INSTITUTE OF SEISMOLOGY
UNIVERSITY OF HELSINKI

REPORT S-58

EVOLUTION OF THE MIDDLE CRUST IN CENTRAL FENNOSCANDIA

EXCURSION 2013 of MIDCRUST Project

19th – 23rd August 2013

PROGRAMME AND EXCURSION GUIDE

Kaisa Nikkilä, Francis Chopin, Pietari Skyttä, Timo Kilpeläinen, Tapani Rämö, Pentti Hölttä, Annakaisa Korja

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Helsinki 2013

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Foreword

The excursion is arranged by the MIDCRUST project, an on-going national multidisciplinary research project focusing on the Evolution of the middle crust in Central Fennoscandia. It is funded by the Academy of Finland and K.H. Renlund foundation. ***This excursion*** provides a broad overview of Paleoproterozoic tectonic and magmatic processes that took place in the vicinity of middle crust in this part of the Fennoscandian Shield. The excursion will be a very good opportunity to discuss evolution of syn- to late-orogenic processes and how they can be better understood by using cross-disclipinary geoscientific studies: petrology, geochemistry, isotope geology, structural geological methods, seismic reflection, magnetic and gravimetric data and modelling.

The excursion is organized by the Universities of Helsinki, Turku, Åbo Akademi and Geological Survey of Finland. The excursion traverses exposed parts of upper middle crust and lower upper-crust in Central-Finland and Ostrobothnia. The excursion studies FIRE deep seismic reflection lines and their surroundings. It begins from Pyhäjärvi, Central-Finland, and proceeds via Karstula, Kyyjärvi, Perho and Kauhava to Kokkola, Bothnian Bay. The excursion will then follow coastline to the south. The excursion ends at Vöyri. (Fig 1-3)

Helsinki, August 15.8.2013

Annakaisa Korja, Francis Chopin, Kaisa Nikkilä, Pentti Hölttä, Tapani Rämö, Pietari Skyttä, Timo Kilpeläinen

MIDCRUST Excursion organizers

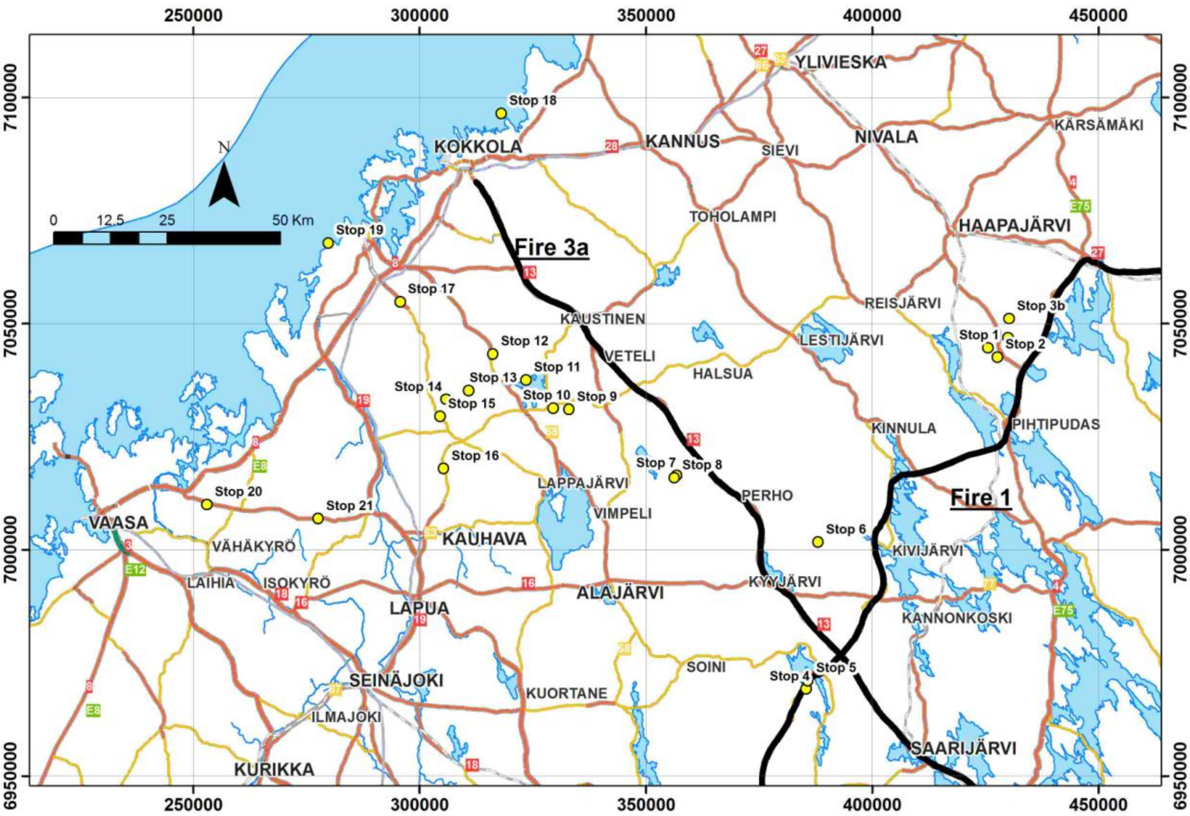


Figure 1 Road Map with excursion sites and seismic lines

Excursion on "Evolution of the middle crust in Central Fennoscandia"

Day 1.	**Mini-symposia and drive to Central Finland Granitoid complex**	
Monday	08:30–09:00	Registration
19 august	09:00–11:00	Mini-symposia at Kumpula campus, Helsinki
	11:00–11:30	Lunch at Kumpula campus
	11:30–12:00	Car pack
	<u>12:00</u>	<u>Beginning of the excursion</u>
	12:00–15:30	Drive to Central Finland
	15:30–16:30	Jyväskylä road quarry – *Low-angle deformation zone/crustal flow structures*
	16:30–18:30	Drive to Pihtipudas
		Accommodation at Pihtipudas
	19:30	Dinner at Pihtipudas
Day 2.	**Upper-middle crustal detachment and Central Finland orogenic plateau/magmatic core**	
Tuesday 20	**Leaders: Kaisa Nikkilä, Annakaisa Korja, Olav Eklund**	
20 august	8:30–9:00	Drive to Elämäjärvi
	9:00–11:00	Elämäjärvi shear zone – *Upper-mid-crustal detachment zone (STOP 1-3)*
	10:30–12:30	Drive to Karstula
	12:30–13:30	Lunch at Viitasaari
	13:30–15:00	Karstula quarry – *Sheared granitoids (STOP 4)*
	15:00–15:30	Drive to Southern Karstula quarry
	15:30–16:30	Karstula South – *localized deformed subalkaline granitoid rock (STOP 5)*
		Accommodation at Karstula Evangelical Institute
	19:00	Dinner (and sauna) at Karstula Evangelical Institute
Day 3.	**Central Finland orogenic plateau – Vaasa dome external part**	
Wednesday	**Leaders: Kaisa Nikkilä, Annakaisa Korja, Francis Chopin, Olav Eklund**	
21 august	8:30–9:30	Drive to Kyyjärvi
	9:30–11:30	Tuohikangas – *Sub-vertical shear zone within metasediments and granitoids (STOP 6)*
	11:30–12:30	Pack lunch on outcrop
	12:30–13:30	Drive to Perho/Peltokangas area
	13:30–14:30	Peltokangas area – *Sheared contact between CFGC and Vaasa dome (STOP 7–8)*
	14:30–15:00	Drive to the Evijärvi area
	15:00–17:00	Evijärvi East – *Primary structures within the dome (STOP 9–11)*
	17:00–18:00	Drive to Kauhava
		Accommodation at Kauhava
	19:00	Dinner at Kauhava
Day 4.	**Vaasa dome – From low grad metamorphism to metatexitic part**	
Thursday	**Leaders: Francis Chopin, Pentti Hölttä, Annakaisa Korja, Olav Eklund**	
22 august	8:30–9:00	Drive to the Evijärvi area
	9:00–13:00	Evijärvi to Kortesjärvi – *Polyphased deformation away from the dome core (STOP 12–14)*
	13:00–14:00	Pack lunch on outcrop
	14:00–14:10	Drive to Kortesjärvi area
	14:10–16:00	Kortesjärvi area – *Polyphased deformation at the margin of the dome core (STOP 15–16)*
	16:00–16:40	Drive to Forsby
	16:40–17:40	Forsby – *Polyphased deformation at the margin of the dome core (STOP 17)*

17:40–18:00 Drive to Kokkola
Accommodation at Kokkola
19:00 Dinner at Kokkola

Day 5. Friday 23 august

Vaasa dome – From metatexite to diatexitic /granitoid cores

Leaders: Francis Chopin, Pentti Hölttä, Anna Kotilainen, Olav Eklund

8:30–09:00 Drive to Kokkola coastal line
09:00–10:00 Kokkola outcrop – *Polyphased deformation towards the dome core (STOP 18)*
10:00-11:00 Drive to Nykarleby coastal line
11:00-12:00 Jakobstad/Pietarsaari outcrop – *Polyphased deformation within dome core (STOP 19)*
12:00–12:30 Drive
12:30-13:30 Lunch at Nykarleby
13:30–14:45 Drive to Vöyri West
14:45–15:30 Vöyri quarry – *Megacrystic Vaasa granodiorite (STOP 20)*
15:30-16:15 Drive to Vöyri East
16:15-17:00 Frakaninkalliot – *Even-grained Vaasa granodiorite (STOP 21)*

<u>17:00</u> <u>End of the excursion</u>

17:00-23:00 Drive to Helsinki (dinner at 18:00 on the road)

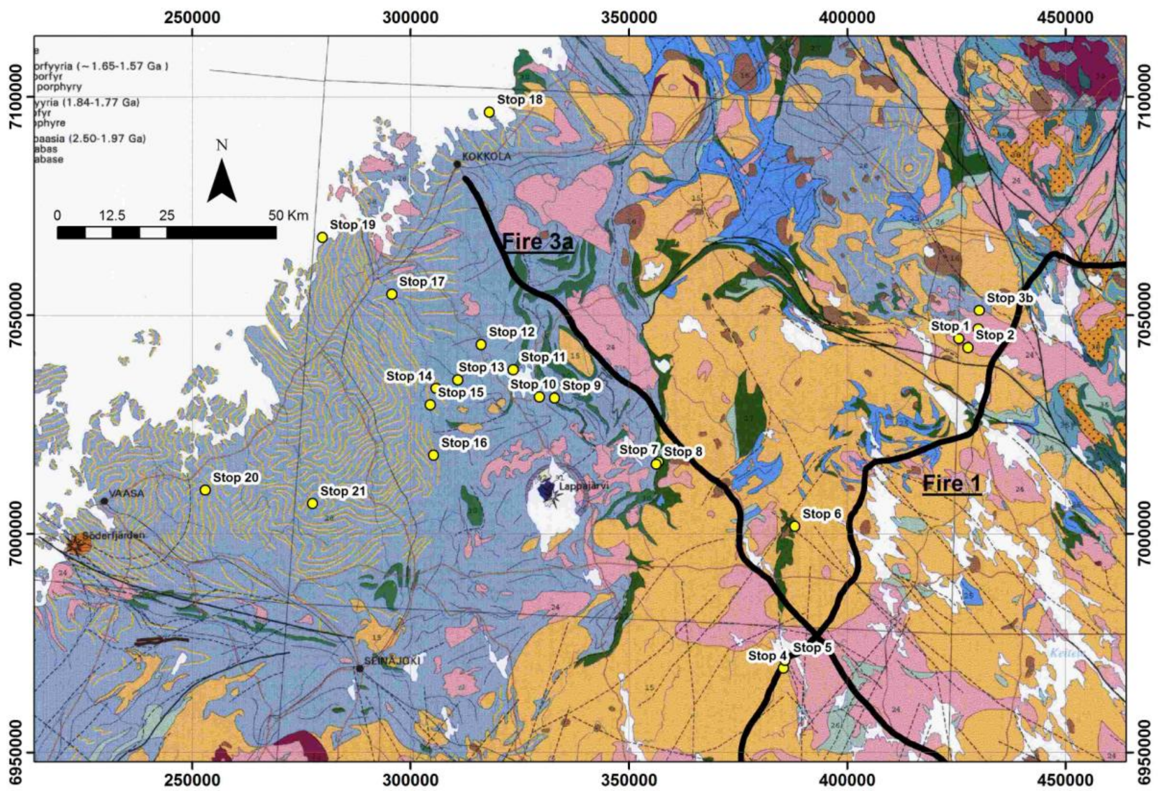


Figure 2. Excursion sites with 1:200000 bedrock map (courtesy of Geological Survey of Finland).

