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# A PRELIMINARY MODEL OF THE CRUSTAL STRUCTURE OF THE EASTERN FINLAND ARCHAEAN COMPLEX BETWEEN VARTIUS AND VIEREMÄ, BASED ON CONSTRAINTS FROM SURFACE GEOLOGY AND FIRE 1 SEISMIC SURVEY

By
Asko Kontinen and Jorma Paavola

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The western margin of the Archaean Karelian craton, or eastern Finland Archaean complex (EFAC), constituted 1.9–1.8 Ga ago the foreland of the Svecofennian orogen. This paper presents a preliminary cross-section (2D) interpretation of the crustal structure along the FIRE 1 reflection seismic transect across the central part of the EFAC. The available geological data and interpretation of the FIRE 1 profile combined indicate that the EFAC comprises a thrust stack of dominantly 2.85–2.70 Ga high-grade, granite-migmatite gneiss units, accreted in a continent-continent type collisional orogeny. Although significant Svecofennian contribution to the structure of EFAC is a viable option, the mostly little deformed nature and vertical-subvertical attitude of the crosscutting pre-Svecofennian, Palaeoproterozoic dolerite dykes indicate its stacked structural architechture would be chiefly of Archaean origin. Yet the EFAC has experienced an overall amphibolite facies metamorphic overprinting (for the present surface, obviously higher grade deeper) ca. 1.85–1.80 Ga ago. This is, conforming with some earlier works, addressed to a long-standing (from 1.90 to 1.80 Ga) burial of the EFAC below a 15–20 km thick thin skin thrust complex from the Svecofennides. The Kainuu-Outokumpu zone and EFAC-Svecofennia boundary line, often interpreted as important E-verging crustal suture zones, are nearly imperceptible features in the FIRE 1 data, and are thus considered rather major strike-slip fault/shear than suture zones. The lower crust of the EFAC is seismically nearly transparent. The most probable cause to this is that the conductive heating of the lower crust during the 1.9–1.8 Ga thrust burial of the EFAC was associated with pervasive static metamorphic dehydration/recrystallization and related homogenization of the acoustic properties of the lower crust. Massive, granoblastic textures and ca. 1.8 Ga metamorphic ages of the lower crust mafic xenoliths in the ca. 600 Ma old kimberlite pipes in the western margin of the EFAC are in accord with this proposal.

Key words (GeoRef Thesaurus, AGI): crust, deep seismic sounding, reflection methods, FIRE, deep-seated structures, block structures, tectonics, two-dimensional models, Archaean, Eastern Finland

*A. Kontinen and J. Paavola, Geological Survey of Finland, P.O. Box 1237, FIN-70211 Kuopio*

*E-mail: asko.kontinen@gtk.fi*

# INTRODUCTION

The recent vibroseismic FIRE 1 survey by GTK transects the NE part of the Eastern Finland Archaean complex (EFAC), which ca. 1.90–1.80 Ga ago formed the immediate foreland of the collisional Svecofennian orogen (Fig. 1). The main purpose of this paper is to represent a preliminary cross section (2D) interpretation of the crustal structure of the EFAC along the FIRE 1 line and to provide brief descriptions of the main geological and seismic features of the contained main tectonic units. The here studied 240 km long NE part of the FIRE 1 (for technical details of FIRE 1 data acquisition and processing, see Kukkonen et al. 2006, *this volume*) starts at Vartius on the E boarder of Finland, crosses the late Archaean Kuhmo greenstone belt (KGB), the Palaeoproterozoic Kainuu schist belt (KSB), the Iisalmi block of late Archaean granulites, and ends at the EFAC-Svecofennia boundary zone (ESBZ) at Vieremä (Figs. 1–2). The EFAC comprises mainly late Archaean high-grade, dominantly migmatitic gneisses (Sorjonen-Ward & Luukkonen 2005), and is locally covered by remnants of Palaeoproterozoic, autochthonous Sariola, Jatuli and Lower Kaleva (2.5–1.95 Ga) and allochthonous Upper Kaleva (<1.95 Ga) strata (Laajoki 2005). A Svecofennian amphibolite facies metamorphic overprinting of the EFAC is registered at 1.85–1.80 Ga by K-Ar and Ar-Ar ages of its hornblendes (Kontinen et al. 1992, Kontinen 2002). This overprinting has been interpreted in terms of conductive heating related to a long-lasting burial of the EFAC under a thick nappe complex thrust from Svecofennides to overlay it between 1.90–1.80 Ga ago (Kontinen et al. 1992). In

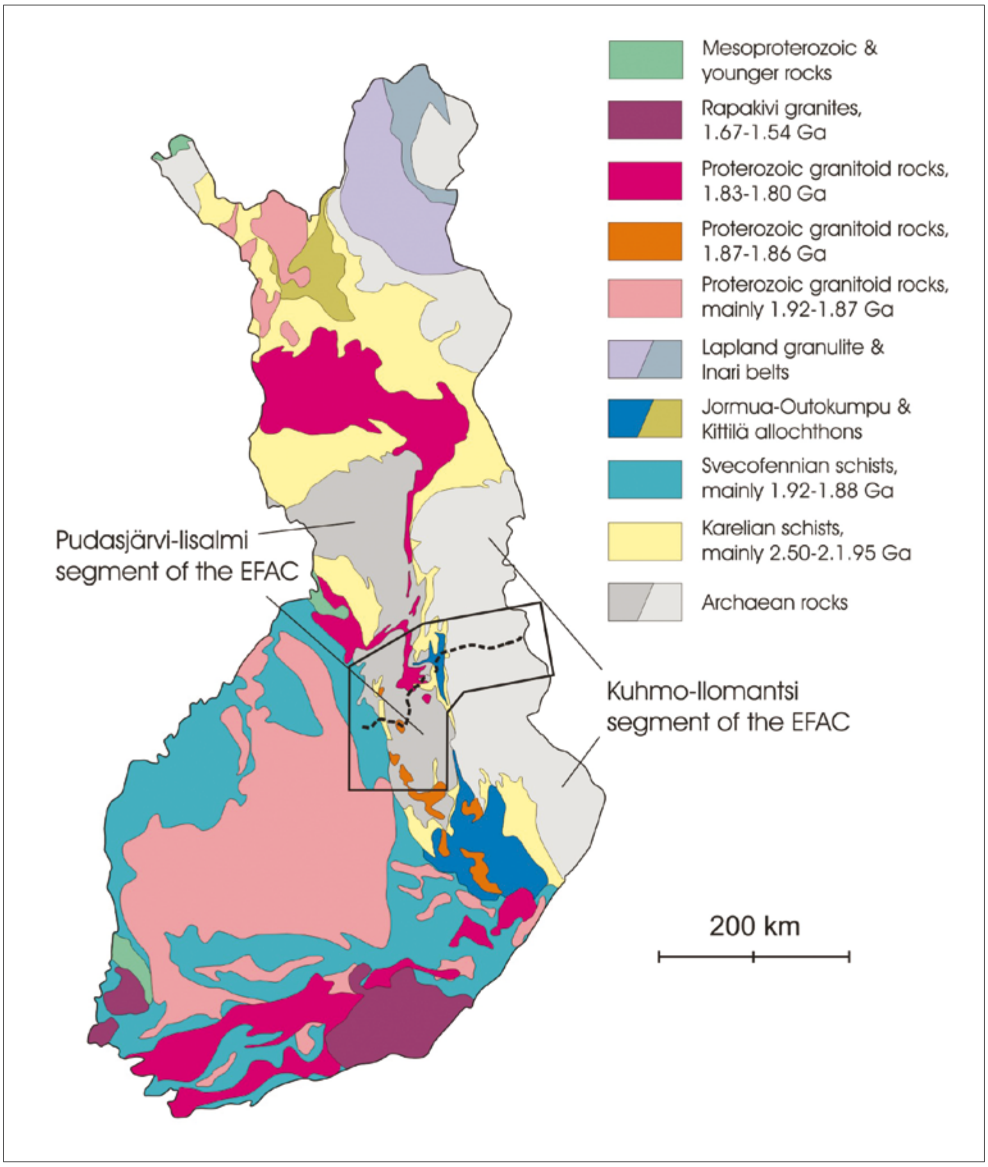

Fig. 1. Geological map of Finland showing the location of sections 1 and 2 of the FIRE 1 survey (bold dashed lines). The area of the map in Fig. 2 is outlined. Generalized and modified from Korsman et al. (1997).

