykes and alkaline intrusions, including diamond-bearing diatremes, have disrupted the craton, the latest apparently of Devonian age.

Previous geophysical research

Few major areas in Europe have such comprehensive coverage of high quality geophysical data as the Fennoscandian Shield. Numerous parallel and intersecting seismic refraction surveys with up to 1800 km offset, gravity and magnetic data and information on the electrical conductivity, geothermal and rheological properties of the upper crust provide details on the physical properties of the entire crust and a gross picture of the lower lithosphere and asthenosphere (a.o. BABEL Working Group, 1993; Babuska et al., 1988; Blundell et al., 1992 and references therein; Elo, 1989; Glaznev et al., 1992; Guggisberg and Berthelsen, 1987; Korhonen, 1987; Korja and Hjelt, 1993 and references therein; Korja et al., 1993; Korja and Heikkinen, 1995; Kukkonen, 1993; Luosto, 1991; Velikhov et al., 1994).

Seismics

Although much of the Fennoscandian Shield has a flat topography, seismic studies indicate that the variations of crustal thickness (Fig. 5.4) are comparable to those found in active orogenic belts. Moho depth ranges between 40 and up to more than 60 km in the Svecofennian Orogen. Most of these variations are associated with a moderately reflecting high-velocity (v_p 7.0 - 7.4 km/s) lower crustal layer (Fig. 5.3), overlying a mantle with a velocity of c. 8.2 km/s. The combined upper and middle crust (with v_p up to 6.8 km/s at the base of the middle crust), in contrast, has a relatively uniform thickness of 30-35 km throughout the region.
Anomalous thinning of the crust occurs along sets of listric shear zones that sole into detachments at two different levels: at the base of the middle crust and at the Moho. Laminated reflectivity in the lower crust and a strongly reflective subhorizontal Moho characterize these areas of relatively thin crust. The Ladoga-Bothnian Bay Zone, which has been involved in the thrusting of the Svecofennian Orogen onto the Karelian Province, is less reflective. The Karelian Province is underlain by a thin high-velocity (v_p > 7 km/s), reflective layer in the lowermost crust and the Moho is at about 43 km. Seismic reflection studies on land (Fig. 5.5) across major geological structures have been initiated only recently.
In contrast to the well-constrained crustal data, the lithosphere thickness is much less well known. Low resolution surface wave and body wave studies suggest thickening from the southern border of the Shield in Sweden to the central Proterozoic and Archaean part in Finland and thinning again towards the Atlantic and Arctic Oceans.

Potential field properties

In the Kola Peninsula, the middle crust has a reduced density in an area coinciding with a regional

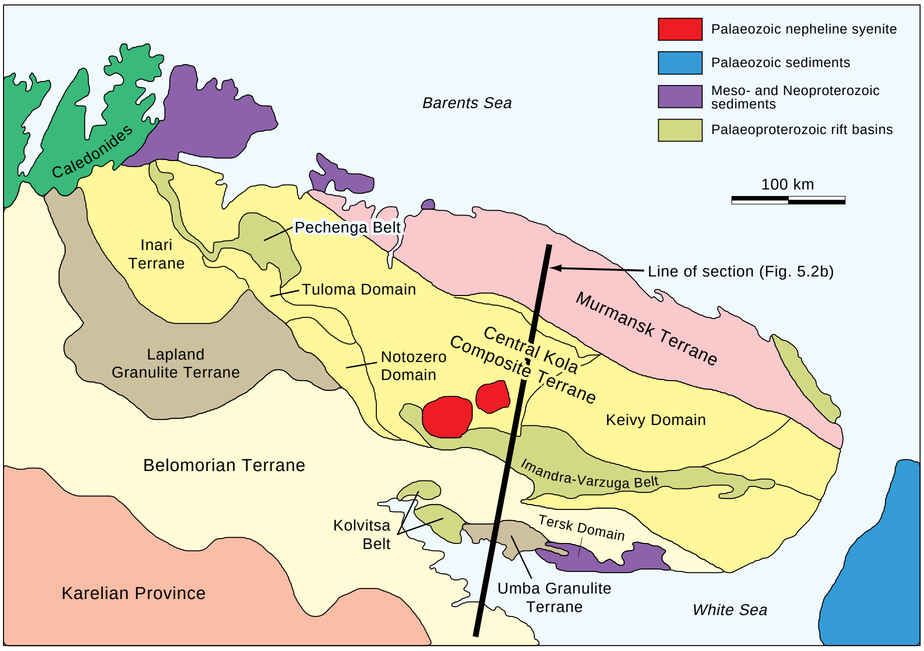

Figure 5.2a: Tectonostratigraphic terranes in the Lapland-Kola Orogen from Balagansky and Glaznev (pers. comm. 1994) and incorporating data from Marker (in Blundell et al., 1992).