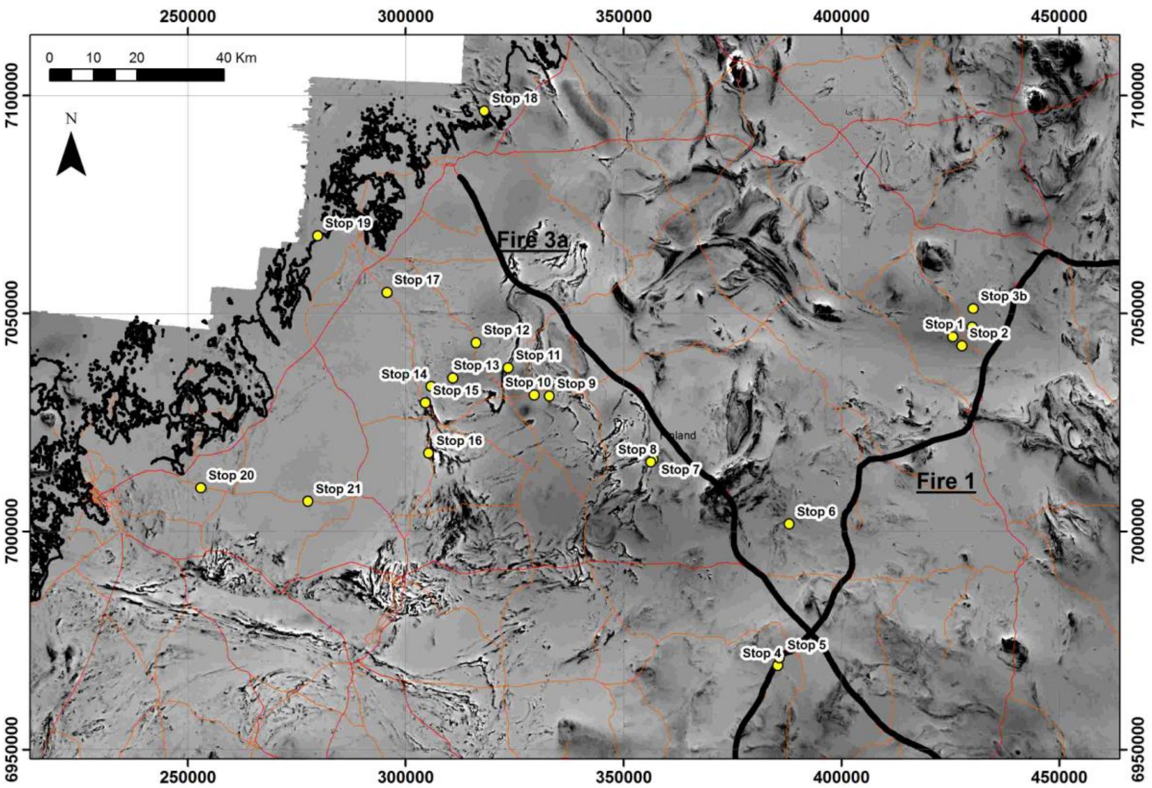


Figure 3. Excursion sites with an aeromagnetic map (courtesy of Geological Survey of Finland).

Introduction

The Svecofennian bedrock is a granite gneiss terrane that represents 15-20 km deep section through an evolved core of a paleo-orogen (Fig. 4). It is part of a larger orogenic system associated with the construction of the Nuna supercontinent. Similar to Alpine systems the Svecofennian orogeny consists of arc terranes accreted at an older continental margin and it has been evolved in many stages including subduction, oblique collision and post-collisional extension [*Lahtinen et al.*, 2005; *Korja et al.*, 2006]. The present exposure level of the Svecofennian orogenic crust is probably very close to the upper-middle crust transition and, therefore exposed bedrock is an interplay between upper middle crustal and lower upper crustal blocks.

The deep seismic reflection profiles (FIRE) crossing the core of the Svecofennian orogen in two perpendicular directions suggest that the more than 55 km thick crust is composed of three seismically distinct layers that was developed after collision (Fig.5-6). The profiles show complementary crustal scale structures of compression and extension in orthogonal directions [*Korja and Heikkinen*, 2008; *Korja et al.*, 2009]. Preliminary analogue modeling on the rheological and deformational behavior of a three layer crust in convergence coupled with perpendicular extension suggests that some of the large-scale crustal structures seen on FIRE profiles were either formed or at least reactivated during post-collisional spreading [*Nikkilä et al.*, 2009].

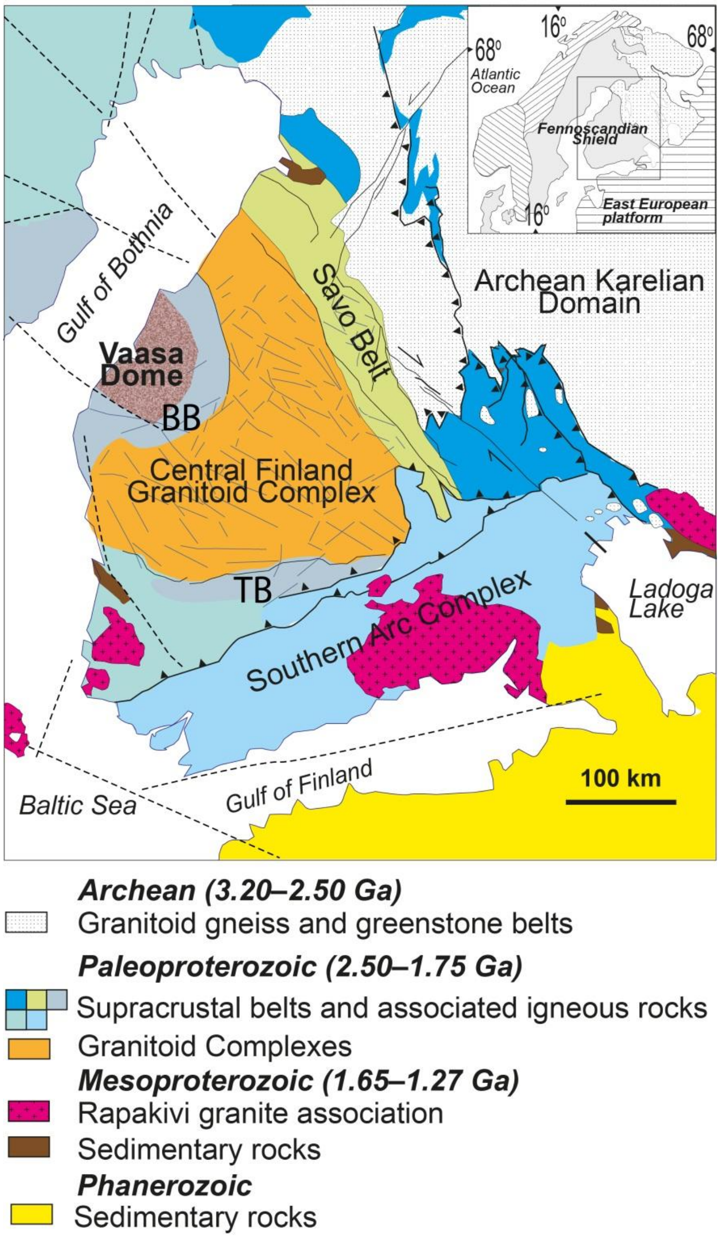


Figure 4 Tectonic map of the Svecofennian orogen in Northern Europe [modified after *Korja et al.*, 2009]

Central Finland forms the core of the Svecofennian orogen, where microplates, intervening basins and arcs are accreted to continental plate (Karelia) at around 1900 Ga [*Lahtinen et al.*, 2005, *Korja et al.*, 2009]. The original thickening took place in the directions of the plate movements. Because the converge was oblique, large strike slip faults developed along the Keitele microcontinent margin. As a consequence, some of the accreting material was diverted along the faults and may display escape tectonics. Lateral spreading of the orogen was possible towards the west and north, where the crust was thinner. Core complex formation is predicted at the western non-fixed boundary.

This excursion will study structural, metamorphic and magmatic evolution of **Central Finland granitoid complex (CFGC) and Vaasa gneiss dome. CFGC** is situated on the former upper plate (Keitele mc) and it displays the deformation and magmatic patterns of the lower part of the upper crust and hosts exposures of upper-middle crust (U-M or S-I) detachment zone (**Elämäjärvi deformation zone**). **Vaasa gneiss dome** displays a granite core surrounded by partially molten supracrustal lithologies. It is hypothesized to represent an up-rise of the westward flowing middle crust.

Geological background

In its central part, the Svecofennian orogen comprises rocks formed within the Karelian continent, Savo Arc and Western Finland Arc Complex and is bordered in the south by the Southern Finland Arc Complex (Fig 4) [*Korsman et al.*, 1999]. The major terrane boundaries are marked by crustal-scale electrical conductors [*Korja et al.*, 1993; *Korja*, 2002] and crustal-scale reflective zones [*Korja and Heikkinen*, 2008]. An evolutionary model [*Lahtinen et al.*, 2005; *Korja et al.*, 2006] suggests that the central part of the orogen is underlain by a Paleoproterozoic microplate (Keitele) under which oceanic crust was subducting from the east and south producing the Savo and Tampere Belts, respectively. After the surrounding ocean was consumed, the microplate collided with the continental parts of the arriving plates and the orogeny was initiated. The crust overthickened and collapsed and in these processes the crust attained its characteristic large thickness (> 56 km), thick high velocity lower crust [vp> 6.8 km/s between depths 30-60 km; *Korja et al.*, 1993] and thick high velocity lithosphere [> 200 km; *Sandoval et al.*, 2004].