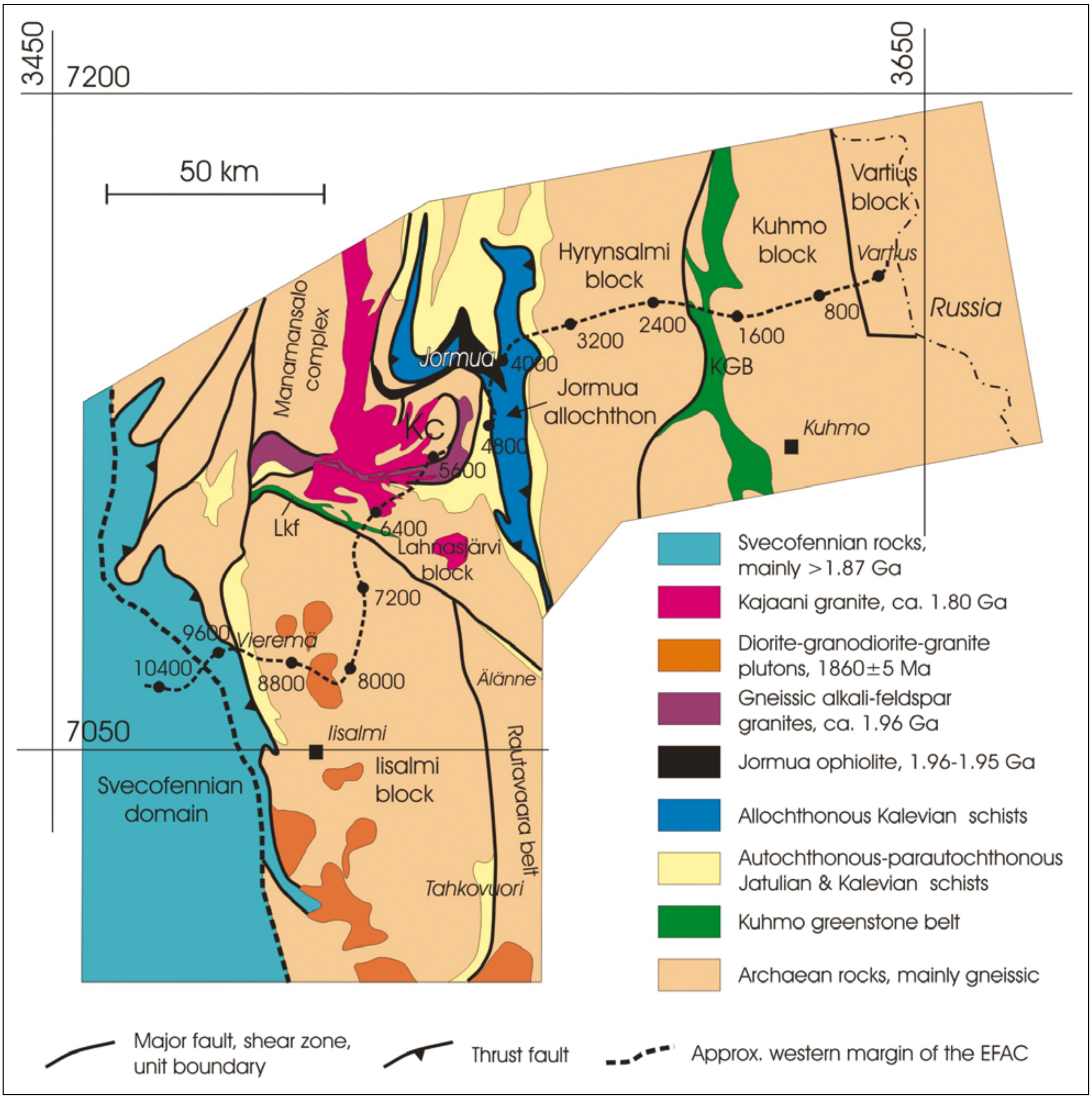

Fig. 2. A simplified geological map of the part of the EFAC crossed by the FIRE 1 survey. The map is showing by bold black lines the boundaries of the crustal blocks distinguished in Fig. 3. The dots with numbers at the survey line pick up some CMP points for reference. KGB= Kuhmo greenstone belt, Kc = Kajaani complex, Lkf = Lautakangas formation.

central part of the EFAC the related peak temperatures were ca. 600° C at pressures of ca. 5–6 kb (Pajunen and Poutiainen 1999).

Although crystalline continental crust was for long considered a relatively poor target of reflection seismic studies, with ever continuing improvements in field acquisition and data processing technologies, dramatically detailed and informative seismic images have been obtained for many areas of such crust (look e.g. for images at http://www.earthscrust.org/earthscrust/science/). Also in the case of EFAC the main crustal units of distinct surface geology seem to differ in their seismic reflection characters enough to allow interpretation of the FIRE 1 profile for their subsurface crustal distributions and internal structural patterns.

The most important source of crustal reflections is in acoustic impedance contrasts related to horizontal-subhorizontal boundaries between rock layers of significantly differing seismic velocities and/or densities. In such a thoroughly high-grade metamorphic gneissic-granitoid crust as along the FIRE 1, the most distinct reflections probably are from interlayered, flat-lying mafic–felsic gneisses, whereas domains of lithologically more homogeneous and/or geometrically irregular granitoid gneisses and/or plutonic rocks can be expected to produce far less/weaker and more diffuse/complex reflections. Besides lithological contacts/layering, distinct reflections can be produced also by prominent shear and detachment/thrust zones.

In this particular case it is important, that, although the EFAC is a principally Archaean entity, due to its position in the foreland of the Svecofennian orogen, at least some Svecofennian modification and reorientation of the Archaean structural and related reflection patterns, and addition of new such features probably has occurred. In addition, Palaeoproterozoic ultramafic–mafic sills and dykes swarms are one more cause of post-Archaean distinctive reflections. However, besides the 2.4 Ga layered intrusions and 2.2 Ga gabbro-wehrlite (“karjalite”) sills (Iljina & Hanski 2005, Vuollo & Huhma 2005), both concentrated along the Karelian cover–basement interfaces, any sizeable Proterozoic mafic intrusions within the EFAC are rare. The Proterozoic dolerite dyke swarms, although in several generations a ubiquitous feature in the EFAC (Vuollo & Huhma 2005), are unlikely to contribute significantly in the seismic data, simply as most of the included dykes are vertical-subvertical and usually less than 50 m thick. This situation is certainly true for most of the surface of the EFAC, and we do not know any pressing reason for that the dyke attitudes and dimensions would be substantially different deeper in the crust.

We distinguish along the FIRE 1 line, based on the surface geology and FIRE 1 seismic data, eight main lithotectonic units, most of which we will call neutrally as ”blocks”. The geological and seismic features, the latter as seen in the FIRE 1 data, will be briefly described. The geological descriptions are based mainly on published sources; where references are missing, unpublished data of the present authors has been used. Figure 2 shows the blocks on a simplified geological map and Fig. 3 on a cross-section interpretation for the FIRE 1 line. It should be noted that the cross-section in Fig. 3 represents the crooked-line of the FIRE 1 measurements with the complexities in true 3-D structures involved. The reflector strikes and dips quoted in the text usually involve considerable uncertainty as dominant part of the FIRE 1 survey was just for one mostly straight line, and which in places had unfavourable, highly oblique to parallel orientation with respect to the important block boundaries and/or within-block structural grains. The treatment below is mainly for main structural features of the upper 20 km of the crust.