magnetic anomaly below the Keivy block (Fig. 5.2a). The lower crust beneath the White Sea and central part of the Belomorian Terrane has a transitional layer with increased thickness and increased density. This layer has been explained to result from tectonic stacking of the Belomorian Terrane either in the Archaean or in the Palaeoproterozoic and subsequent crust-mantle readjustment either during the Riphean or during the Palaeozoic, when kimberlite pipes were emplaced. Further details of major structures within the Lapland-Kola Orogen are obtained by 3-D modelling.

The gravity field and surface topography of the Fennoscandian Shield do not correlate with the marked variations in Moho topography. This has been explained as due to phase transitions of mafic rocks to eclogites, implying the absence of an important density contrast at the Moho.

High-altitude aeromagnetic data, together with results from magnetic modelling of the Fennolora seismic profile, indicate a more magnetized deeper crust in the Svecofennian region compared to the Archaean of Karelia. Patterns of linear magnetic anomalies are indicative of fractured upper crust and/or regions intruded by numerous mafic dykes. In some areas (e.g. in the highly fractured Ladoga-Bothnian Bay Zone, Fig. 5.3) both magnetic and gravity lineaments indicate lateral block displacements juxtaposing different older structural patterns. Palaeomagnetic research, however, has so far not been able to resolve these block movements within the shield.

Geoelectric and geothermal studies

Geoelectric data from magnetotelluric (MT) and magnetovaritional (MV) studies cover exceptionally large parts of the Shield. Controlled source measurements have been possible in the Kola area using an 80-kW impulsive magneto-hydrodynamic generator and VLF-techniques.

The highest resistivities have been found in the Murmansk Terrane of the Kola peninsula. The Central Finland Granitoid Complex (CFGC; Fig. 5.3) and the Karelian crust are dominantly resistive areas, sufficiently extensive that soundings down to the deep lithosphere are feasible. Within the Svecofennian Orogen, major inclined seismic reflectors and/or electrical conductors, extending at least to the middle crust, have been interpreted as internal terrane boundaries or as suture zones. Highly conductive belts associated with graphite- and sulphide-bearing schists exist in various regions of the Shield such as the Keivy, Imandra-Varzuga (Fig. 5.2a) and the Kainuu Schist Belts (KSB; Fig. 5.3). The collisional boundary between the Svecofennian and the Karelian Province has been imaged as a discontinuous conductive zone.

In the central Shield, crustal thickness variations are apparently not reflected in the measured heat flow variations, which are controlled largely by upper crustal heat sources. Heat flow values in the Kola area, and in Karelia are thus correlated with the distribution of crustal heat sources. Geothermal modelling predicts relatively low levels of mantle heat flow, particularly in the central part of the Shield and in Karelia and a poorly distinguished asthenosphere in the White Sea-northern Karelia area.

General Evolutionary Model

Relatively little is known about the Archaean history of the Fennoscandian Shield. Crust formation took place mainly between 2.7 - 2.9 Ga during the Lopian orogeny and a single Archaean continent probably existed before c. 2.45 Ga. At this time rifting of the Archaean craton began, manifested by the widespread development of layered mafic and anorthositic intrusions. Crustal separation followed reactivation of the early rifts. The Svecofennian (“Svionian”) ocean, of which the c. 1.97 Ga Jormua ophiolite is a possible remnant, opened to the present south and west of Karelia. Subduction of the Svionian ocean and crustal accretion in the Svecofennian Orogen was dominantly westward or southward. Collision of the Svecofennian arc terrane(s) with the Archaean of Karelia c. 1.9 Ga ago resulted in eastward overthrusting and crustal thickening, but with limited uplift and orogenic collapse. The region is still underlain by exceptionally thick (60km) crust and low pressure metamorphism is characteristic at the present-day erosion surface.