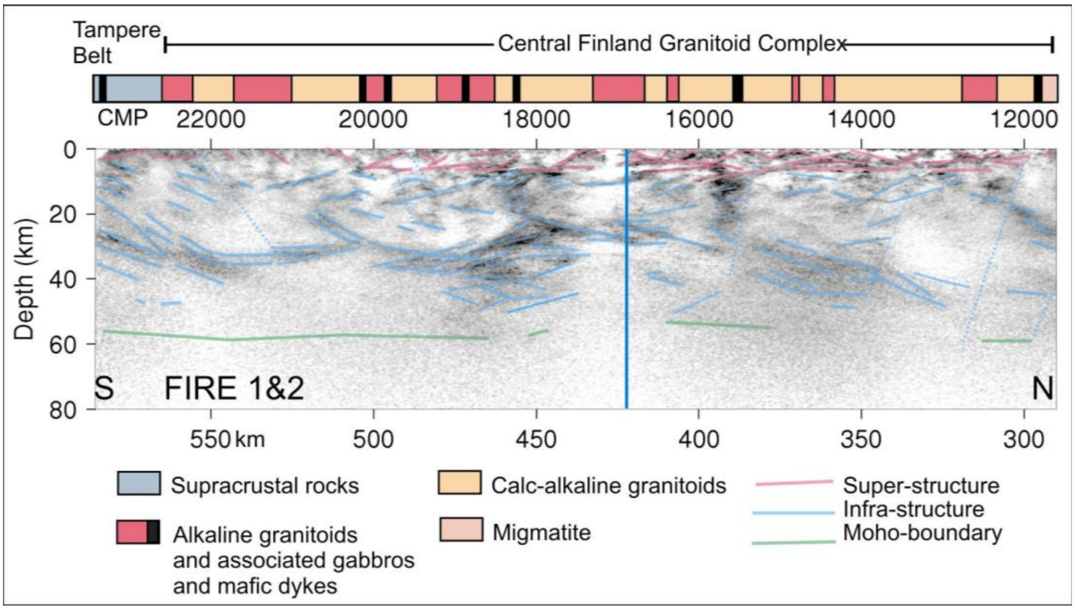


Figure 5 ***An interpretation of the crustal structure along deep seismic reflection profile FIRE 1&2 after Korja et al. [2009]. No vertical exaggeration. Note the difference in reflective properties of upper, middle and lower crust.***

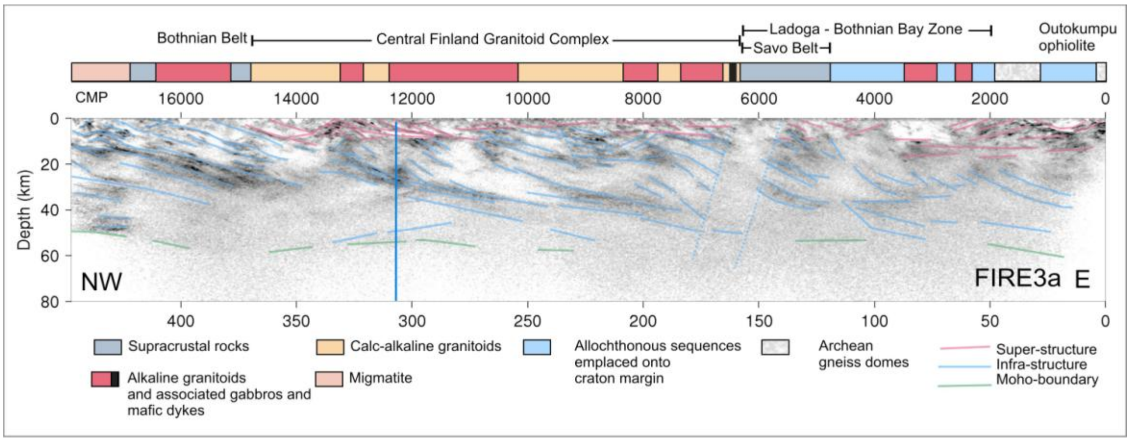


Figure 6. ***Deep seismic reflection profile FIRE3a [Korja and Heikkinen, 2008] perpendicular to Svecofennian orogenic front.***

The Western Finland Arc Complex (WAC) comprises supracrustal belts (**Bothnian Belt – BB**, Tampere Belt – TB) surrounding the Central Finland Granitoid Complex (CFGC) (Fig. 1). The Bothnian Belt (1.90-1.87 Ga) in the west comprises a large migmatite-granitoid complex as well as metaturbiditic sequences hosting mafic volcanic units- collectively referred to as Vaasa gneiss dome [Chopin et al., 2012]. Both Bothnian and Tampere supracrustal belts have been subjected to regional metamorphism and poly-phase deformation and have been intruded by calc-alkaline and minor alkaline 1.89-1.86 Ga granodiorite and granite intrusions [*Nironen*, 1989; *Mäkitie*, 2000; *Korsman et al.*, 1999].

Regional-scale low-altitude **aeromagnetic anomaly map** (Fig. 3) provides an excellent tool for studying various regional-scale structural features, especially high-strain zones. The more magnetic supracrustal and mafic rocks form local anomaly maxima in the background composed of granitoid intrusions and migmatites. The postcollisional alkaline granites as well as Vaasa gneiss dome porphyritic granites are displayed as homogenous, featureless magnetic minima whereas in outcrop they show discrete and localized shearing and faulting. The pervasively deformed granitoid rocks and migmatites are magnetically heterogeneous with the deformation patterns giving rise to distinct magnetic fabrics. Shear zones cutting the bedrock are displayed as linear magnetic minima or maxima disrupting the continuous background magnetic fabric.

Central Finland granitoid complex (CFGC) was emplaced during syn- and post-collisional orogenic events at 1.89-1.87 Ga. The intrusion of the igneous rocks was coeval with the peak of the HT-LP metamorphism (T = 700 -800^{o} C, P = 400 - 500 MPa) and deformation [*Korsman et al.*, 1999]. **CFGC** consists of two suites of granitoid intrusions and associated mafic and volcanic rocks [*Elliot et al.*, 1998]. The volcanic rocks are somewhat older than the intrusive rocks [Mänttäri, pers. com]. The marginally older suite of granitoid rocks is composed of calc-alkaline tonalites, granodiorites and granites (1.90-1.88 Ga) with minor amounts of mafic plutonic rocks and co-magmatic volcanic sequences [*Harris et al.*, 1986; *Korsman et al.*, 1997; *Nironen et al.*, 2000].]. The suite has traditionally been called syncollisional [*Korsman et al.*, 1997], but based on the ongoing studies it post-dates collision. The suite contains remnants of folded supracrustal fragments and the rocks are pervasively deformed, with a pattern of persistent gently E-SE plunging lineations [*Kilpeläinen et al.*, 2008].

A series of subalkaline (A-C-type), occasionally pyroxene-bearing granites with minor granodiorite and quartz monzonite plutons intruded the complex at 1.88-1.86 Ga [*Elliot et al.*, 2001]. The plutonic rocks emplaced within the uppermost, brittle part of the crust, in an extensional tectonic setting [Nironen et al., 2000], are a slightly younger than the supracrustal rocks. The younger suite is structurally homogenous except for the localized shearing developed along the intrusion margins and along aplitic dykes and veins. The deformation is localized into NE-SW and NW-SE oriented shear zones.

It is suggested that present exposure level of the CFGC is interplay between lower part of the paleo upper crust and upper part of the paleo middle crust. The décollment zone between upper-middle crust (U-M) is exposed as subhorizontal to low-angle **Elämäjärvi deformation zone** in the northeastern part of the complex (Fig7).

To the west, the CFGC is bordered by the **Vaasa gneiss dome** which is cored by diatexites and granitoids [*Korsman et al.*, 1997] and gradually mantled by supracrustal rocks made of biotite-plagioclase schists and gneisses derived from pelites and greywackes with thin metabasite-andesite intercalations [*Vaarma and Pipping*, 1997; *Kähkönen*, 2005; *Williams et al.*, 2008 and references herein]. Late Rare-Element-pegmatites are widespread away from the core [*Alviola et al.*, 2001; *Mäkitie et al.*, 2001]. In the metamorphic belt, the grade increases from medium-T amphibolite facies to lower-T granulite facies towards the core of the dome [*Mäkitie and Lahti*, 1991; *Alviola et al.*, 2001; *Mäkitie et al.*, 2001]. The age of the derived pelites and greywackes sequence is 1.90–1.92 Ga [*Huhma*, 1986; *Lahtinen*, 1994 *Kähkönen*, 2005, *Williams et al.*, 2008], with a regional peak metamorphism bracketed at 1.89–1.86 Ga [*Mäkitie*, 1999, 2000 and *Chopin et al.*, this work]. It is similar to the age of magmatism and support the idea that the metasedimentary rocks are the sources of the granitoids [*Mäkitie et al.*, 2012; *Kurhila et al.*, 2012; *Suikkanen*, 2013]. The structural analysis highlights the importance of a strong N–S directed shortening giving rise to an early metamorphic foliation. Approximately N–S striking shears zones bound the eastern Bothnia metamorphic belt [*Chopin et al.*, 2012]. *Mäkitie et al* [2012] proposed that the granitoid core of the Vaasa dome represents a magma layer formed by extensive in situ melting of the crust.

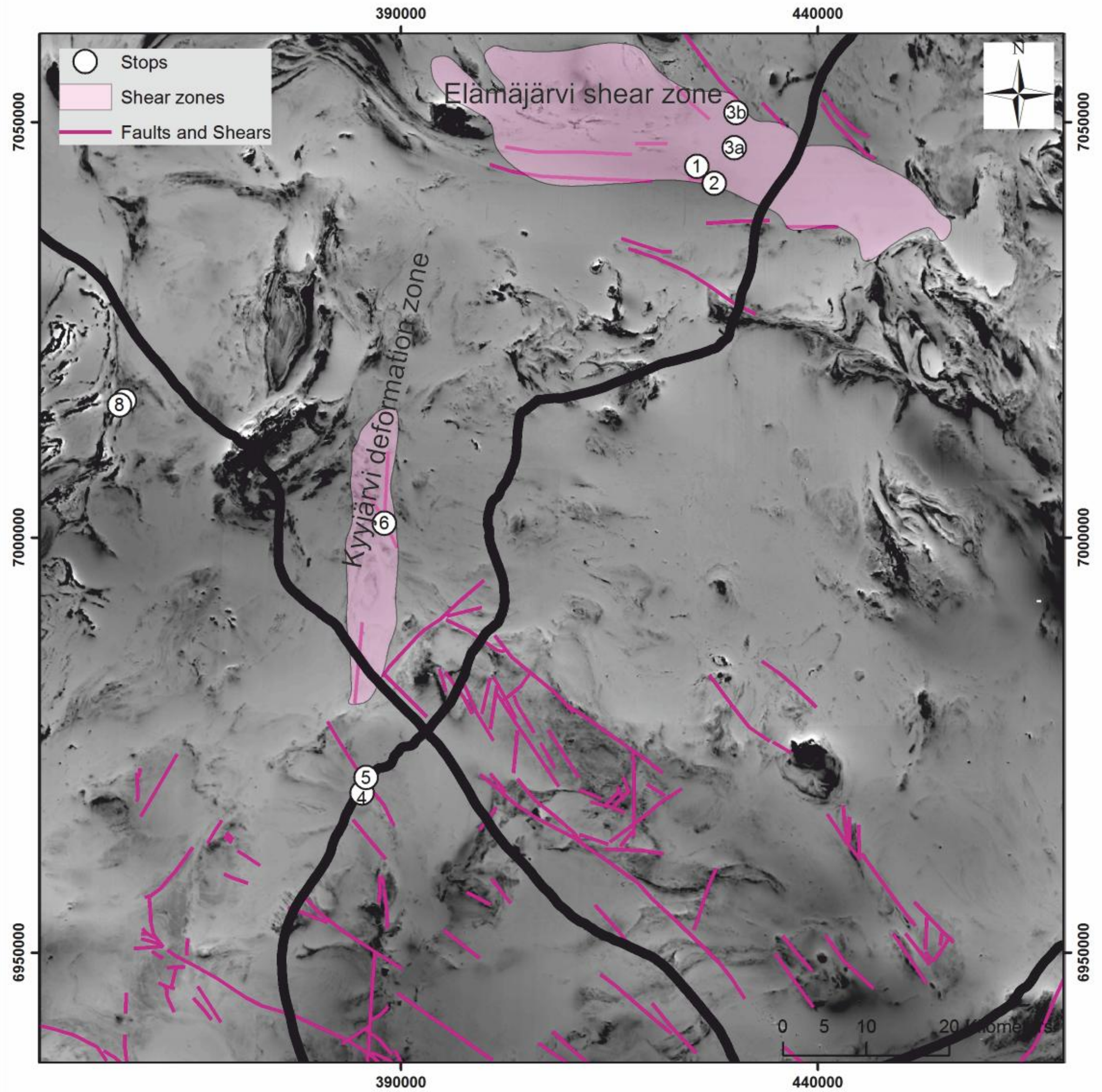


Figure 7 Aeromagnetic map of CFGC and stops 1-8. Shear zones represent one of the orthogonal pair of shears (N-S and E-W trending), magenda lines represent other pair (SE-NW and NE-SW trending) and riedel faults. (courtesy of Geological Survey of Finland).