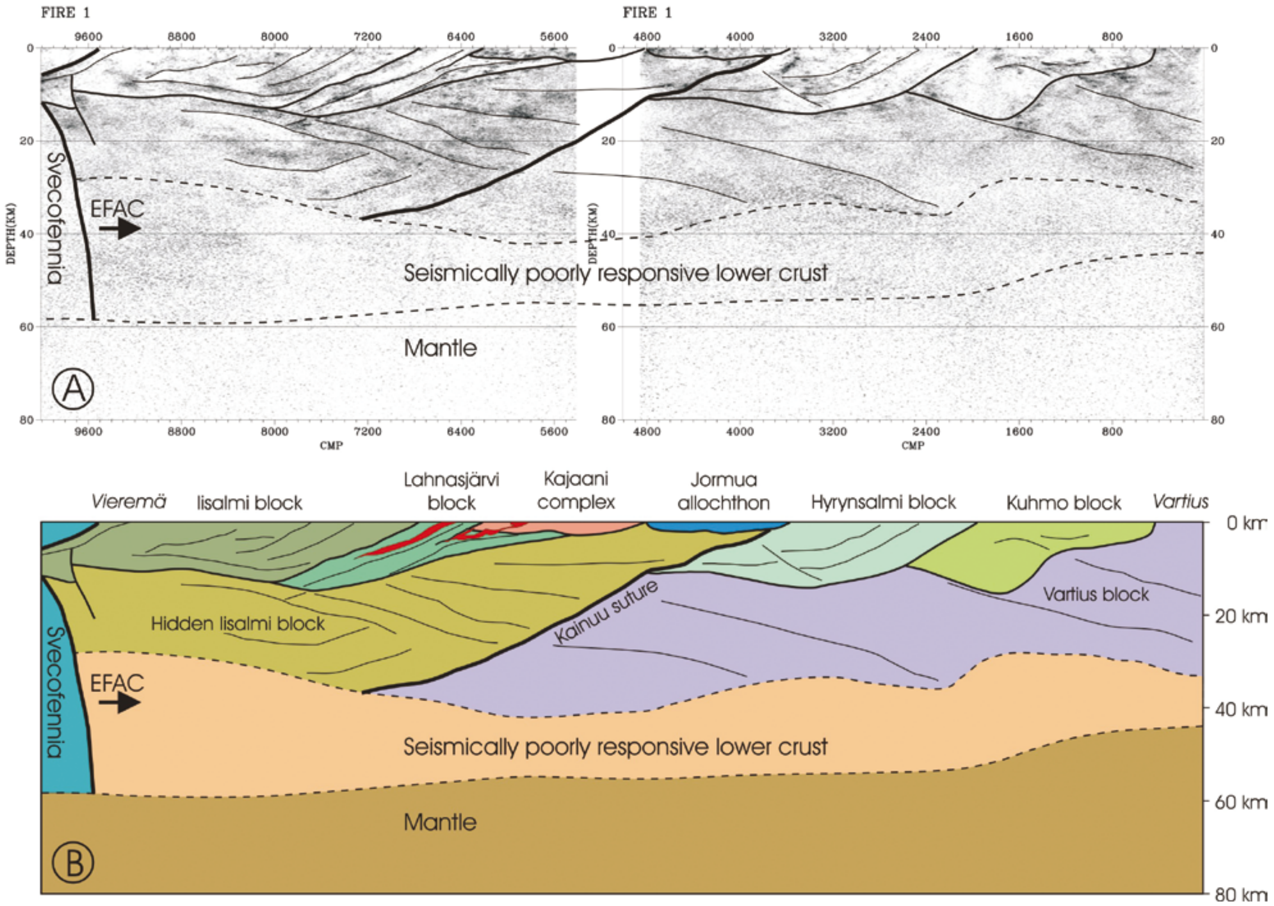

Fig. 3. Sections 1 and 2 of FIRE 1. (A) Migrated images with lines accentuating important reflections and changes in reflectivity. (B) An interpretation in terms of main crustal blocks. The readings at the upper edges of the sections in A refer to the CMP points in Fig. 2. Vertical to horizontal scale 1:1 in both A and B.

## DESCRIPTION OF THE MAIN CRUSTAL BLOCKS

### Vartius block

The Vartius block at the Russian border and at the beginning of the FIRE 1 line comprises mainly upper amphibolite to granulite grade stromatic and schlieren-type migmatites, most of them with amphibolite-mafic gneiss mesosomes and granodiorite-tonalite leucosomes (Luukkonen 2001). No isotopic age data is available from these dominantly orthogneissic rocks, but probably they were magmatically formed, and tectonically reworked to gneisses between 2850 and 2700 Ma ago. The Vartius gneisses show mostly retrograde amphibolite facies mineral assemblages, but local relics of garnet-pyroxene assemblages in the mafic gneisses attest to an upper amphibolite to granulite facies thermal climax of the Archaean metamorphism (Luukkonen 2001). Large occurrences of well-preserved Archaean granulites are present immediately on the Russian side of the border (e.g. Korsakova et al. 1987). Due to common preservation of high-grade magnetite in the Vartius block, it appears as a strong magnetic high in regional magnetic anomaly maps.

Palaeoproterozoic dolerite dykes are common in the Vartius block. Most of these dykes are relatively little deformed but show partial to complete static hydration under lower amphibolite facies conditions (Kilpelä, 1991), attesting to that the amphibolite facies retrogression in the host gneisses would be at least partly of Svecofennian origin. The dykes strike mostly NW-SE or E-W and are vertical-subvertical as most Palaeoproterozoic dolerite dykes in the EFAC (e.g. Salmi 1986, Kilpelä 1991, Toivola 1988, Korsman et al. 1997, Kousa et al. 2000, Vuollo & Huhma 2005).

The Vartius block is characterized by a relatively good general reflectivity although mostly without such well defined layered fabric as is typical of large parts of the below described Hyrynsalmi and Iisalmi blocks. The block is bounded in the E by the 2800–2700 Ma Kostomuksha greenstone belt (e.g. Puchtel et al. 1998) and in the W by the Kuhmo block. The W contact against Kuhmo block appears as a sharp N-S linear in magnetic and gravity anomaly maps, which is suggesting it was defined by a fault. The FIRE 1 data indicates the contact surface would dip to the W, below the Kuhmo block, in an angle first steep but then apparently shallowing to 20–30°. Lithosphere of similar relatively intense but rather incoherent seismic reflectivity as in the Vartius block seems to extend in depth far in the W, making up there the middle crust below the Kuhmo and Hyrynsalmi blocks. There are some strong, apparently flat-lying reflections in the upper part of the section of Vartius block below the Kuhmo block. These reflections probably are from bodies rich in mafic granulites, presumably derived from originally greenstone inclusions.

### Kuhmo block

The western margin of the Kuhmo block hosts the classic Kuhmo greenstone belt (KGB), which consists of sequences of amphibolite-grade, dominantly ultramafic and mafic volcanic and some intercalated sedimentary rocks (e.g. Piirainen 1988). The greenstones are bordered with intrusive or faulted-sheared contacts by large, foliated tonalite-granodiorite plutons and amphibolite-tonalite-throndhjemite migmatites (e.g. Horneman et al. 1988). The E part of the Kuhmo block consists of deeper eroded, largely gneissic-migmatitic section of the KGB type bedrock, with only local, small remnants of mainly ultramafic-mafic amphibolite-grade schists (Luukkonen 2001). The oldest volcanic components in the KGB are at least ca. 2.80 Ga in age, while the large, foliated plutons bordering the belt yield magmatic ages in the range of 2.79 to 2.73 Ga (e.g. Hyppönen 1983, Luukkonen, 1988a, 1988b, 1992, 2001, Vaasjoki et al. 1999, Käpyaho et al. 2004). A mesosome of the migmatitic gneisses E of the KGB, in the middle part of the Kuhmo bock, has given an age of 2843±18 Ma (Luukkonen 1985).

Palaeoproterozoic dolerite dykes within the Kuhmo block, as well as the ca. 2.22 Ga layered gabbro-wherlite sills in the KGB, are usually hydrated to lower amphibolite facies assemblages (Hanski 1986, Kilpelä 1991). Yet the dykes are mostly relatively little deformed and seem to preserve also their intrusion stage, vertical-subvertical dips and NW-SE linear strikes largely unchanged (Fig. 4A, Kilpelä 1991, Luukkonen 1988a, 1988b, 2001). This suggest that the block has experienced only relatively little post-Archaean reworking, which Luukkonen (1985, 1992) posits to be controlled by and restricted mainly in pre-existing Archaean fault/shear zones. Nonetheless, the amphibolite facies metamorphic assemblages in the dolerite dykes indicate Svecofennian peak temperatures >500 °C for the whole Kuhmo block.