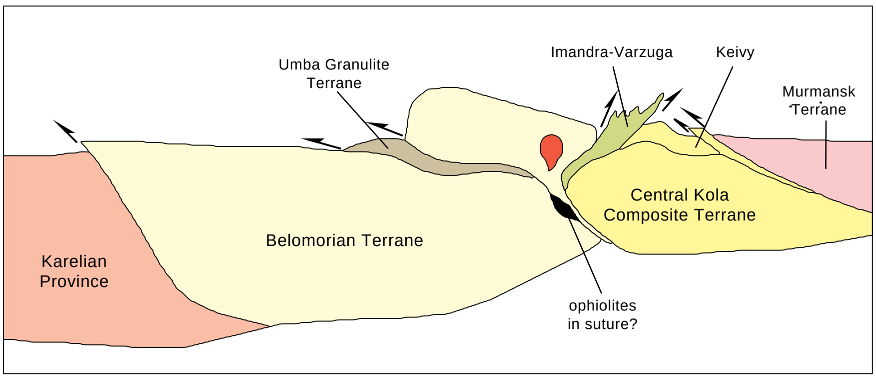

Figure 5.2b: Schematic cross-section along the line shown in Fig. 5.2a. Based on Marker (pers. comm., 1994) and Balagansky (pers. comm., 1994).

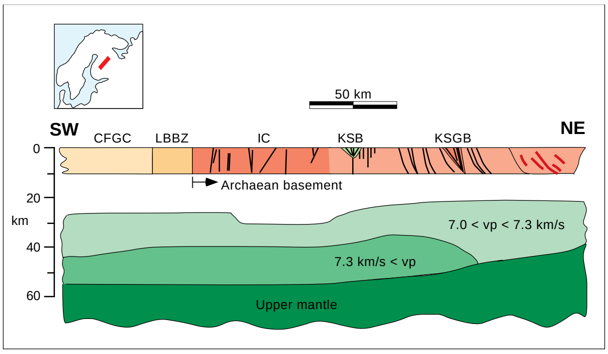

Figure 5.3: Simplified crustal section across the boundary between Svecofennian and Karelia. Upper 10 km of the crust is based on a lithological model, lower crust: seismic velocity model (summarized from preliminary results of GGT/SVEKA, Korsman and Korja, 1996). CFGC = Central Finland Granitoid Complex (with granite and gneiss bodies of various sizes); LBBZ = Ladoga-Bothnian Bay Zone; IC = Iisalmi Complex; KSB = Kainuu Schist Belt (contains the Jormua ophiolite); KSGB = Kuhmo-Suomussalmi Greenstone Belt.

To the north of Karelia, a separate ocean opened within the Lapland-Kola Orogen. Subduction of the northern ocean is implied by the development of juvenile metasediments and calc-alkaline magmatic igneous rocks. Subsequent collision - along the line of the Lapland Granulite Belt - resulted in major crustal thickening followed by exhumation at or before c. 1.87Ga, locally from depths exceeding 30 km. The geometry of the major structures together with the geographical distribution of arc material suggests that subduction was northward directed - i.e. opposite to that in the Svecofennian Orogen. The pattern of opposing subduction polarity on either side of Karelia may explain the relative lack of reworking of the Karelian Province - a relatively stable region of hard lithosphere sandwiched between the Lapland-Kola and Svecofennian Orogens.

Outstanding Features

The Fennoscandian Shield has much in common with other well exposed parts of ancient cratons, such as the Canadian Shield. Archaean blocks are surrounded by Proterozoic accreted terranes. Plate tectonic processes, though not necessarily identical to those operating today, resulted in the opening of oceans and back- and fore-arc basins, the development of subduction zones associated with magmatic arcs, the obduction of ophiolites and the accretion of sedimentary wedges. Within the Archaean blocks, subduction-related phenomena and ancient ocean crust have been widely recognised, but their interpretation is controversial; Archaean and Palaeoproterozoic geodynamics may have differed fundamentally.

The Fennoscandian Shield is a particularly favourable region for studying Archaean-Palaeoproterozoic dynamics. Outstanding features include:

1) The presence of two well-defined, contrasting Palaeoproterozoic orogens, in which extensive detailed work has already been carried out. Access to much of the data base in northern areas has only been possible in recent years.
2) Late Archaean evolution is well defined in Karelia and parts of the Lapland-Kola Orogen
3) The presence of great differences in crustal thickness and composition beneath the different parts of the Shield, with some of the thickest crust on Earth preserved beneath the peneplained Svecofennian Orogen.
4) Subaerial exposure (lack of sedimentary cover) and large areas of relatively homogeneous resistive rocks facilitate geophysical probing into the deep lithosphere.
5) Marine reflection seismic profiling (BABEL) in the Baltic Sea has provided high quality images of the crust and upper mantle, providing strong incentive for new investigations both on land and in the White Sea.
6) Shallow reflection seismic profiles on land (e.g. Fig. 5.6) have provided excellent images of upper crustal structure.
7) The Kola superdeep (c. 12 km) borehole provides unique opportunities for *in situ* study of the deeper parts of the upper crust and for calibration of geophysical techniques.
8) The powerful magneto-hydrodynamical (MHD) generator at Murmansk and special VLF transmitters allow unique investigations of lithosphere-asthenosphere relationships.
9) The presence of Palaeozoic xenolith-bearing dykes provides local evidence of lower crustal and upper mantle composition and age.