This might also represent a crustal metamorphic core-complex with up-rise of the westward flowing middle crust at the western edge of the Keitele mc where the crustal thickness begins to decrease [See also seismic line Fire 3a through the Bothnia belt].

Part I. Central Finland granitoid Complex

The CFGC (fig 8) is sheared along SE-NW striking deformation zones dominant all over the complex. The strongly deformed (pervasively sheared) and the locally deformed (faulted) sets of coeval plutons represent deformation at different levels of the crust prior to exposure at the surface. Pervasive deformation is inferred to been interpreted to be an older feature connected to collision, whereas localized shearing is connected to collapsing structures [Nironen, 2003; Korja et al, 2009]. Regardless, shearing does not always follow lithological units. The faults transecting CFGC form a pattern of two orthogonal shear zones sets. The pervasively sheared mylonitic deformation zones form an orthogonal pair of E-W striking gently dipping shear zones and N-S striking subvertical shear zones (Fig 7). Another pair of shear zones, observed throughout the area, is displayed as sharp NW-SE trending magnetic minima (Fig 7), displaced by more subtle NE-SW trending changes in magnetic intensity. Field observations indicate them to contain a dextral strike-slip component [*Nironen*, 2003]. The latter pair of faults are often found at the fringes of sub-alkaline granite intrusions and seem to have partially controlled their emplacement, under extensional or transtensional conditions [*Nironen*, 2003]. A transtensional environment is also implied by the local development of Riedel faults between NW-SE faults and the deflection of older structures towards the faults.

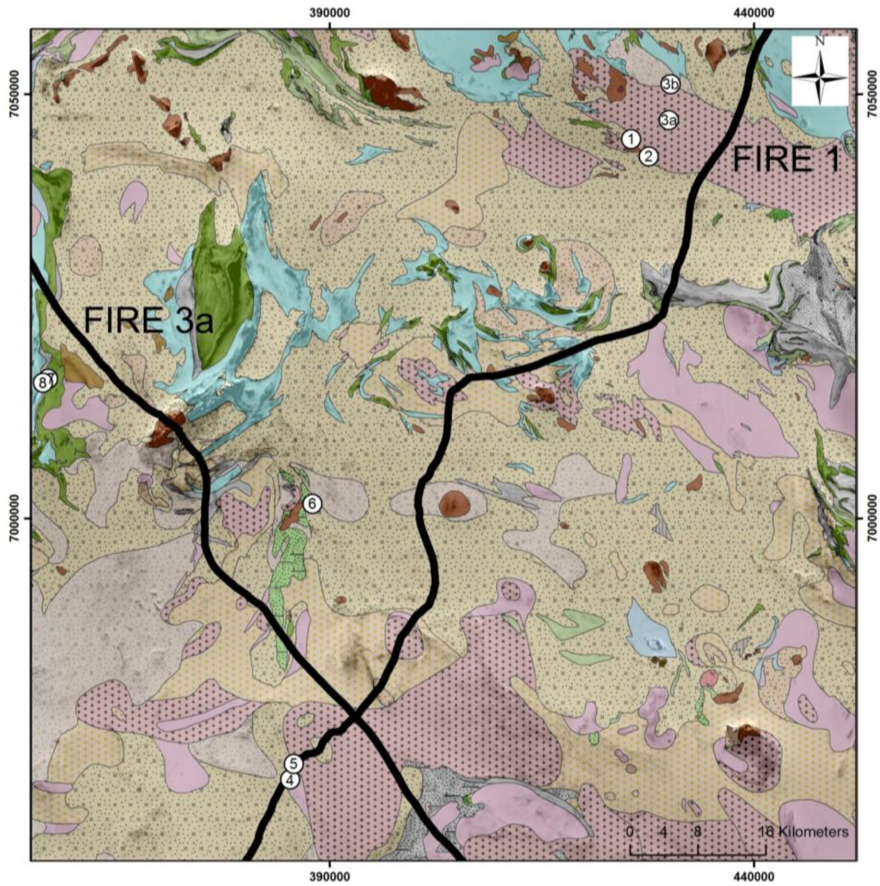


Figure 8 Stops 1-8 on the 1:200000 bedrock maps (CFGC) and aeromagnetic map (courtesy of Geological Survey of Finland).

Two typical lineation directions are observed in CFGC area: E-plunging low angle ones (like stop 1), and SE-plunging moderate to steeply dipping ones (stops 5 and 6). E-W trending lineation seems to be an older feature, whereas, SE-NW is related to younger ultramylonites and they present the latest stretching direction. The most prominent of the identified E-W feature is the ***Elämäjärvi deformation zone*** (Stops 1-3), located in the northern part of CFGC. The subvertical **Kyyjärvi deformation zone** (Stop 6) is in the NW part of the CFGC (Fig 7).

Note that preliminary age determinations suggest that both types of granitoid magmatism and the stage, pervasive deformation are synchronous events. It is therefore likely that some of the more deformed sub-alkine granites have been classified as deformed calc-alkaline granites.

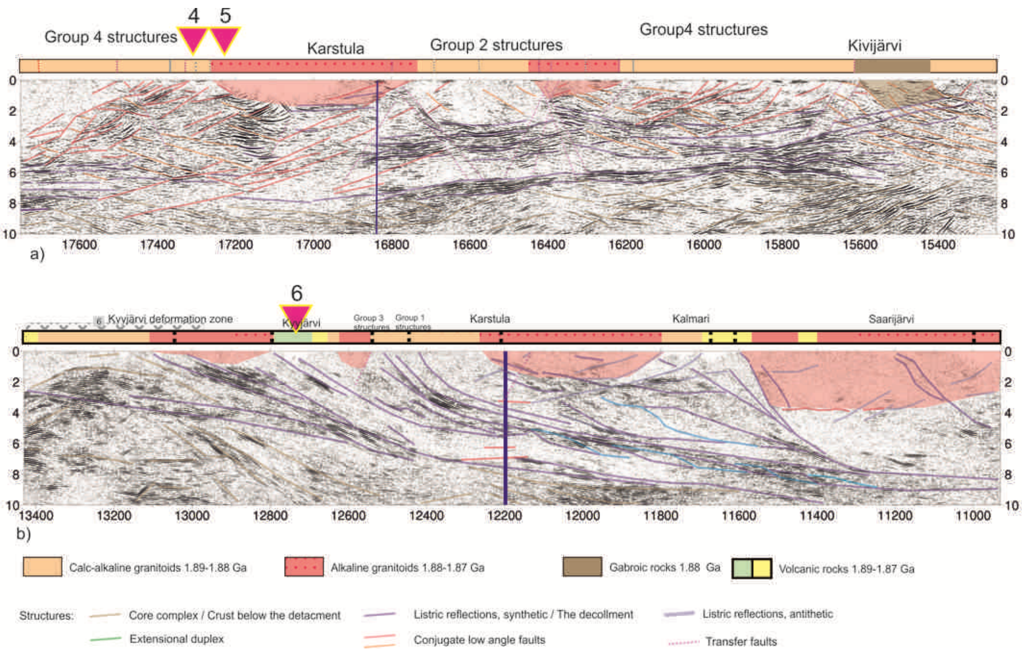


Figure 9. Geological interpretations of the uppermost 10 km of the crust along a) FIRE 1&2 line between CMP points 15250 and 17750 and b) FIRE 3a line CMP points 10930 and 13430 on a grey-scale variable intensity DMO section (Korja et al., 2009). Locations of the sections are shown in Figure 1 and 2. Excursion sites are shown with red triangles. (a) The section displays the geometrical relationships between the apparently flat-lying high-amplitude reflections, the subvertical transparent zones and the less prominent low-angle reflections. The low-angle reflections could also be oblique cuts of more upright reflections. (b) Note the sequential development of listric reflections and extensional duplexes.

Central Finland granitoid Complex – Outcrop descriptions (Annakaisa Korja, Kaisa Nikkilä, Pietari Skyttä, Timo Kilpeläinen)

Elämäjärvi deformation zone **(Stops 1-3s)** is a 10 km wide and 70 km long macro-structure characterized by highly strained rocks with gently-dipping to sub-horizontal fabrics (Fig 11). The shear zone is best observed where it deforms the alkaline 1870 Ma Pyytsalo granite [*Kousa et al.*, 1994] but it can be followed into the surrounding lithologies as well. Within the Pyytsalo granite, the deformation induced lithologies range from sheared coarse-porphyritic granite to augen gneiss, mylonite and to ultramylonites cutting mylonites suggesting that the shear zone was active for a long time and that the style of deformation changed from lower level ductile (sheared granite) to upper level brittle (ultramylonite breccia) deformation. The Elämäjärvi shear zone displays oblique shearing with gently ESE plunging lineations (10-20^{o}) and kinematic indicators suggesting westward movement of the hanging wall along low-angle oblique slip planes (Stop 1) [*Kilpeläinen*, 2007, *Kilpeläinen et al.*, 2008].

The deep seismic FIRE1-line crosses Elämäjärvi deformation zone (Fig. 10). The upper crustal structure is characterized by gently dipping high amplitude reflections disrupted and displaced by transparent sub-vertical zones. The section is interpreted to image how the low angle faults (Elämäjärvi shear zone) and strike slip faults expose the upper-middle crust décollement in blue (Fig. 10b). The low-angle shear zone is expressed by outcrops of the “post-collisional” Pyytsalo granite 1.87 Ga: the outcrops form low east–west ridges with steep southern edges and more gently dipping north sides.