Several kilometre-size domains of low, incoherent

Fig. 4. Photographs of early Proterozoic dolerite dykes typical of the crustal blocks along the FIRE 1. (A) Nearly vertical contact of a ca. 25 m wide metadolerite in an Archaean tonalite-granodiorite gneiss at Purnu (x=7151 140, y= 4462 670), Kuhmo, Kuhmo block. (B) A ca. 15 cm wide, near vertical metadolerite dyke sharply cutting an Archaean banded tonalite gneiss at Marjohaka (x=3512 477, y=7049 329), Iisalmi, Iisalmi block. (C) A ca. 1 m wide, near vertical pyroxene dolerite dyke in an amphibolite-banded Archaean tonalite gneiss at Mäntylahti (x=7022 620, y=3522 730), Lapinlahti, Iisalmi block (D) A ca. 6 m wide, near vertical metadolerite dyke in an Archaean leucogranite at Särkiharju (near the large open pit of Kemira GrowHow, x=7001 095, y=3537 809), Siilinjärvi, Iisalmi block. The dykes in C and D locate in the S part of the Iisalmi block out of the map area in Fig. 2.

reflectivity with intervening domains of strong, flat-lying reflectors characterize the FIRE 1 image of the Kuhmo block. We address this reflection pattern to granitoid plutons and enclosed remnants of greenstones and derived mafic-felsic banded gneisses. As the FIRE 1 line runs nearly parallel with the broadly E-W foliation trend of the block, its internal structural architecture remains uncertain; presence of moderately to steeply NW-dipping thrust faults and panels have been proposed based on surface geological information (Luukkonen 1992). The KGB, ca. 2.5 km wide at the FIRE 1 line, has no clear manifestation in the seismic data. The FIRE 1 seismic data yields an impression of that the contact between the Kuhmo and Hyrynsalmi blocks W of the KGB was a major tectonic detachment surface, dipping in a shallow angle (ca. 30°) to the W. This interpretation is consistent with the mylonitized, augen gneiss nature of the granitoids along the W contacts of the KGB. Based on the FIRE 1 image, the Kuhmo block, as well as the Hyrynsalmi block west of it, seems to have a maximum depth extension of about 13 km. As we noted above, the middle crust underlying these blocks has similar reflection characteristics as the Vartius block (cf. Fig. 3).

## Hyrynsalmi block

The Hyrynsalmi block consists of interlayered upper amphibolite facies paragneisses, tonalite-banded amphibolites and granodiorite-tonalite gneisses, all these rocks being intruded by large plutons of K-feldspar megacrystic tonalite-granodiorite-granite of the Konivaara type and irregular bodies of often magnetite-bearing leucogranites (Hyppönen 1983, Luukkonen 1988a, Kontinen 1991, Kontinen & Meriläinen 1993, Käpyaho et al. 2006). Detrital zircons from paragneiss samples are mostly 2.75–2.70 Ga in age (Kontinen et al. in prep.), while the bulk of the megacrystic granitoids and leucogranites crystallized ca. 2.70–2.69 Ga ago (Luukkonen 1988, Käpyaho et al., 2004). The available age data suggests that the Hyrynsalmi block had a considerably younger and possibly largely unrelated formation history compared to that of the adjacent Kuhmo block.

Palaeoproterozoic dolerite dykes are abundant across the entire Hyrynsalmi block. The dykes are thoroughly hydrated to lower amphibolite facies assemblages (hornblende+plagioclase±garnet±quartz) and are mostly weakly to pervasively strained with often distinctly schistose and/or lineated fabrics (Salmi 1986, Kilpelä 1991). In spite of their usually schistose-lineated fabrics, the dykes still show mostly vertical-subvertical dips, and, like the dykes in the adjacent Kuhmo block, seem to preserve also their intrusion stage, dominantly NW-SE strikes largely unmodified.

The Hyrynsalmi block is characterised by gently (ca. 30°) W-dipping banded reflectivity that can be traced to depth of about 12–13 km, where the main reflectors terminate abruptly against crust with similar reflectivity character as in the Vartius block. Based on the FIRE 1 the block forms a wedge dipping in a shallow angle below the KSB (including the Jormua allochthon) and E edge of the Hidden Iisalmi block, tapering there soon out. As we noted above, a detachment surface nature of the eastern, gently W-dipping contact against the Kuhmo block is apparent. It is important to note that the W contact of the Hyrynsalmi block actually coincides with the first order late Archaean tectonic boundary ("Kainuu suture") between the 3.4–2.7 Ga Pudasjärvi-Iisalmi and 2.85–2.7 Ga Kuhmo main segments of the EFAC (cf. Fig. 3). At FIRE 1 this feature is, however, wholly buried below the KSB and is thus not available for direct observation.

## Hidden Iisalmi block

We denote with "Hidden Iisalmi block" the large, unexposed upper-middle crustal block that differentiates in the FIRE 1 image below the Lahnasjärvi and Iisalmi blocks in the area W of the KSB. The block is characterized, especially for its E part, by a somewhat stronger and more complex reflectivity than the Vartius type crust, which seems to constitute the middle crust further in the E. The relatively strong reflectivity hints of layered mafic-felsic gneisses, while many subhorizontal truncations in the reflectivity pattern suggest considerable and complex internal tectonic stacking. We believe, that, as in the surficial blocks of the EFAC, the reflectivity pattern also in this deep hidden block would be chiefly of Archaean origin.

## Jormua allochthon

The KSB on the FIRE 1 consists of Jatulian (2.3–2.0 Ga) shallow water arenites and younger, Lower and Upper Kalevian mainly metaturbiditic mica schists (Kontinen & Meriläinen 1993, Laajoki 2005). The Upper Kalevian mica schists derive form deep-sea, sand-dominated turbidites (<1.94 Ga) and are tectonically mixed with ophiolite fragments (1.95 Ga) and also a few, thin (<1 km) but up to several tens of kilometres long slices of pervasively sheared, mylonitized Archaean gneissic migmatite rocks (Kontinen 1987, Kontinen & Meriläinen 1993, Kontinen & Eskelinen 2005). An allochthonous, from W over the EFAC transported nature of this package, which we will call the Jormua allochthon, seems most likely (Peltonen et al. 1996). The gneissic slices in the allochthon may be imbricate fault slices from the immediately underlying Archaean basement, or more exotic nappe slivers transported in their present positions within the allochthon. The available geological, gravity and the FIRE 1 seismic data indicate that the Jormua allochthon would comprise only a thin, in maximum up to 2–3 km thick veneer on the underlying, ca. 53 km thick Archaean crust. The SE tip of the largest of the ophiolite inclusions, the Jormua ophiolite (see e.g. Peltonen & Kontinen 2004), is crossed by the FIRE 1, but with little manifestation in the seismic data.

The metaturbidites and Archaean slivers of the Jormua allochthon register remarkably intense dextral shearing in a late stage ("D4") of the Proterozoic tectonic evolution of the KSB, strongly concentrated along a few apparently subvertical N-S trending strike-slip faults (cf. Kärki et al. 1993, Kärki & Laajoki 1995). Noting that the boundary of the Pudasjärvi-Iisalmi and Kuhmo-Ilomantsi domains of the EFAC situates just below and along the KSB, we assume that the Svecofennian "D4" was involving dextral strike-slip reactivation of this ultimately Archaean N-S-trending suture zone. The subvertical N-S faults related to the “D4” deformation are not discernible in the FIRE 1 seismic data, however. This is probably due to the subvertical nature of the prominent faults. But, on the other hand, much of the survey line in the critical area between CMD points 3800 and 4800 runs oblique to nearly parallel with the main D4 faults and shear zones.

## Kajaani complex

The W part of the domal shape Kajaani complex locating to the SW of the Jormua ophiolite consists mainly of wacke-drived migmatitic paragneisses, locally interleaved with layers of arkosic to orthoquartzitic gneisses. In the E part of the complex there occur, but paragneisses and amphibolites, also abundant tonalitic-throndjemitic and granodioritic-granitic orthogneisses (Havola 1997). The paragneisses and quartzites are similar to the earliest Proterozoic or latest Archaean paragneisses in the Puolanka area to the W of the N branch of the KSB (Laajoki 1991, Kontinen et al. 1996). The garnet-muscovite bearing Kajaani granite, probably ca. 1.80 Ga in its age (Vaasjoki et al. 2001), is an abundant component over large areas of the Kajaani complex, especially in its W part (Havola 1997). Noteworthy is that this granite does not form anywhere larger plutons but frequently occurs in <1m to 200 m wide dykes sharply crosscutting the foliations and migmatite structures of the host gneisses. The dykes range flat-lying to vertical, showing no other tendency to preferred orientation but that the youngest dykes tend to be vertical-subvertical and strike SE-NW.

The central and S parts of the Kajaani complex are characterized by mostly relatively shallowly (0–50°) to the S and SE-dipping foliations (Fig. 5A). At its N margin the complex is bordered by the 1.95 Ga Jormua ophiolite, with a 60–80° S-dipping faulted-sheared contact. In the E and S the complex is fringed by a 1–4 km wide stripe of the ca. 1.96 Ga old Otanmäki-type gneissic alkali-feldspar granites. The contact of between these granites and the central gneiss complex is only poorly known as it is lake-covered in the E and heavily intruded by veins of the Kajaani granite in the W. However, the very sharp nature of the contact zone on magnetic anomaly maps, and structural observations from nearest outcrops suggests that it would involve a major left-lateral/reverse fault. Further evidence supporting fault-controlled large displacement between the alkaline granites and the underlying Kajaani complex include that the latter completely lacks intrusions, even thin veins, of the former.