These outstanding features prompt the definition of a number of key questions concerning the evolution of craton lithosphere in general and the Fennoscandian Shield in particular. The SVEKALAPKO subprojects, summarized below, seek answers to these questions.

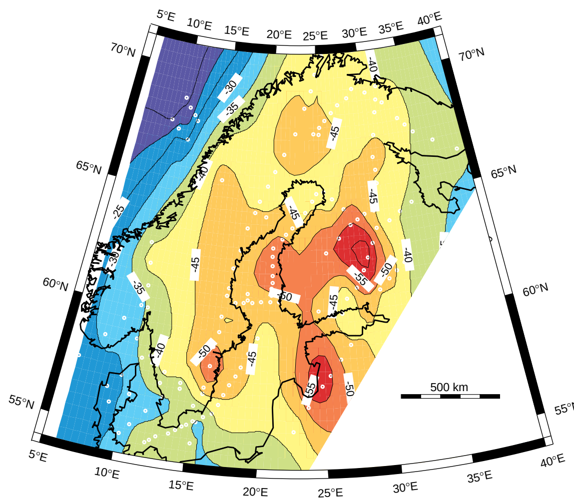

Figure 5.4: Moho depth in Fennoscandia (modified after Luosto, 1991). Dots mark points where crustal thickness has been determined.

SVEKALAPKO RESEARCH

1. Thermal history and kinematics of major crustal structures in the northeastern Fennoscandian Shield: Lapland-Kola orogen and Karelia *(Apatity, Chernogolovka, Copenhagen [MNH, U], Dublin [UCD], Leeds [U], Leicester [U], Lund [U], Moscow [GIN, VVIGAC], Oulu [U], Petrozavodsk [KGE], St. Petersburg [IPGG], Stockholm [MNH]).*

Metamorphic petrology and geochronology integrated with kinematic analysis of deformation fabrics will be used to quantify the thermal and tectonic evolution across the SVEKALAPKO transect. Zircon and titanite dating from the Belomorian-Karelian boundary zone will monitor metamorphic conditions in both Archaean and Palaeoproterozoic times while Ar-Ar work on Archaean rocks, especially in Karelia, will address the extent of Palaeoproterozoic reworking. Calibration of P-T-t and T-t paths will entail combined Rb-Sr, U-Pb, Sm-Nd and Ar-Ar studies on appropriate metamorphic minerals with specific emphasis on migmatitic leucosomes and discordant minor intrusions that have clear structural relations. Target areas will be the Umba Granulite Terrane / Kolvitsa Belt, Keivy Domain, Kainuu Schist Belt and the boundaries between the Murmansk and Central Kola Terranes, and between the Belomorian Terrane and the Karelian Province (cf. Figs. 5.2 and 5.3).

2. Geochemical, isotopic and geochronological constraints on crustal evolution and tectonic setting *(Apatity [RAS], Copenhagen [DLC, U], Dublin[UCD], Edinburgh [U], Espoo [GSF], Leicester [U], Luleå [U], Lund [U], Moscow [GIN, IGEM, VIGAC], Oulu [U], St Petersburg [IPGG, VSEGEI], Stockholm [LIG], Trondheim [NGU]).*

Detailed geochronology and further crustal residence age mapping is needed in the Belomorian Terrane, within the Karelian Province, in the little known Murmansk Terrane. Suspected Palaeoproterozoic arc terranes will be investigated, e.g. in the southern Kola Peninsula (Tersk domain) and in the Inari Terrane. Geochemical and radiogenic isotopic investigations will test the possible ophiolitic (and/or arc) affinities of the well-preserved Palaeoproterozoic “rifts” such as the Pechenga and Imandra-Varzuga Belts. The structure, age and origin of Palaeoproterozoic dyke swarms and ophiolites will be investigated and compared with similar rocks in the Canadian Shield.