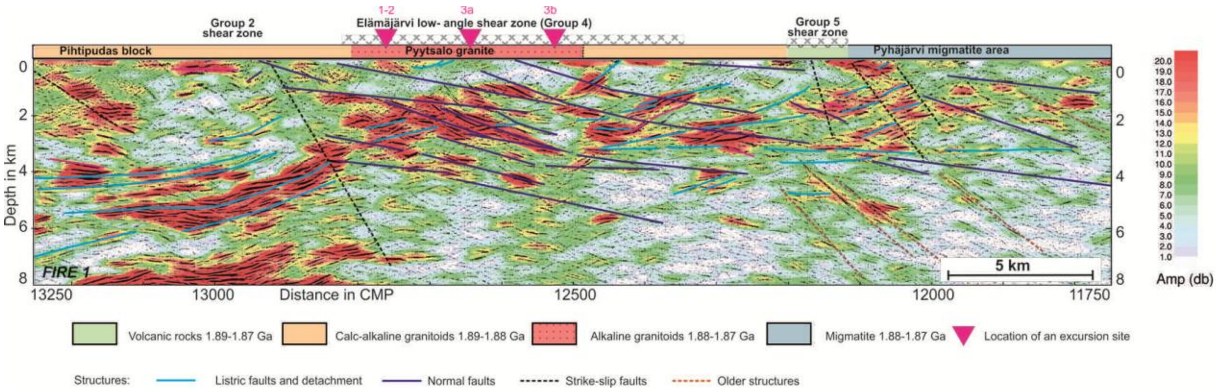


Figure 10 Elämärvi deformation zone. a) A typical morphology of the outcrops of the Elämäjärvi deformation zone. View to the west. 012-TK-06, 7043011, 428548 (EUREF-FIN). [Kilpeläinen, 2007]. b) Crustal structure of the uppermost 8 km of the north-eastern edge of the Central Finland Granitoid Complex along FIRE 1&2 after Korja et al. [2009]. Locations of the section are shown in Figure 1 and 2. Excursion sites are shown with red triangles. The deformation structures have been interpreted on a colour-coded seismic reflection section.

#STOP 1#

Outcrop name: 014-TK-06
Locality: Kiurulampi, Pyhäjärvi
GPS coordinates (ETRS-TM35FIN): 425527 E, 7044649 N
General location: Elämäjärvi deformation zone
Lithology: Protomylonitic porphyritic granite

A type location of Elämäjärvi deformation zone with a low angle shear and low angle oblique lineation. Subhorizontal to low angle protomylonitic shear with augen gneissic to protomylonitic fabric. The asymmetry of the porphyroclasts suggest westward movement of the hanging wall. A precipice showing a vertical section of the low angle structure, S = 050/20, L =080/10

#STOP 2#

Outcrop name: 08-TK-06
Locality: Palomäki, Pyhäjärvi
GPS coordinates (KKJ): 3427762, 7045563
General location: Elämäjärvi deformation zone
Lithology: Protomylonitic porphyritic granite. Cuts at different angles. S=002/35, L= 062 /10. The originally coarse-porphyritic granite has been deformed into augen gneiss with schistosity (C) dipping relatively gently towards north (002°/35°) and a sub-horizontal lineation plunging ENE (062° /10°). The shear indicators (S-C) suggest left-handed oblique shear (hanging wall towards W).

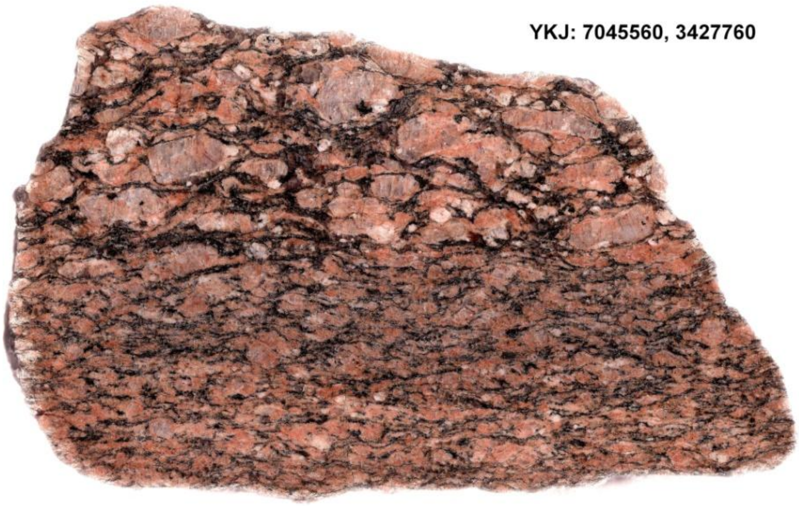


Figure 11 A typical protomylonite of the Elämäjärvi shear zone. Notice the varying intensity of shearing. The protolith is porphyritic granite. Width of the sample ca 27 cm. Photo: Timo Kilpeläinen. (Kilpeläinen et al., 2008).

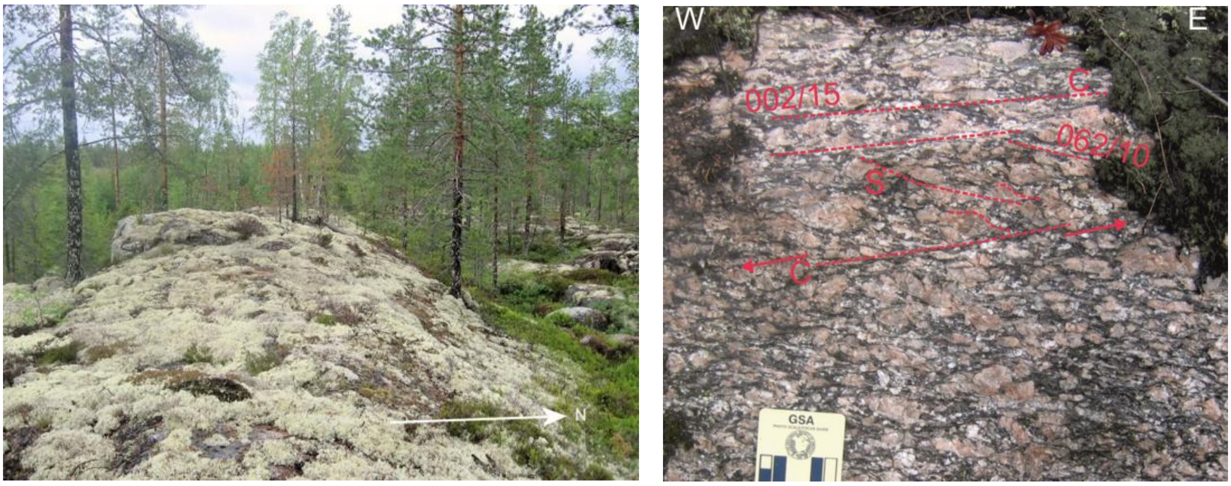


Figure 12 (a) The low angle of the Elämäjärvi shear zone is reflected by outcrops of the postcollisional Pyytsalo granite: the outcrops form low E-W ridges with steep southern edges and more gently dipping north sides. (b) The vertical surface of a southern edge of an outcrop of the Pyytsalo granite (view towards north). The originally coarse-porphyritic granite has been deformed into augen gneiss with gently dipping schistosity (002/35º) and a sub-horizontal lineation (062/10º). The shear indicators suggest left-handed shear (roof towards W). (Stop 2) (Korja et al., 2009).

#STOP 3a#

Outcrop name: 024-TK-06
Locality: Hautamäki, Pyhäjärvi, **map sheet 3321**
GPS coordinates (KKJ): 3430140, 7049853
General location: Elämäjärvi deformation zone
Lithology: Mylonitic, porphyritic granite, at places unakitic
The outcrop area is composed of augen gneiss, low angle protomylonite, at places mylonitic. When climbing the ridge you may follow how the structure develops from protomylonites into a mylonite. S = 35-50/30-35

Figure 13 Protomylonite develops into ultramylonite, low angle shearing (Stop 3a). 024-TK-06. a) An outcrop showing the effect of intensified shearing from bottom to top. b) A low angle protomylonite at the base of the ridge.

#STOP 3b#

Outcrop name: 023-TK-06
Locality: Kivimäki, Pyhäjärvi, map sheet 3321
GPS coordinates (KKJ): 3430349, 7054076
General location: Elämäjärvi deformation zone
Lithology: The protolite is most likely porphyritic granite. Several generations of quartz veins at different orientations. In thin sections, the porphyroclasts display mylonitic structure disrupted by another generation of mylonitic structure. Several generations of mylonites.
S = 070/25

Figure 14 Ultramylonite. Several generations of mylonitic fabric. The porphyroclasts display mylonitic structures disrupted by later generations of mylonitic structure. TK-23-2006, 3430349, 7054076. (Stop 3b) Photo: A. Korja

Karstula-Kyyjärvi - Late synorogenic to postorogenic sheared intrusions in the central part of the complex

The lineations of Karstula-Saarijärvi area can be divided into two groups. E-W trending low-angle lineations are the predominant feature all over the complex, whereas the SE-trending moderate to steeply plunging lineations are concentrated into the localized shear zones. They occur as slicken-side lineations (stop 5), which show oblique slip movement on the shears [Korja et al, 2009]. The localized shears are found in the Karstula-Saarijärvi area where they cross-cut both the youngest intrusive rocks and older supracrustal rocks. The localized shears, which are interpreted as transfer faults to major listric structures, separate adjacent blocks moving relative to each another in both vertical and horizontal directions and, hence, may expose different levels of the crust.

The subvertical N-S trending **Kyyjärvi deformation zone** (stop 6) might represent an old stacking structure which has been reactivated during the collapse stage. The décollement zone has exposed as a mylonite.

#STOP 4#

Outcrop name: 1-KMW-12
Locality: Vuorijärvi- Karstula quarry
GPS coordinates (ETRS-TM35FIN): 385347 E, 6969271 N
General location: calc-alkaline granodiorite close subalkaline granitoid
Lithology: This quarry hosts a slightly porphyritic granodiorite quarried for road construction. The rock is pervasively deformed and recrystallized. The material has been weak during the latest deformation stage. The outcrop displays two deformation stages; the younger one with low-angle ductile shearing c_1=032/19 (Fig. 16) with top-to-NE-kinematics (normal faulting)and an older one with lineation plunging E (L=090/29).
Age: A new age determinations 1884±2 Ma [Mänttäri, pers. com.] Similar granodiorites have earlier been interpreted as "syncollisional". The new zircon age, however, suggests that some foliated granodiorites with small amounts of mafic inclusions are coeval with the "postcollisional" intrusions.