The FIRE 1 survey crosses the S-margin of the Kajaani complex at Lehtovaara. The fringe of the Otanmäki-type gneissic granites is there ca. 4 km wide and characterized by pervasive, mostly S-dipping (20–60°) foliation and shallowly (10–40°) SW-dipping stretching and mineral lineations. A narrow stripe of E-W striking, variably S-dipping (40–90°) Jatuli quartzites and Lower Kalevian mica and black schists separates the alkaline granites from the Archaean migmatite gneisses of the Lahnasjärvi block next in the S. The contact of the Proterozoic rocks with the Lahnasjärvi gneisses is defined by a sharp, ca. 50° S-dipping fault. Abundant criss-cross cutting, mostly undeformed dykes of the Kajaani granite are found all over the boundary zone, and are very abundant also further S inside the Lahnasjärvi block.

There are only few detailed field notes available on Proterozoic dolerite dykes within the Kajaani complex. Those that exist yield a mixed picture; namely, there are observations of vertical-subvertical, remarkably well-preserved, nearly undeformed dykes that sharply cross–cut the shallowly S-SE-dipping foliations in the host migmatite gneisses, but also of dykes that are pervasively strained, faulted, and locally folded for their margins. The preliminary observations from the dyke-gneiss relationships suggest that main structural features in the Kajaani complex, including the shallowly S-SE-dipping gneiss foliations in its central and S parts, would be of Archaean origin, but with some heterogeneously distributed Svecofennian modification. Getting a more detailed idea of the nature and magnitude of the Svecofennian modification would require further field study.

The section 2 of the FIRE 1 crosses the SE corner of the Kajaani complex, but unfortunately so that the survey line is running nearly parallel with the local foliation trend. Nonetheless, the seismic data indicate a ca. 3 km thick surficical veneer of strong but discontinuous flat-lying reflectors with a sharp basal contact on crust that has similar gently S or SW-dipping, well-defined layered reflectivity as the Lahnasjärvi block to the S.

The FIRE 1 indicates that the Kajaani complex is only a few kilometres thick surficical layer, which supports interpretation of it as an allochthonous unit. One previously proposed scenario is that the Kajaani complex and the associated Otanmäki type gneissic alkali-feldspar granites would represent a Svecofennian

Fig. 5. Photographs of rocks typical of the middle part of the Iisalmi block. (A) Flat-laying migmatic mica gneiss at Kainuun Sanomat (x=7124 510, y=35533 550), Kajaani, Kajaani complex. (B) Gently dipping mafic-felsic banded gneiss at Linkokangas (x=7093 540, y=3518 000), Sonkajärvi, Iisalmi block. (C) A garnet-pyroxene amphibolite from a mafic layer in mafic-felsic banded gneiss at Niemisenmäki (x=7074 040, y=3511 060), Vieremä, Iisalmi block (D) A detail of sharply discordant contact between a nearly vertical, several metres thick metadolerite dyke intruded in the gently dipping gneiss in (B). Photos: Asko Kontinen (A), Jorma Paavola (B–D)

allochthonous sliver(s) from the outer, strongly thinned W margin of the presumably ca. 1.95 Ga ago broken up Karelian craton (cf. Peltonen et al. 1996, 1998). An alternative scenario would be that the Otanmäki granites intruded into a narrow fault zone between the Kajaani and Lahnasjärvi blocks, perpendicular to the 1.96 Ga ago rifting craton margin. Later, during the Svecofennian orogenesis the granite-intruded fault zone was translated to a N-verging "D4" thrust zone. The latter scenario would imply that the Kajaani complex with its mostly flat to gently dipping gneisses was an ultimately Archaean but during Svecofennian reactivated thrust slice. More field work on the block contacts and deformation of Proterozoic dolerite dykes crosscutting the Kajaani complex are needed before any serious attempt to resolve between these two models, or some other, can be presented.

## Lahnasjärvi block

The main components of the triangle-shaped Lahnasjärvi block between the Kajaani complex and Iisalmi block, and which is in the E bordered by the KSB, are late Archaean migmatitic tonalite-trondhjemite gneisses, amphibolite-intercalated micaceous paragneisses and gneissic granodiorites-granites. In addition, there are local domains of abundant crisscrossing dykes, plugs and more extensive sheet-like intrusions of the Kajaani granite (Havola 1981, Havola 1997, Paavola 2003, Kontinen and Eskelinen 2005). The domains rich in the Kajaani granite enclose arkosic paragneisses, which hints about that the granites were derived by partial melting of similar but probably more abundant paragneisses deeper in the crust. A similar connection between the Kajaani granite and arkosic Archaean paragneisses is obvious also in the W part of the Kajaani complex. However, there are no isotope geochemical data either on the Kajaani granite or the associated paragneisses for testing this hypothesis.

The Lahnasjärvi block is in the E and N fringed by bands of Jatuli-type arkosites and quartzites. Although the intervening contacts are presently defined by faults, it seems obvious that these Jatuli metasediments represent only slightly displaced, "down-faulted" autochthonous cover of the block. The linearly SE-running contact between of the Lahnasjärvi block and the Iisalmi block in the SW is poorly exposed and thus its proper nature is imperfectly known, but it seems to be defined by a steeply (65–80°) SW-dipping fault (Laakajärvi fault) with some significant Proterozoic, obviously reverse component, at least for its SE end at Älänne. In the NW end of the Laakajärvi fault, on its Lahnasjärvi side, there is a narrow belt of amphibolitic metavolcanic rocks and mica schists (Fig. 2), informally named to Lautakangas formation by Laajoki & Luukas (1988). The SW contact of the Lautakangas formation against the Iisalmi block is defined by the Laakajärvi fault, while in the N the included amphibolites grade with appearance of leucotonalite bands into migmatites of the Lahnasjärvi complex. Laajoki & Luukas (1988) argued that the Lautakangas amphibolites would be earliest Proterozoic, Sumian in age. However, our observations that the amphibolites grade locally into migmatites cut by unmigmatized pre-Svecofennian metadolerites, imply they are more likely of Archaean (greenstone belt) origin.

The pre-Svecofennian dolerite dykes of the Lahnasjärvi block tend to be pervasively amphibolitic, schistose and lineated, and sometimes show folded, tilted and rotated contacts. Major part of this deformation, that must have seriously affected also the Archaean host rocks, was probably related to the late Svecofennian "D4" N-S compression inferred by Kärki & Laajoki (1995). Dykes of the Kajaani granite have been observed to crosscut relatively undeformed the tectonic fabrics in the metadolerites. Hence the Proterozoic "D4" deformation seems at least for its main part to be an earlier event than the presumed emplacement of the Kajaani granite 1.80 Ga ago.

The NW corner of the Lahnasjärvi block crossed by the FIRE 1 is characterized by alternating layers of relatively low and high reflectivity dipping in a shallow angle (10–20°) towards the S or SW. At the surface the panels of the weak reflectivity coincide with plentiful outcrops of Kajaani granite. There may thus occur S-dipping sheets rich in the Kajaani granite extending far to the S and below the Iisalmi block. Based on the seismic image the NW corner of the Lahnasjärvi block seems to form a 10 km thick wedge dipping in a shallow angle (10–20°) below the Iisalmi block. The contacts both with the hanging wall Iisalmi block and the footwall Hidden Iisalmi block appear in the seismic image sharp and probably represent major detachement surfaces. We interpret the Iisalmi and Lahnasjärvi blocks being thrust onto the Hidden Iisalmi block that is described below. The vertical-subvertical attitudes and lower amphibolite grade of the Proterozoic dolerites within the granulitic parts of the Iisalmi block suggest the thrusting had occurred already during the Archaean. During the Svecofennian orogeny, some reactivation of the Archaean detachment faults (e.g., the Laakajärvi fault) evidently took place, probably mainly in association with the "D4" when the Iisalmi and Lahnasjärvi blocks were pushed northwards and against the Kajaani complex (cf. Kärki et al. 1993, Kärki & Laajoki 1995). How large the related displacements, e.g. in terms of relative vertical uplifts of the Iisalmi and Lahnasjärvi blocks, actually were, is difficult to estimate. We do not see compelling reasons to assume anything more than a few kilometres at the maximum.