3. Deep crustal and mantle xenoliths and anorogenic alkaline magmatism of the Fennoscandian Shield *(Apatity [RAS], Brussels [U], London [BC, KU], Freiberg [BA], Granada [U], Keyworth [BGS], Moscow [IGEM, TSNIGRI], St. Petersburg [VSEGEI], Stockholm [MNH], Tübingen [U]).*

Alkaline magmatic rocks, including kimberlite pipes and lamprophyre dikes, crosscut the Archaean and Palaeoproterozoic of the northeastern Fennoscandian Shield in Finland and Russia. Their ages range from 1.84 to 0.34 Ga. The long age range provides an opportunity to test whether crustal and mantle magmatic sources have been coupled over time and to investigate aspects of the age and nature of the lithosphere using geochemical and isotopic measurements. Comparison will be made on related rocks from Arkhangelsk, Middle Timan, South Kola, Onega Peninsula and Belarus. Particular attention will be paid to the large Devonian nepheline-syenite intrusions (Khibin and Lovozero, Fig. 5.2a) and carbonatite complexes on the Kola Peninsula. Many of the alkaline intrusions and breccia pipes contain both crustal and mantle xenoliths which provide unique samples of the subsurface at the time of magmatism. Petrological, petrophysical, geochemical and isotopic investigations will concentrate on xenolith suites from south Kola.

4. Reflection seismics *(Apatity [RAS], Barcelona [ICTJA], Cambridge [BIRPS], Dublin [UCD], Espoo [GSF], Helsinki [U], Moscow [GEON, IPE, SG], Murmansk [SG], Oulu [U], St. Petersburg [RG, SG, VNIIO, VSEGEI], Uppsala [U]).*

A series of seismic reflection (CMP) experiments is planned (Fig. 5.5) to image the major boundaries and deep crustal and upper mantle structure from the Arctic Ocean-Fennoscandian Shield transition zone, right across the Lapland-Kola Orogen, through the Karelian cratonic core and across the collision zone between it and the Palaeoproterozoic Svecofennian island arc complex. The reflection experiments are expected to shed light on the mechanisms of crustal thickening, the nature of the collision zones in the southern and northern margins of the Karelian craton and the nature and timing of the ancient tectonic events. A larger sample of Archaean crust will determine whether the velocity structure and reflectivity of the Archaean lithosphere differs from that of the younger (Proterozoic) continental regions.

4.1 Kola-Karelia reflection profiles

The northwestern profiles (#1, Fig. 5.5) will extend from the Arctic Ocean-Fennoscandian Shield transition zone through the Kola Superdeep hole (SG-3) across the Central Kola Terrane, the Pechenga Belt, the Lapland Granulite Belt, and the boundary between the Belomorian Terrane and the Karelian Province. The northeastern profile (#2, Fig. 5.5) across the Kola peninsula will map the Murmansk Terrane/ Central Kola Terrane boundary (Kolmozero-Voronya zone), the Keivy Domain/ Central Kola Terrane contact zone, the Imandra-Varzuga Belt in order to test models for the deep structure (e.g. Fig. 5.2b) and the location of major sutures. The southern profiles (#s 3 and 4B, Fig. 5.5) will map the deep structure of the Karelian Archaean block and its northern boundary. They will connect with the APROPOS profile in Finland.

4.2 Archaean-Proterozoic palaeosuture (APROPOS)

A reflection seismic profile (at least 300 km long) is planned to cross the collision zone between the Karelian Archaean block and the Palaeoproterozoic Svecofennian island arc complex (#4A, Fig. 5.5). It will target the anomalously thick (55-60 km) crust of Central Finland in addition to details of the collision zone. The reflection data are expected to shed light on the structure and formation of the 1.97 Ga Jormua ophiolite and the Outokumpu complex.

4.3 White Sea seismic profiles (Pomorje/WABEL)

The WABEL project consists of five marine reflection profiles in the White and Barents Seas with total length of 1100 km. Wide-angle reflections and refractions will be recorded with OBSs and onshore three-component seismic stations. Surface geological features that shall be imaged at depth include: The Murmansk/Central Kola Terrane boundary (Kolmozero-Voronya zone), the Keivy Domain/ Central Kola Terrane contact zone, the Imandra-Varzuga Belt, and the Kandalaksha-Dvina palaeorift developed along the axis of the White Sea.