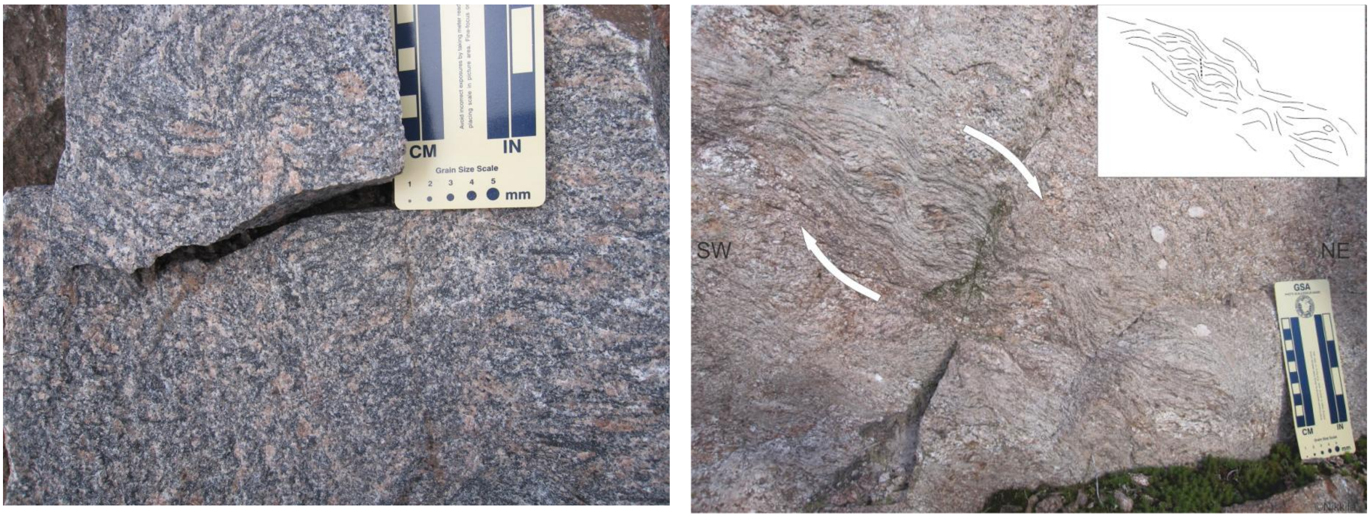


Figure 15. 1-KMW-12. A deformed granodiorite. To the right, a low-angle ductile shear with a foliation boudinage. A normal fault.

#STOP 5#

Outcrop name: 2-3-KMW-13
Locality: Korkeamäki- Karstula
GPS coordinates (ETRS-TM35FIN): 385799 E, 6971065 N
General location: Subalkaline granitoid
Lithology: This outcrop is only 2 km north of the site 4. The outcrop consists of medium- and even-grained granite that is changed from undeformed granite to ultramylonitic granite. The changes in the intensity of the shearing can be observed while walking across the < 10-m-wide outcrop. The localized shear foliation dips deeply to SW (c_1= 212/60) and the stretching lineation (L) plunges SE (148/34). The shear sense is top-to-the-NE (reverse fault) and the fault has a dextral strike-slip component. The mylonitic foliation has been isoclinally folded in the high-strain core of the zone where also cataclasite has been formed. These mylonitic SE-NW trending shear zones are representatives of transfer faults [Korja et al. 2009].

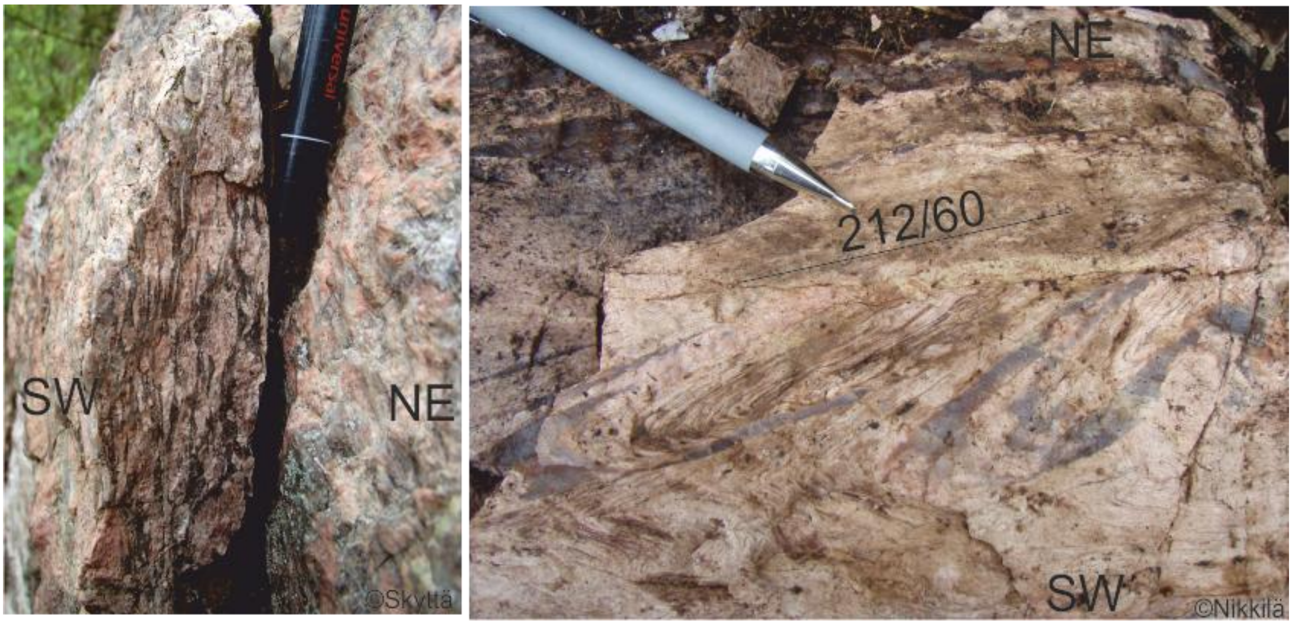


Figure 16. Localized shearing. . Granite has been deformed into ultramylonite. Qtz-veins and shear foliation have been folded.

#STOP 6#

Outcrop name: 8-KMW-12
Locality: Tuohikangas-Kyyjärvi
GPS coordinates (ETRS-TM35FIN): 388023 E, 7001701 N
General location: Kyyjärvi deformation zone
Lithology: The outcrop is composed of even-grained mylonitic granite to augen gneiss. The granite cross-cuts layered intermediate-volcanic rocks. Both the volcanic and intrusive rocks are pervasively sheared. Foliation is sub-vertical and to SW-dipping (c_1=240/88, L_1=140/75). The kinematic indicators suggest a weak sinistral horizontal component and a strong vertical component (NE up, SW down?). The strike is parallel to those in stops (# 4 and #5), but the shearing is more pervasive. This indicates that the rock units of this site (6) might have been deformed at deeper levels of the crust than those on sites 4 and 5.
Age: Concordia age for granite is 1880±2 Ma [Mänttäri, pers.com]

Figure 17. A mylonitic granite and volcano-sedimentary unit. E up, W down.

Part II. Vaasa Dome

A detailed field study has revealed complex tectonometamorphic evolution of the dome. The tectonic contact between the Vaasa Dome and the Central Finland Granitoid Complex is a N–S striking, steeply dipping shear zone with uncertain kinematics (Stops 7-8). Nevertheless, we suggest a general uplift of the whole western Vaasa Dome with respect to the CFGC in the east. A first tectonometamorphic event increasing grade from east to west is visible within the Bothnia belt. Where preserved, the first metamorphic foliation is roughly moderately dipping to subhorizontal. It records only low amphibolites facies metamorphism in eastern most part (Stops 9-12), whereas a first stage of melting is present closer to the western core (Stops 13-15). The second event formed as a response to N–S to NNW–SSE directed crustal shortening and resulted in the formation of E–W to WSW–ENE trending steep axial planar cleavage to pervasive, subvertical foliation (Stops 12-15). The intensity of this deformation seems to increase as we approach the granitoid dome core in the west. At first order, the grade of metamorphism increases also in the same direction: i.e. from low amphibolites facies (Stops 9-12) to metatexite (Stops 13-15 and 18-19)/diatexite (Stops 16-17 and 19) with more syn-tectonic granitoids within the Bothian Belt closer to the core (Stops 18-19). Late stage deformation was localized along the boundary between the Bothian Belt and the granitic core of the dome. Within the boundary zone, the intense deformation of soft high-grade metatexite to diatexite produced a NNW–SSE striking sub-vertical shear zone (Stops 15-17 and 19). In the core of the dome, some syntectonic intrusions show sub-horizontal direction of flow close to this contact, but a minor vertical component could be also present. Other syn tectonic granitoids are structurally more homogeneous (Stops 20-21). Late to post- tectonic pegmatites and granitoids are widespread in the whole massif.

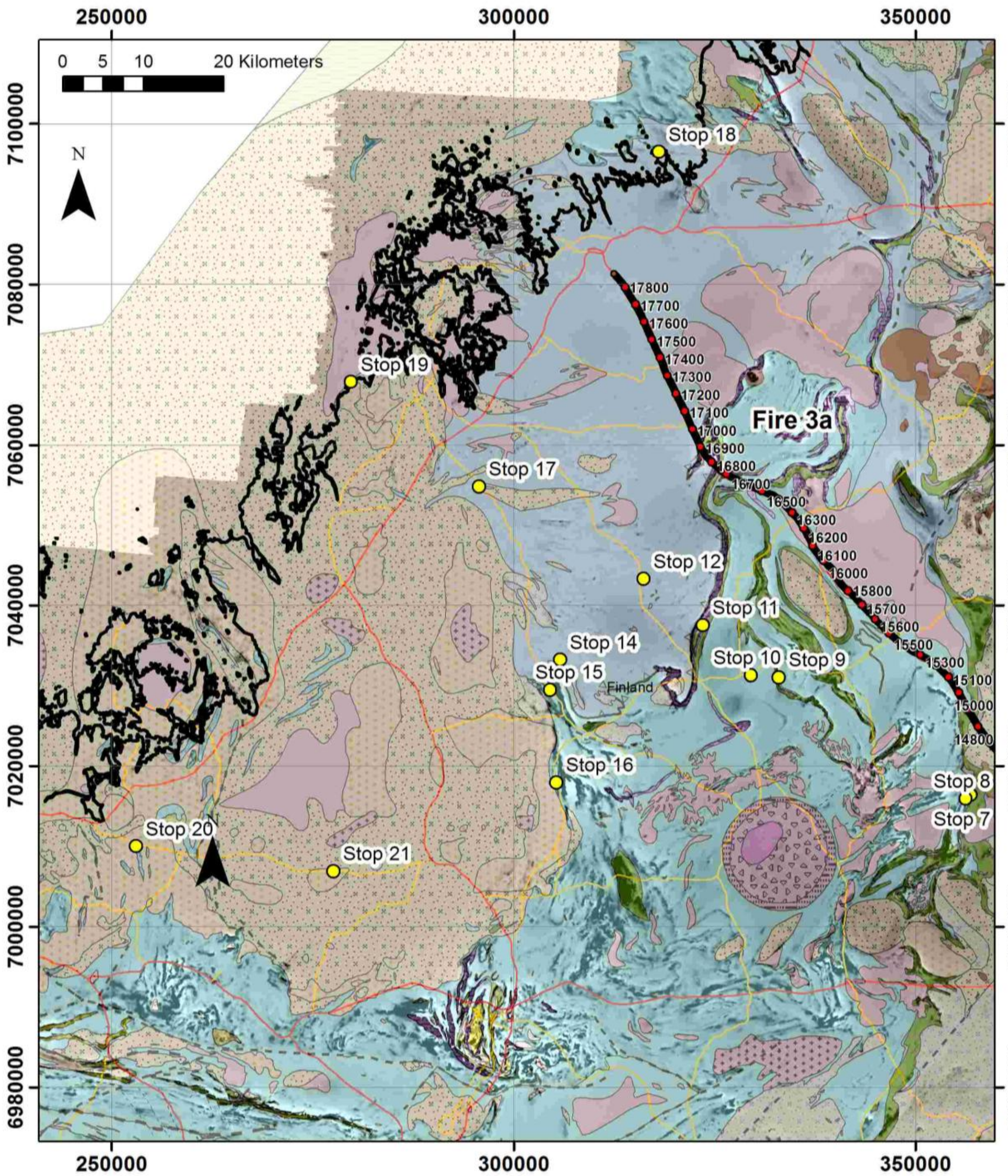


Figure 18 Location of sites 7 to 19 (Vaasa dome) on the 1:200000 bedrock map and aeromagnetic map (courtesy of Geological Survey of Finland).