## Iisalmi block

The NW part of the Iisalmi block crossed by the FIRE 1 consists dominantly of upper amphibolite to granulite-grade banded amphibolite-tonalite-granodiorite gneisses (Fig. 5B), with local horizons of more homogeneous, less deformed, 2706±3 Ma old hornblende quartz diorites of the Naimakangas suite (Paavola, 1991, 2003). The banded gneisses of the middle-north part of the Iisalmi block have not been dated, but similar rocks in the central-southern part of the block show zircon ages up to 3.12 Ga and Sm-Nd depleted-mantle model ages up to ca. 3.20 Ga (Paavola 1988, Mänttäri & Hölttä 2002). There are several granulite facies domains in the central part of the Iisalmi block, in which banded mafic-felsic amphibolite-tonalite-throndhjemite gneisses are intruded by relatively undeformed enderbite plutons of ca. 2.70 Ga in age. The plutons of the Naimakangas suite in the NW part of the main Iisalmi block are probably cogenetic with these enderbites (Mänttäri & Hölttä 2002). The Rautavaara gneiss belt in the SE part of the Iisalmi block (Fig. 2) appears to be a dominantly younger (<2.80 Ga) unit than the main Iisalmi block, probably representing an independent tectonic terrane welded to the main block slightly before emplacement of the ca. 2.70 Ga enderbite and Naimakangas intrusions (Mänttäri & Hölttä 2002). A distinct component in the Rautavaara belt are enclaves of variably garnet, cordierite, orthoamphibole and chlorite containing gneisses; these obviously after strongly altered mafic-felsic volcanic and sedimentary rocks (Paavola 1999, Hölttä & Paavola 2000). The W part of the Iisalmi block is spotted by a N-S running chain of roundish, 1860±5 Ma old, late kinematic Proterozoic intrusions consisting variably of hornblendite, diorite, quartz diorite and granodiorites-granites (Paavola 1988, 1991, 2003, Ruotoistenmäki et al. 2001). One of these plutons (Kauppilanmäki) is crossed by FIRE 1, showing up in the seismic image as a patch of relatively poor reflectivity. In the SW, along the W margin of the block, there also occurs, locally abundantly, microtonalite dykes (Paavola 1988), whose emplacement probably slightly preceded the emplacement of the 1.86 Ga plutons.

It is important to note that the Iisalmi block preserves minor *in-situ* erosional remnants of Palaeoproteroic cover strata. Sariola-Jatuli type conglomerates and quartzites occur at its SE corner at Tahkovuori and Pisa (Fig. 2, Paavola 1984), and along its NE margin at Älänne (Fig. 2, Kontinen & Eskelinen 2005). The Vieremä (Salahmi) schist belt on its NW margin consists dominanly of lower Kaleva type, amphibolite-grade metaturbiditic wackes (Fig. 2, Laajoki & Luukas 1988, Korkiakoski & Laajoki 1988, Pietikäinen & Vaasjoki 1999). The absence of Jatuli type rocks from below the Vieremä belt suggests there occurred some significant uplift of the W part of the Iisalmi block preceding the presumably 2.0–1.95 Ga lower Kaleva deposition.

Palaeoproterozoic dolerite dykes are abundant throughout the Iisalmi block; at least 2.3 Ga and 2.1 Ga age populations are present (Toivola 1988, Toivola et al. 1991, Hölttä et al. 2000). Undeformed to weakly deformed, pristine to partly amphibolite grade metamorphosed pyroxene dolerites are a norm in the central part of the block crossed by the FIRE 1 line. Especially well preserved are the dykes in the areas of well-preserved, granulite facies Archaean rocks. The dykes in the N part of the Iisalmi block are usually relatively more extensively hydrated and also a bit more deformed than the dykes in its middle and S parts. But these dykes, similarly as the dolerite dykes elsewhere in the main Iisalmi block, are systematically vertical to subvertical (cf. Figs. 4B–4D, 5D), and seem to have preserved also their original strikes largely unchanged, which appear to have been usually NW-SE trending. This implies that also the crosscut host Archaean gneisses have their pre-Svecofennian strike and dip orientations largely intact.

The part of Iisalmi block crossed by FIRE 1 is characterized by a pronounced, distinctly well-layered reflectivity dipping in a shallow angle (ca. 20–30°) to the S-SE. The seismic fabric seems to reflect the gently S-SE-dipping (0–40°) mafic-felsic layering characteristic of the gneisses along the survey line (Fig. 5B). This is plausible as there are considerable density contrasts between the mafic (hornblende+plagioclase±clinopyroxene±orthopyroxene±garnet) and felsic (quartz+plagioclase+biotite±hornblende) lithosomes of these usually distinctly well-layered gneisses. The FIRE 1 images suggest that the Iisalmi block would form a plate with a thickness of 15 km for its middle part, and a sharp, detachment style basal contact dipping in a shallow angle towards the S-SE. Metamorphic pT-determinations on the Archaean garnetiferous pyroxene amphibolites (Fig. 5C) in the Vieremä area in the N yield a relatively high pressure indication of 11.3 kb, whereas somewhat lower values of 8–10 kb are obtained from similar amphibolites in the Varpaisjärvi area in the S (Hölttä & Paavola 2000). Noting the probable N-verging transport and possible related uplift of the Iisalmi block in the late "D4" stage of the Svecofennian orogenesis (cf. Kärki and Laajoki, 1995), the observed palaeopressure difference could perhaps reflect a bit more Proterozoic uplift and exhumation in the N part of the block.

It is important to recognize that the Palaeoproterozoic cover sediments on, and dolerite dykes in the Iisalmi block both have been peakmetamorphosed under the lower amphibolite facies pT conditions, with no evidence of preceding high amphibolite or granulite facies metamorphism, not even for dykes that are hosted in well-preserved granulites. This fact attests to that the exhumation of the granulites of the Iisalmi block was first and foremost an Archaean process. Overall, there is little evidence to support interpretations of principally Svecofennian exhumation of the granulite blocks, which has been suggested, e.g., by Paavola (1986) and Ward & Kohonen (1988).

The W contact of the Iisalmi block is coinciding with the boundary zone between the EFAC and Svecofennian domains, which is often understood in terms of a collisional suture. The FIRE 1 crosses the ESBZ at Luupuvesi ca. 15 km to the W of Vieremä, where the estimated outer edge of the EFAC locates below (overthrust) Svecofennian migmatites and amphibolites of the Näläntö-Piippola belt. Some 30 km to the S of Luupuvesi, Archaean gneisses of the Iisalmi block are seen in a direct contact against

Svecofennian migmatites, and the situation persists for over 100 km further towards the S. We infer that the situation would very probably be similar also at Luupuvesi if the seemingly relatively thin and from W thrust Näläntö-Piippola gneiss belt (Laajoki & Luukas 1988, Pietikäinen & Vaasjoki 1999) would be removed. The overall impression from the available geological data is that the ESBZ is for its whole length across the central Finland a very abrupt feature, in the middle-lower crust possibly defined by just a single, very narrow, vertical strike-slip type fault/shear zone.

## DISCUSSION

### Proterozoic versus Archaean tectonic development

Considering the tectonic history of the EFAC, it seems reasonable to assume that its present tectonic structure and seismic properties would be a combined result of principally three main tectonic factors: (i) the late Archaean orogenesis, (ii) extensional tectonics during the 2.5–2.0 Ga platformal stage and subsequent ca. 1.95 Ga break-up of the Karelian craton, and (iii) tectonic reworking in the connection of the Svecofennian orogenesis.

During the 2.5–2.0 Ga period the EFAC was part of a relatively stable supercraton (Superia?, cf. Bleeker 2003), from which the Karelian craton seems to have spawned ca. 1.95 Ga ago (Peltonen et al. 1996, 1998). It seems that by ca. 2.3 Ga, at the latest, the entire craton had been eroded and peneplanised to the sustained thickness of ca. 35±5 km that is usual for Archaean cratons. During the following 400 Ma platformal period, the supercraton, and EFAC as part of it, was, probably for most part of the time, thinly covered by mature sandstones and carbonates (Kontinen 1986, Laajoki 2005). The many dyke swarm episodes (2450, 2300, 2200, 2100, 1970 Ma) indicate repeated periods of mantle activation below and connected extensional tectonics within the craton, probably related to mantle plumes impinging the base of the lithosphere. Nevertheless, the relative rarity of coarse alluvial and volcanic strata, and lack of evidence of 2.4–2.0 Ga compressional deformation in the Karelian cover sequence suggest that no major rifting and thinning or major shortening and related thickening of the crust occurred within this long period of relative tectonic quiescence.