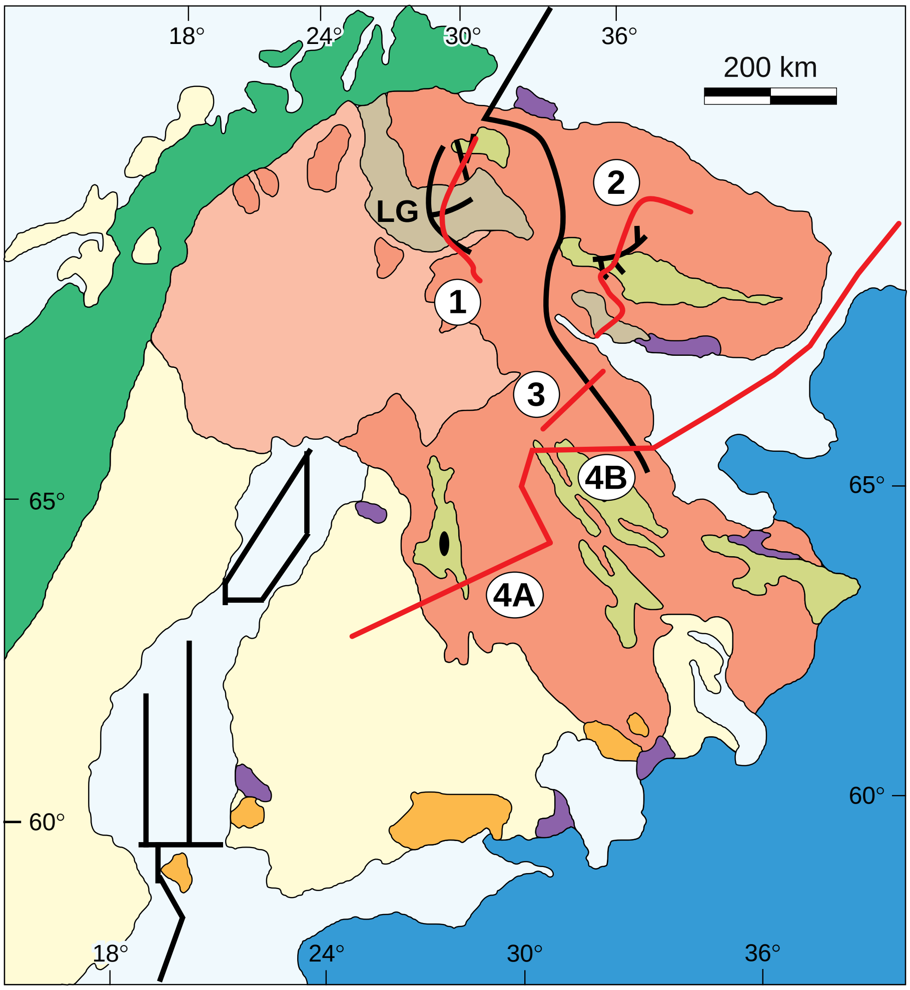

Figure 5.5: Existing CMP-reflection profiles (black lines; BABEL, 1993; Sharov, pers.comm., 1995) shown on the geological map of Fig 5.1. Field work along the longest land profile is in progress. Proposed reflection seismic profiles of SVEKALAPKO are red lines: 1. follow-up of the existing CMP-profile across the Lapland Granulite Belt (Fig. 5.6); 2. across Kola main structures (cf. Fig. 5.2a); 3. across the northern generalized tectonic boundary in Fig. 5.1: 4A. across the boundary between Svecofennian and Karelia (cf. Fig. 5.3); 4B. extension of 4A across Karelia to tie up with the longest land CMP and extend into the White Sea.

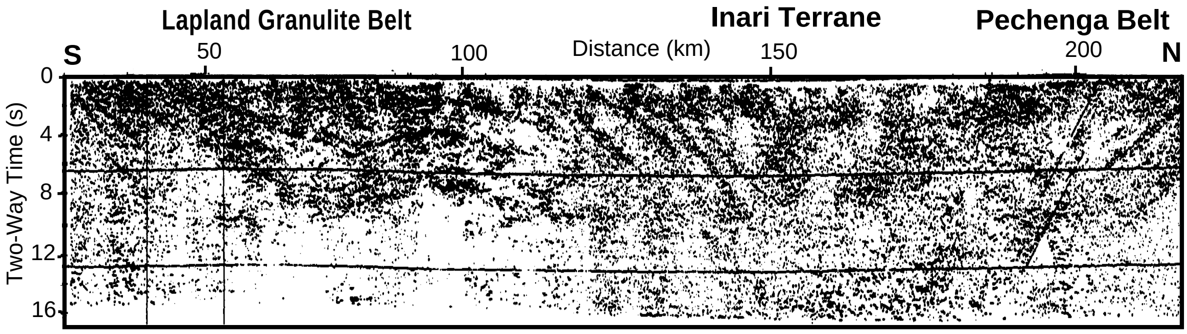

Figure 5.6: Reflection seismic profile through the Lapland Granulite Belt ("LG" on Fig. 5.5). Diagram supplied by N. Skopenko, RosGeofizika.