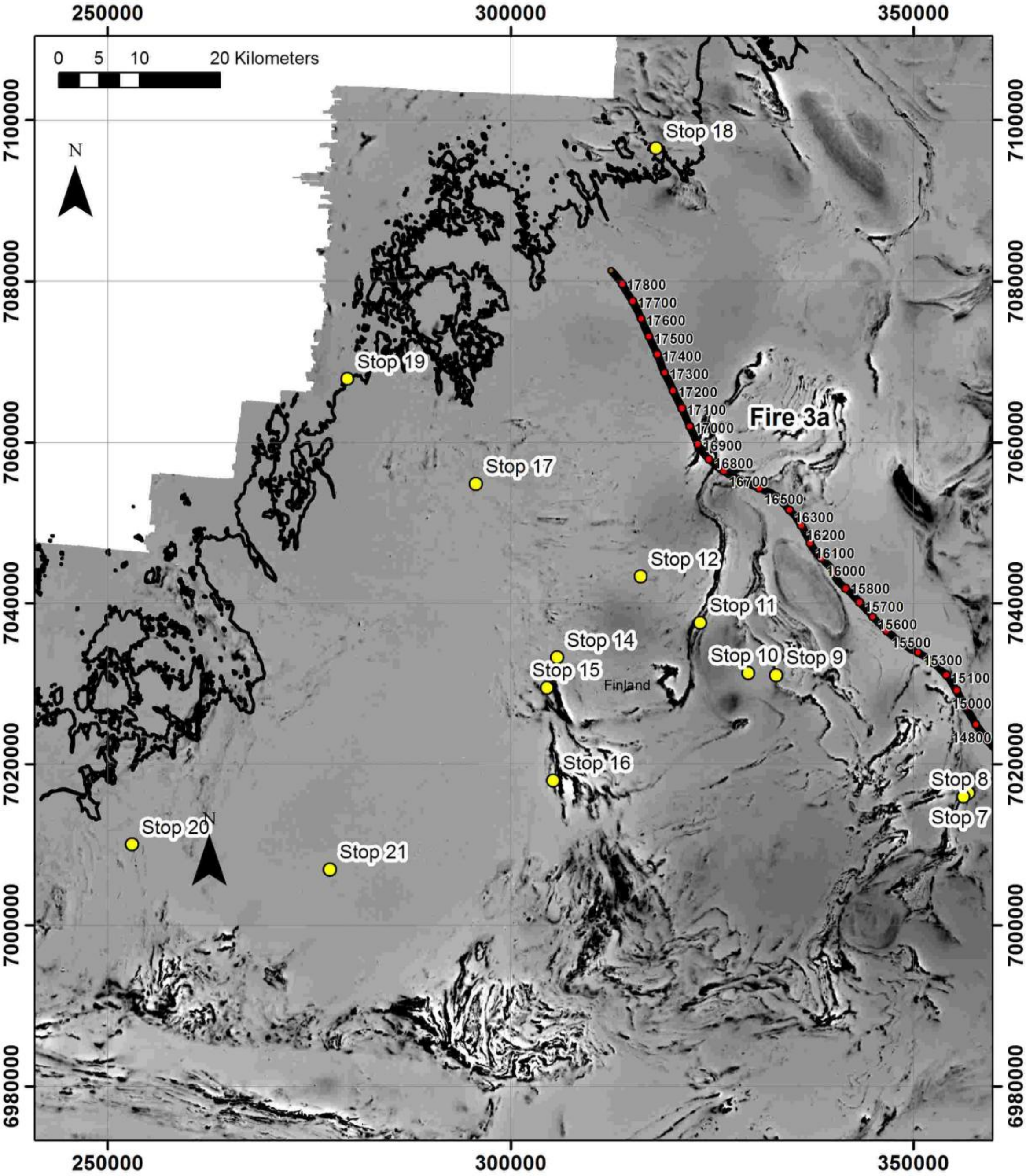


Figure 19 An aeromagnetic map of Vaasa dome and stops 7-21 (courtesy of Geological Survey of Finland).

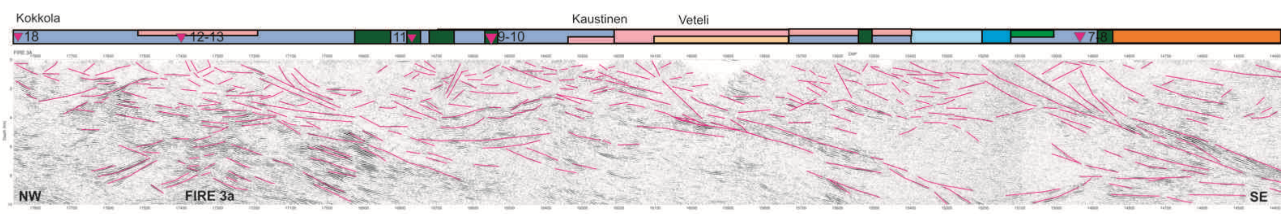


Figure 20 An upper crustal section along FIRE3a seismic line.. The section crosses the Vaasa Dome, Bothian belt and Bothnia-Central Finland contact. Note how the moderate to shallow dipping structure become steep to subvertical close to surface. Section is processed by P. Heikkinen.

Vaasa Dome – Outcrop descriptions (Francis Chopin, Pentti Hölttä, Anna Kotilainen, Tapani Rämö, Markus Vaarma)

Peltokangas area – Sheared contact between CFGC and Vaasa dome

The boundary between the CFGC and the Vaasa dome is a major N-S striking ductile shear zone. Preliminary kinematic analysis shows an upward movement of the Vaasa block with respect to the CFGC. The shear zone probably developed at amphibolite facies metamorphic condition. In one locality, kyanite has been found in metapelitic rocks.

#STOP 7#

Outcrop name: FJCH-2012-144
Locality: Perho - Peltokangas – Kivilahti
GPS coordinates (ETRS-TM35FIN): 356847 E – 7016425 N
Leaders: Francis Chopin, Pentti Hölttä
General location: North-South boundaries between the CFGC and the Vaasa dome.
Lithology: Various medium-grained metabasites originated from basalt, tuff, andesite or volcanic breccia with plagioclase-rich enclaves.
Mineralogy: Hb+Pl±Bt+Ep+Cal+Grt. Minor indications of gold mineralization?
Structure: Strong sub-vertical metamorphic foliation striking N-S, bearing a strong sub-vertical stretching lineation. The lithological layering is parallel to the metamorphic foliation.
Microstructure: Mylonitic texture with porphyroclasts of amphibole (50–1000 µm long) and seritized plagioclase within a fine-grained matrix of plagioclase.

Figure 21. Metabasite with sub vertical N-S foliation. The pencil indicates the sub-vertical lineation.

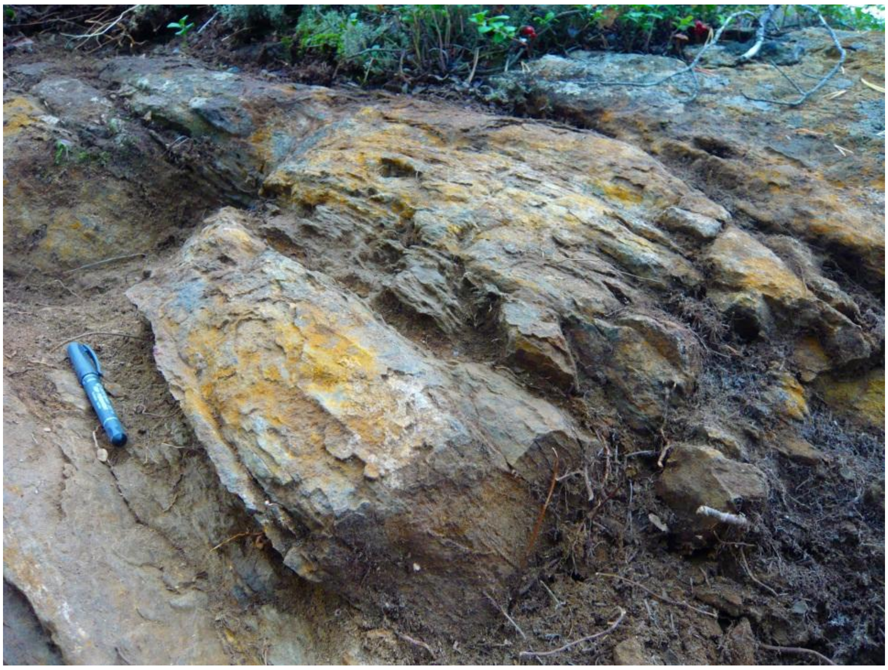
#STOP 8#

Outcrop name: FJCH-2012-145
Locality: Perho - Peltokangas – Pilleskytö
GPS coordinates (ETRS-TM35FIN): 356261 E - 7015942 N
Leaders: Francis Chopin, Pentti Hölttä
General location: North-South boundaries between the CFGC and the Vaasa dome
Lithology: Graphite-schist, metagreywackes and metavolcanic rocks. Trm-Qtz pegmatites.
Mineralogy: Presence of gold mineralization ?
Structure: Strongly folded/sheared metamorphic foliation with development of a N-S striking, sub-vertical cleavage/shear plane. Fold axis / stretching lineation is also subvertical.

Figure 22 Folded/sheared metasedimentary rock. The pencil roughly indicates the North direction.

Evijärvi East – Primary structures within the Vaasa dome

#STOP 9#



Outcrop name: FJCH-2012-82
Locality: Veteli - Puupakka
GPS coordinates (ETRS-TM35FIN): 332979 E - 7031069 N
General location: Eastern margin of the Vaasa dome
Lithology: Fine-grained low-grade graphite-schist.
Mineralogy: Fsp+Ep+Graph
Structure: Gently W-dipping metamorphic foliation bearing a WSW dipping lineation.
Microstructure: Fine-grained mylonitic texture (plagioclase, epidote, graphite) cross-cut by thin Epidote+Graphite veins.

Figure 23 Gently west dipping graphite schist from the Eastern Evijärvi area. The pencil is parallel to the metamorphic layering

#STOP 10#

Outcrop name: FJCH-2012-83 (PSH-11-58)
Locality: Evijärvi - Kotikangas
GPS coordinates (ETRS-TM35FIN): 329505 E – 7031348 N
General location: Eastern margin of the Vaasa dome
Lithology: Low-grade **p**aragneiss with metavolcanic enclaves
Mineralogy: Bt+Qtz+Pl±Crd+Grt+Ms+Chl
Structure: Gently west dipping metamorphic foliation bearing a WSW plunging lineation.
Microstructure: Fine-grained granolepidoblastic texture with few garnet grains (< 250 µm large) and cordierite pseudomorph completely replaced by pinite. Biotite from the fine-grained matrix is retrogressed into chlorite.

Figure 24 Gently west dipping paragneiss with metabasite (?) enclaves. The pencil is parallel to the foliation.