The western margin of the EFAC appears very sharp-cut and there is relatively little evidence for rifting in its surface geology and that could be related to the inferred 1.95 Ga break-up of the Karelian craton. Kontinen (2002) has addressed this enigma to strike-slip cut out and removal of the rifted/attenuated parts of the craton margin already in a very early stage of the Svecofennian tectonics.

Owing to the foreland position of the EFAC during the putatively collisional Svecofennian orogeny, its related structural modification could have been severe. The seismic data alone do not form an unambiguous basis for reliable evaluation of the nature and scale of the possible Svecofennian reworking, but this can be done only in integration with other geophysical and geological information. With respect to uppermost crust an ideal case would be to have geological marker(s) in the EFAC that would facilitate distinction and quantification of the Svecofennian tectonic effects. Fortunately, we have an excellent such a marker in the 2.5 to 1.95 Ga dolerite dykes, which dissect the EFAC in many dense swarms. These dolerites are a tremendously useful tool because they are ubiquitous and most of them originated as vertical, kilometres to tens of kilometres long, usually spectacularly straight-striking narrow dykes. Moreover, there is no evidence of their metamorphism or deformation before the Svecofennian orogeny. Altogether, the 2.4–1.97 Ga dolerites provide a perfect media for analysing the metamorphic and deformation effects of the Svecofennian orogeny on the EFAC.

Observations on the 2.5–1.95 Ga dolerite dykes along the FIRE 1, summarised briefly in the sections above, indicate that the Svecofennian tectonic effects on the EFAC were of surprisingly limited magnitude. This is apparent from that there is evidence of significant distortion, tilting and/or rotation of the dolerite dykes, and thereby of their Archaean hosts only for the Kajaani complex and Lahnasjärvi block, both locating between the KSB and the Iisalmi block. This is somewhat surprising observation considering the evidence of amphibolite facies Svecofennian (1.85–1.80 Ga) metamorphic overprinting across the entire EFAC. Massive Svecofennian thrusting onto the EFAC has previously been inferred as the ultimate cause of this overprinting (Kontinen et al. 1992, Pajunen & Poutiainen 1999). The relatively unreworked nature of the EFAC implies that the Svecofennian thrusting must have been of thin-skin nature without any major tectonic reactivation in the EFAC. To construe the actual tectonic configuration that was supporting the remarkably longevity of the 1.9–1.80 Ga thrust loading on the EFAC is out of the scope of this paper, but we suspect this probably was connected with the position of the Karelian craton in this time in between the opposite-verging and broadly concurrent Svecofennian and Belomorian orogens.

So, if the thrust stack style structure of the EFAC as we interpret it in the Fig. 3 was essentially an Archaean output, what were the timing and tectonic character of the causative tectonic processes? Isotopic age and thermo-barometric data across the EFAC indicate that the accretional tectonism causing its stacked structure occurred ca. 2.70 Ga ago at high amphibolite to granulite facies metamorphic conditions. The stacking involved gneissic-migmatitic units, some of them registering high amphibolite facies to granulite facies temperatures and also relatively high pressures up to 11 kb (Hölttä & Paavola 2000, Mänttäri & Hölttä 2002). This suggests that the process leading to the tectonic stacking and subsequent cratonization of the EFAC was related to a major continent-to-continent style orogenic event. In this event the Pudasjärvi-Iisalmi and Kuhmo-Ilomantsi segments of the EFAC were bulldozed together (at the Kainuu suture) within a (at 2.7 Ga) much wider (in the west, note the “lost craton” separated from the Karelian craton ca. 1.96 Ga ago) collisional orogenic system than what is now preserved in the EFAC.

## Jormua ophiolite and ”Kainuu suture”

One of the important questions to which the FIRE 1 was expected to contribute was that of the formative tectonic setting of the Jormua ophiolite and the enclosing Upper Kaleva metasediments. Two contrasting models have been proposed: (i) the Jormua ophiolite and enclosing metasediments represent remnants of a rift-basin closed at ca. 1.9 Ga ago, and in which the opbiolites were formed ca. 50 Ma earlier (e.g. Kontinen 1987, Kohonen 1995), or (ii) a basal part in a nappe complex in which the ophiolite was transported ca. 1.90 Ga ago to its present position (from a root zone to the “west” of the present E margin of the EFAC) (Peltonen et al. 1996). We consider the FIRE 1 seismic image, likewise unpublished gravity models (Seppo Elo, pers. comm.), which consistently suggest that the Kalevian mica schists in the middle of the KSB would form just a thin (<2–3 km) surficical veneer on the >55 km thick EFAC, provide strong support for interpretations that the Jormua allochthon is an erosional remnant of an overthrust sheet rather than *in situ* fill of any sort of a crustal scale rift basin. Another strong argument for this interpretation is the exiguity of evidence in the sedimentary and structural record of the KSB for a cycle between 2.0–1.95 Ga crustal-scale rifting through a Red Sea type narrow ocean and the post-1.9 Ga collisional basin closure (which in terms of rift models is required to explain the ophiolites and deep sea character of the Upper Kaleva).

It is important to note that the prominent “D4” strike-slip faults along the Kainuu schist belt coincide with the underlying Archaean (ca. 2.7 Ga) suture between the Iisalmi-Pudasjärvi and Kuhmo main segments of the Karelian craton. This is probably not by chance, but rather the D4 deformation within the KSB was controlled by the inherited crustal weakness related to the underlying Archaean suture. Thus, although there was no Svecofennian suturing across the KSB, the late Svecofennian “D4” deformation of the belt nevertheless had a kind of, although inherited and indirect, suture aspect.

## EFAC-Svecofennia boundary

FIRE 1 profile crosses the EFAC-Svecofennia boundary zone (ESBZ) at Luupuvesi ca. 10 km to the W of Vieremä, thug allowing seismic based assessment of the tectonic nature of this major domain boundary. Various models of the nature of the ESBZ have been presented; too many to be discussed here in detail, but the most often proposed include: the ESBZ represents either (i) a collisional-accretional suture, (ii) a strike-slip fault or (iii) a combination of both (e.g. Park 1985, Nironen 1997, Korsman et al. 1999, Lahtinen et al. 2005). The almost indistinguishable nature of the ESBZ in the FIRE 1 seismic data is an enigmatic feature for a collissional orogenic front since no evidence is present for such seismically well perceptible major frontal thrust ramp which is typical of frontal edges of many initially perpendicular collisional orogens, such as the Mesoproterozoic Grenville (White et al. 2000) or Palaeoproterozoic Trans-Hudson orogen (White et al. 2000). We note that Kontinen (2002) has proposed that the ESBZ would involve a narrow transcurrent fault zone along which the Svecofennia strike-slipped to its present position as a largely “ready-assembled” protocontinent, perhaps as late as, or even later than ca. 1.85 Ga ago. In this model the strike-slip emplacement of the Svecofennia was assumed to have been preceded by a more perpendicular collision of the EFAC by some forerunning, continental-scale landmass, which was subsequently cut off and transported to an unknown destination. This is definitely not a mainstream view, but as any detailed studies especially devoted on the tectonic evolution of the ESBZ are yet missing, exact timing of the final docking of the Svecofennia must be considered an open question. Anyway, one aspect in the strike-slip model of Kontinen (2002) would nicely explain the plain seismic image of the ESBZ; namely, he proposed that the rifted/attenuated (at ca. 1.95 Ga) and subsequently collisionally shortened (at ca. 1.90 Ga) margin of the Karelian craton was cut off and strike-slip transported away already in a very early stage of the Svecofennian tectonism. If the slip was concentrated in a narrow vertical zone a seismically relatively undistinct boundary could have been generated. This is what we currently see between the EFAC and Svecofennia.

It is worth mentioning that in some tectonic interpretations the Iisalmi and Lahnasjärvi blocks have been seen as an exotic allochthonous unit transported and thrust onto the EFAC in an early stage of the Svecofennian orogenesis (e.g. Park 1985; Korja et al. 2004). However, at least two serious arguments can be raised against this hypotheses. First, obvious Jatulian and Kalevian metasediments similar to those that fringe the eastern Kuhmo-Ilomantsi segment of the EFAC are found also on the Iisalmi block as e.g. at Tahkovuori, Alänne and Vieremä (Fig. 2; Paavola 1984, Paavola 2003, Kontinen & Eskelinen 2005). Second, the Palaeoproterozoic dolerite dyke swarms in the Iisalmi block also seem similar to those in the Kuhmo-Ilomantsi segment of the EFAC, even in terms of the present dyke orientation patterns. Overall, these similarities in the 2.5–1.9 Ga geologies between the Iisalmi block and Kuhmo-Ilomantsi domain badly compromise the hypothesis about their post-1.9 Ga Svecofennian tectonic juxtaposition.