5. Deep seismic research *(Apatity [RAS], Barcelona [ICTJA], Copenhagen [KMS], Dublin [UCD], Grenoble [U], Helsinki [U], Moscow [GEON, IPE], Potsdam [GFZ], Prague [CAS], St. Petersburg [VSEGEI], Strasbourg [EOPG], Uppsala [U], Warszawa [PAS], Utrecht [U], Zürich [ETH]).*

Integrated seismic investigations are planned to reveal the detailed deep structure of the lithosphere-asthenosphere system. This consists of a simultaneous combined passive and active seismic experiment using an extended array of three-component seismic short-period and broad-band recording stations (Fig. 5.7). The project consists of three parts which are strongly interrelated.

5.1 Seismic tomography of the lithosphere-asthenosphere system

A teleseismic tomography experiment is planned in order to investigate lateral depth variations of the lithosphere - asthenosphere boundary and structures within the lithosphere. Taking into account that the lithospheric thickness is expected to be 200 km or more, the tomographic array will be configured to enable good depth resolution down to at least 400 km in the centre of the shaded area shown in Figure 5.7. Additional three-component broad-band recorders at 50 - 150 km intervals will provide data for complementary seismic work such as surface wave studies, waveform matching and diffraction tomography. Suitable experimental array configuration will ensure that the experiment dovetails with the earlier TOR lithospheric tomography project which covers the area from the middle of Sweden through Denmark into North Germany (see TESZ, subproject #5). Thus a continuous lithospheric cross-section of over 2000km length will be produced.

5.2 Long-range deep seismic wide-angle reflection/refraction experiment

Since teleseismic tomography does not yield absolute seismic velocities and has relatively low structural resolution, a complementary controlled source experiment is planned. Shots fired at sea and in lakes both within the SVEKALAPKO area and outside will be recorded by the tomographic array and about 100 extra temporary stations. The gross crustal structure is well known along lines of earlier crustal refraction/wide angle reflection experiments, and such profiles exist in all but the northernmost part of the relevant area. Missing information on the crustal section across Eastern Karelia and the Kola Peninsula will be collected during an extensive deep seismic sounding study that will be linked with the planned seismic reflection experiments discussed above.

5.3 Seismic anisotropy of the lithosphere

The data from the deep seismic sounding and tomographic experiments will be used for seismic anisotropy studies. To verify different models, such as pure horizontal anisotropy and dipping anisotropic structures associated with palaeo-subduction zones, 3-D inversion of shear wave data will be performed. Numerical models of complex geological media with statistically distributed properties will also be studied.

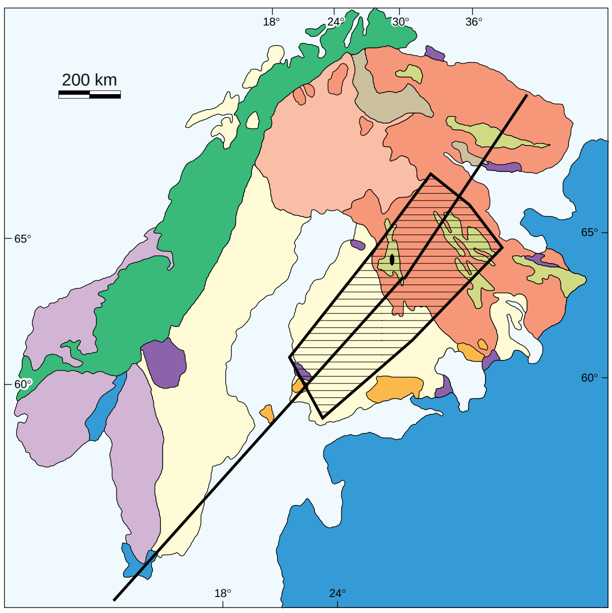

Figure 5.7: Key area of tomography and related experiments and proposed new long-range profile line. The colour code of the geological map is the same as for Fig. 5.1.

6. Geothermal studies: temperature, heat flow and heat production *(Aarhus [U], Apatity [RAS], Espoo [GSF], Genova [U], Oulu [U], Potsdam [GFZ], Prague [CAS], St. Petersburg [VSEGEI], Tartu [U], Uppsala [U]).*
The geothermal studies are aimed at characterizing the deep thermal structure of the lithosphere and to find out the different contributions to the thermal regime, such as lithospheric and crustal thicknesses, deep mantle heat flow, and the crustal heat production. To achieve this, an improved picture is first needed about the surface heat flow density variation and upper crustal heat production, particularly in the Archaean areas, as well as heat production and thermal conductivity in the middle and lower crust. The investigations will consist of the following parts: 1) compilation of existing heat flow density and heat production data, 2) new measurements of heat flow density, 3) measurements of the thermal properties of granulite facies rocks, and 4) integrated modelling of the present and past thermal and rheological regime of the lithosphere during Proterozoic and Archaean times.