Models of primarily Svecofennian exhumation of the granulites in the Iisalmi block have been proposed e.g. by Paavola (1986) and Ward and Kohonen (1988). However, the lack of evidence of granulite facies metamorphism of the Palaeoproterozoic dolerites cutting the granulites is at odds with the primarily Svecofennian exhumation. Adding to this that the dolerites (also in the granulite domains) preserve their intrusion-stage dip and strike attitudes largely untilted and unrotated, the possible Svecofennian exhumation of the granulites and the Iisalmi block is constrained to a simple, maybe only a few kilometres on simple vertical uplift. In any case, some post-1.86 Ga Proterozoic exhumation of the block is required to explain the exposure of the 1.86 Ga granitoids along its W margin.

## Lower crust-mantle interface

Our main focus in this paper was in the structure of the uppermost 20 km of the crust. There are some distinct features in the FIRE 1 deep seismic patterns that we want to comment, however. Archaean-Proterozoic cratons usually have well -reflecting layered lower crust and a sharp seismic Moho typically locating at the depth of 35±5 km (e.g. Clowes et al. 1996, Ludden & Hynes 2000, Reading & Kennett 2003). However, in the case of the EFAC, the lower crust is weak and incoherent in its reflectivity, and the reflection seismic Moho is a barely discernible feature (Fig. 3). Although the tectonic causes for a seismically transparent lower crust and Moho could be many (Eaton, 2005), we consider that in this case the ultimate cause was the obviously exceptionally long-lasted, from 1.9 to 1.82 Ga persisted Svecofennian thrust burial of the EFAC. The associated conductive (plus *in situ* radiogenic) heating of the EFAC peaked (at 1.85 Ga?) with amphibolite facies temperatures (500–600 °C) for the present surface (Kontinen et. al. 1992, Pajunen & Poutiainen 1992, Kontinen 2002), and by all reason at much higher temperatures (>700–800 °C) for deeper levels of the crust. Surface evidence indicates that the Svecofennian thermal peak was attained at static conditions (e.g. Koistinen, 1981; Pajunen & Poutiainen, 1999). So if the high temperature metamorphism in the lower crust also was static and resulted in significant recrystallization (annealing), major reduction in preferred orientation of anisotropic minerals (after previous deformations) such as amphiboles and micas, and related reduction in seismic anisotropy and reflectivity of the lower crust could be suspected. The evidence cited below of massive, granoblastic textures of lower crustal xenoliths in the kimberlite pipes emplaced through the western EFAC provides support of this hypothesis.

Besides causing dehydration and recrystallization (annealing) across the EFAC, the heating related to its long-lasted 1.90–1.80 Ga burial should have been for the middle-lower crust high enough to cause its (partial) melting. However, the relative rarity of Proterozoic granites within the EFAC suggests that only limited related middle-lower crustal melting took place. The principal reason to this probably was the supposedly low granite melt fertility of such dominantly tonalitic-throndhjemitic-granodioritic crust as the EFAC seems to comprise from bottom to top. However, within the area considered here, some localized Proterozoic granite magmatism occurred at ca. 1.86 Ga and 1.80 Ga. The partly mafic nature of the 1.86 Ga plutons and their concentration in a narrow zone near the ESBZ suggest the primary magmas were of mantle origin and probably linked with the late-Svecofennian strike-slip tectonism. The ca. 1.80 Ga Kajaani type pegmatoid granites, however, are an obvious product of Svecofennian infracrustal melting, that seems to reflect the rapid pressure release in the late stage of the presumed 1.84–1.81 Ga extensional collapse of the Svecofennian orogeny boundary zone (e.g. Korsman et al. 1999). However, as we argued above, the preferred association of the 1.8 Ga granites with less thoroughly migmatized Archaean metasedimentrary gneisses suggests that the actual melt production was more fertility than temperature constrained.

Despite the effects of the 1.9–1.8 Ga burial metamorphism, there still is in the FIRE 1 data a faint drop in the lower crustal reflectivity that is defining a surface (cf. Fig. 3), which approximately coincides with Moho previously estimated from refraction seismic data (e.g. Korja et al. 1993, Korsman et al. 1999). It seems that the crust at the EFAC-Svecofennia boundary was quite thick, ca. 60 km, but would thin eastwards within a distance of ca. 100 km to a more normal thickness (for Archaean cratons) of ca. 43 km at Vartius at the NE end of the FIRE 1. A late Svecokarelian 1.86–1.80 Ga mafic-magmatic underplate, indicated by a dense, high-velocity layer at 40–60 km deep at the base of the lower crust, is thought to compensate the thick crust at the EFAC-Svecofennia boundary (e.g. Korsman et al. 1999). Intriguingly, the present total thickness of the EFAC+ Proterozoic cover+Svecofennian underplate seems to correlate positively with the between 1.85–1.80 Ga existed thickness of the Svecofennian trust complex and related burial depth of the EFAC (Svecofennian heating of its present surface). Obviously, the deeper the burial was, the more there was "post-thrust" adiabatic melting of the mantle generating a thicker mafic underplate and thereby possibilities a thicker total crust to be created and preserved.

The transparent nature of also the dense/high velocity underplate at the base of the lower crust of the EFAC suggest it was of massive, homogenous nature or that it emplaced well before the rapid removal of the Svecofennian overthrust complex so that also it was affected by the above inferred late to post-Svecofennian heating and related static recrystallization of the lower crust (of. McBride et al. 2004). As there is kimberlite xenolith evidence of heterogeneous Archaean-Proterozoic nature but yet uniformly massive granoblastic textures and 1.80–1.73 Ga metamorphic ages in the underplate layer (cf. Peltonen et al., 2006), the latter scenario seems more probable.

Based on interpretations of the FIRE 1 seismic image, presence of early Svecofennian (1.92 Ga) lower arc crust underthrust below the W margin of the EFAC has been proposed (e.g. Korja et al. 2004). However, there are no observations of fragments from such arc crust in the kimberlite pipes intruded in the EFAC just some 80 km from the EFAC-Svecofennia boundary (cf. Peltonen et al., 2006, and references therein). Another important constraint from the kimberlite studies is that the mantle below the western margin of EFAC is demonstrably of Archaean SCLM origin with evidence of possible Svecofennian effects only for its uppermost 60–110 km layer (Lehtonen 2005; Peltonen and Brügmann 2006). This, if anything, is strong evidence for the very sharp-cut, vertical and probably very narrow fault zone of the ESBZ extending to a depth of > 250 km.

## CONCLUDING REMARK

The FIRE 1 deep reflection seismic survey opened a new view in the structural architecture of the N part of EFAC. A preliminary model of the contained crustal structure, based on an integrated interpretation of available geological and FIRE 1 data was provided in this paper. When constructing the cross-section model in Fig. 3, we tried to keep our feet on the ground, and provide an interpretation as free of unprovable components as possible. However, interpretation of seismic (and also geological) data of high-grade metamorphic-igneous crust of complex tectonic history is generally very challenging. In the first place this is due to the inherent difficulty of interpretation of the seismic data of such crust. There are almost always several possible interpretations of reflections, and usually very restricted, any means are available, to sort out the most relevant of them (especially for deep reflections). An other major difficulty arises from the fact that the method is not particularly well suited for analysing of subvertical to vertical structures or structures with abundant 3D complexity. Consequently, there easily may be even major crustal features along the FIRE 1 survey line which will not appear at all in the recorded data, or show up in a too hazy or complex way to be correctly interpreted. Obvious examples of such features are the Kainuu-Outokumpu and EFAC-Svecofennia "sutures" that, although being major features in the surface geology and probably also deeper in the crust, do not, however, much differentiate in the FIRE 1 data. Therefore, because even basic information on ages the main phases of magmatism, deformation and metamorphism in many of the included tectonic blocks is still unavailable, it is clear that any interpretation of the FIRE 1 data and crustal structure of the EFAC must yet be considered very much as "work in progress". Finally, it cannot be overly emphasized that reflection seismic data for such highly evolved (collisional orogenic) crust as the EFAC are very strongly biased, if not entirely restricted, to the features related to the very latest accretionary orogenic processes. Thus although seismic imaging is potentially very useful in analysing the finite structures and assembly of orogenic crust, it may tell only little on the possibly very complex preceding tectonism.

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