7. Geoelectric studies of the crust and the lithosphere-asthenosphere boundary *(Apatity [RAS], Berlin [FU], Frankfurt [U], Göttingen [U], Helsinki [FMI], Moscow [IGEMR, IZMIRAN, SG], Nurmijärvi [GOFMI], Oulu [U], Petrozavodsk [KGE], Potsdam [GFZ], St. Petersburg [VIRGR, VSEGEI, U], Uppsala [SGU, U]).*
Geoelectromagnetic studies are aimed at 1) studying the electrical conductivity of the deep lithosphere and asthenosphere with a 900 x 900 km array of c. 50 simultaneously recording five component long period magnetotelluric instruments, 2) determining the conductivity properties of the lower crust with special emphasis on the lateral variations of electrical anisotropy using a combination of mid-period magnetotelluric and controlled source tensor audio-magnetotelluric soundings, and 3) mapping lateral conductivity variations in the upper and middle crust along the proposed reflection seismic lines. These studies will constrain the geological models of the terrain boundaries and correlate them deeper into the crust, possibly into the uppermost mantle. Geoelectric data on the deep crust and upper mantle will provide independent models that are complementary to the seismic models. They allow investigation of the conductivity differences at various depths beneath the tectonic provinces and thus can give additional information on the evolution of the Fennoscandian Shield lithosphere.

8. Effects of the Svecofennian orogeny in the western parts of the Fennoscandian Shield *(Espoo [GSF], Helsinki [U], Oulu [U], St. Petersburg [VSEGEI], Tallinn [GSE], Turku [U], Uppsala [SGU], Amsterdam [VU], Dublin [UCD]).*
The Geological Surveys of Estonia, Finland, Northwest Russia and Sweden, together with some universities, are studying the evolution of the crust and deeper lithosphere in the western part of the Fennoscandian Shield. Regional lithological, structural, metamorphic, geochemical and geophysical data are integrated to obtain the composition of the present-day lithosphere, its evolution through time, and the relation between variations of crustal thickness and heat flux. The timing of deformation and metamorphism and the mapping of suture zones, collisional and extensional structures will help to define in greater detail the main evolutionary stages of the Svecofennian orogeny. Results of these studies are integrated with the results from other SVEKALAPKO subprojects to understand the effects of the Svecofennian orogeny on the Archaean craton and its cover.

9. Metallogenesis and evolution of the Baltic - Barents Sea Mineral Resource Province *(Apatity [RAS], Copenhagen [DLC], Dublin [UCD], Kuopio [GSF], Leicester [U], Monchegorsk [CKGE], Oulu [U], Petrozavodsk [GIKSC], St. Petersburg [IPGG, Mineral, NWRGE, RG, SU, SZG], Trondheim [NGU]).*
The Baltic - Barents Sea Mineral Resource Province of the eastern Fennoscandian Shield has long been a major ore-producing district. This project aims to study the relationship between the deep structure and metallogenesis in the district with a view to developing new exploration models.

10. Deep structure of the Baltic - Barents Sea Mineral Resource Province *(Apatity [RAS], Copenhagen [U], Dublin [UCD], Helsinki [U], Moscow [SG], Oulu [U], St. Petersburg [IPGG, NWRGE, RG, SG], Uppsala [U]).*
Integrated geological and geophysical research is planned along the Murmansk-Kemi segment of a major long-range deep seismic reflection profile running from the Kola Superdeep Borehole to the Black Sea. The results of this project will be used, together with those from other SVEKALAPKO projects, to develop refined models for the evolution and metallogenesis of the Lapland-Kola Orogen and the Karelian Province.

11. Integrated modelling *(Apatity [RAS], Dublin [UCD], Helsinki [U], Moscow [GEON], Oulu [U], Uppsala [U], Zürich [ETH]).*
Integrated modelling of seismic, potential field, geoelectric, thermo-mechanical and petrophysical data will yield the actual structure of the lithosphere-asthenosphere system. In combination with geological constraints on the upper crust, the history of lithosphere-asthenosphere interaction will be modelled back to the Archaean. Specific targets are the 3-D interpretation of steep shear zones, intracratonic rift zones and collisional sutures. Key problems to be investigated concern the influence of Archaean and Proterozoic thermal regimes on lithosphere-asthenosphere dynamics and the evolution and preservation of overthickened crust and lithosphere.

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