#STOP 11#

Outcrop name: FJCH-2012-45
Locality: Evijärvi - Aho
GPS coordinates (ETRS-TM35FIN): 323523 E – 7037579 N
General location: Eastern margin of the Vaasa dome
Lithology: Amphibolite - metavolcanic rock
Mineralogy: Hb+Pl+Cal+Opaque minerals
Structure: Gently west dipping metamorphic foliation bearing a W dipping lineation.
Microstructure: Medium-grained amphibolite with large amphibole porphyroblasts (1-8 mm long) roughly parallel to the foliation. They bear high amount of plagioclase and opaque inclusions. The matrix is made of equilibrated foam texture of plagioclase (40-80 µm large) with numerous opaque minerals in inclusion or at their boundaries.

Figure 25 . Gently west dipping amphibolite

Evijärvi West to Kortesjärvi – Polyphased deformation away from the core of the Vaasa dome

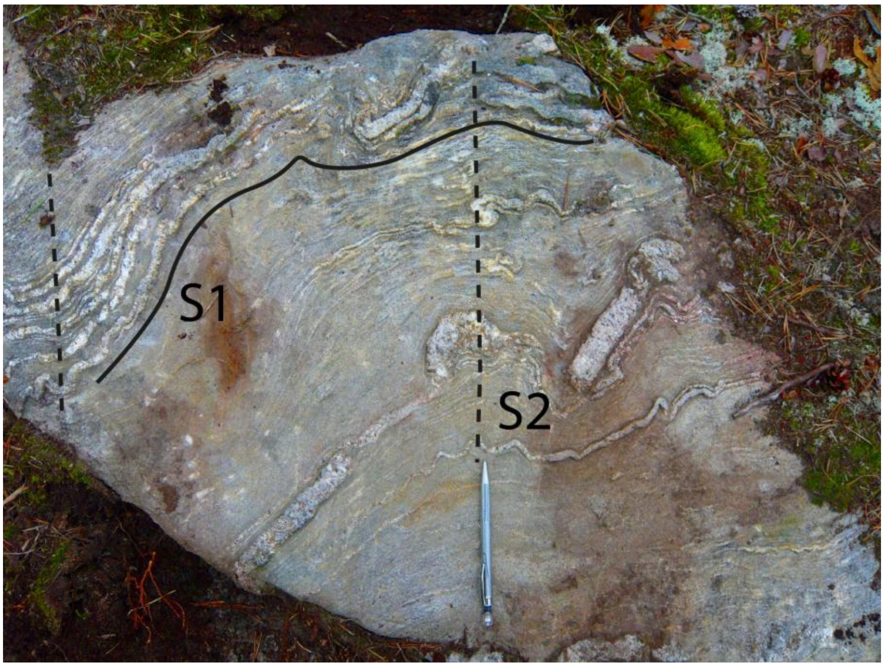
#STOP 12#

Outcrop name: FJCH-2012-48
Locality: Evijärvi - Kattilakoski dam
GPS coordinates (ETRS-TM35FIN): 316167 E – 7043343 N
General location: Eastern margin of the Vaasa dome
Lithology: Low-grade metagreywacke, metapelite with calcschist concretions
Mineralogy: Bt+Ms+Qtz+Fsp
Structure: A metamorphic foliation S0-1 moderately dipping to the NW is affected by a new disjunctive sub-vertical cleavage S2 striking WSW-ENE.
Microstructure: The S0-1 layering is underlined by an alternation of quartz and biotitic rich layers and orientation of Kfs porphyroclasts. The disjunctive cleavage is underlined by reorientation of micaceous phases within quartz rich layers.

Figure 26 New disjunctive, E-W striking cleavage S2 affecting the metasedimentary rock.

#STOP 13#

Outcrop name: FJCH-2012-33 (PSH-11-09)
Locality: Evijärvi - Katilamminkankas
GPS coordinates (ETRS-TM35FIN): 310807 E – 7035233 N
General location: Eastern margin of the Vaasa dome



Lithology: Metatexite - Paragneiss
Mineralogy: Bt+Crd+Sil+And+Ky+St+Pl+Qtz+Ms+Opaques
Structure: The main foliation S1 is steeply inclined to the ENE. It is affected by open to tight F2 folds developing a new S2 sub-vertical axial plane cleavage striking WSW-ENE. Leucosomes are mostly parallel to S1 foliation but melt is also collected within S2.
Microstructure: Cordierite enclosed fibrolitic sillimanite which is in turned replaced by andalusite+biotite.

Figure 27 Metatexite affected by F2 folds. The pencil indicates the ENE strike of the F2 axial plane.

#STOP 14#

Outcrop name: FJCH-2012-34 (PSH-11-11)
Locality: Pedersöre – Härjebacka - Lostenslandet
GPS coordinates (ETRS-TM35FIN): 305777 E – 7033241 N
General location: Eastern margin of the Vaasa dome
Lithology: Metatexite - Paragneiss
Mineralogy: Bt+Crd+Sil+Grt+Kfs+And+Pl+Qtz
Structure: This outcrop show a metamorphic foliation S1 strongly affected by F2 tight folds. The resulting sub-vertical S2 axial planar cleavage, striking WNW–ESE, is well developed. Both leucosomes parallel to S1 or S2 are visible.
Microstructure: Codierite enclosed fibrolitic sillimanite which is in turned replaced by andalusite+biotite.
Age: 1868.2 ± 5.1 Ma and 1868.2 ± 5.1 Ma (U/Pb monazite, outcrop PSH-11-12), 1863.8 ± 7.6 Ma (U/Pb monazite, outcrop PSH-11-8.2)

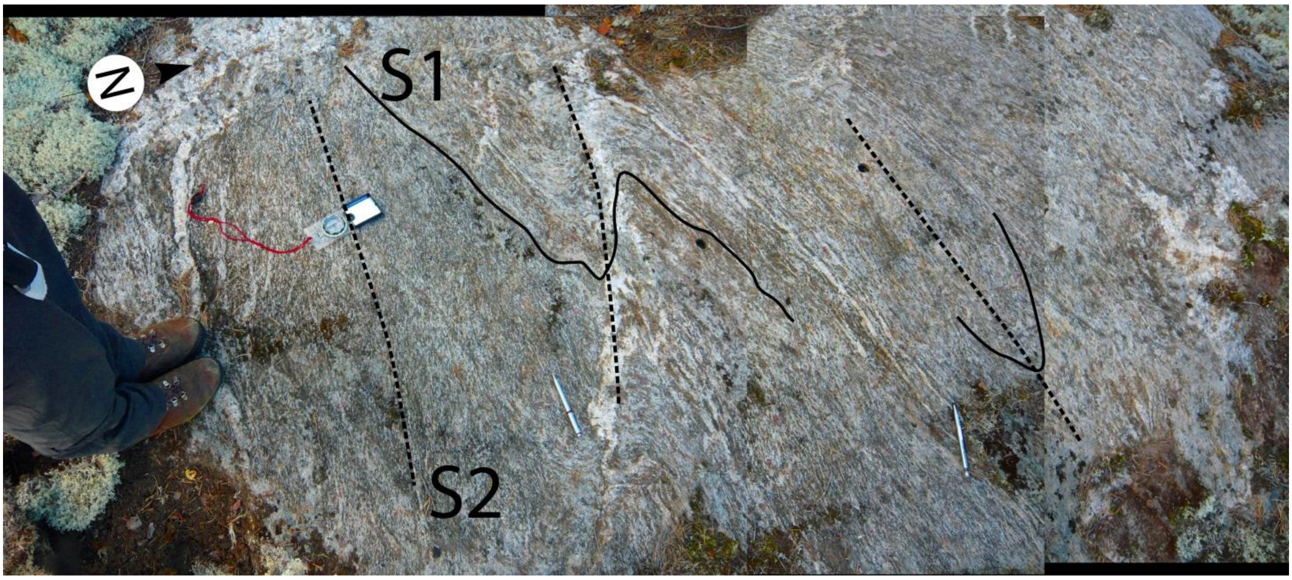
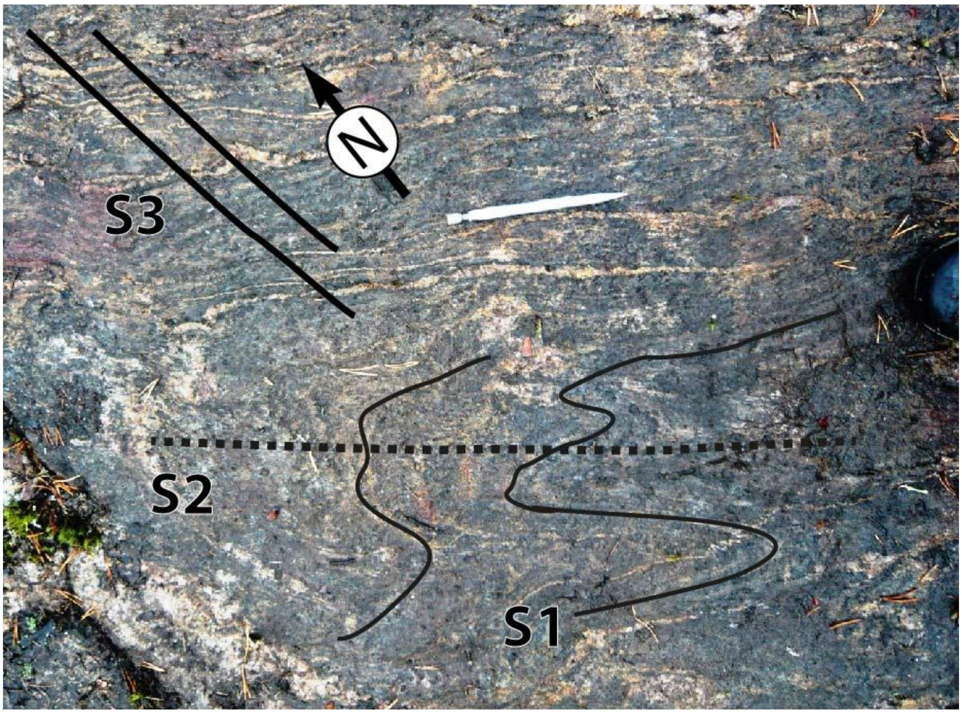


Figure 28 Metatexite affected by F2 folds. S2 cleavage strike WNW-ESE.

Kortesjärvi – Polyphased deformation at the margin of the granitoid core of the Vaasa dome

#STOP 15#



Outcrop name: FJCH-2012-159
Locality: Kauhava - Porholma - Rappukallio
GPS coordinates (ETRS-TM35FIN): 304510 E – 7029507 N
General location: Eastern margin of the granitoid core of the Vaasa dome
Lithology: Metatexite - Paragneiss
Mineralogy: Bt+Crd+Sil+Grt+Kfs+And+Pl+Qtz
Structure: This outcrop show a metamorphic foliation S1 strongly affected by F2 tight folds. The resulting sub-vertical S2 axial planar cleavage strike NW-SE. It is moderately affected by F3 folds associated with a new S3 cleavage roughly striking N–S.

Figure 29 Metatexite affected by F2 and F3 folds.

#STOP 16#

Outcrop name: FJCH-2012-163
Locality: Kauhava - Ylikylä - Sokerivainio
GPS coordinates (ETRS-TM35FIN): 305287 E – 7017991 N
General location: Eastern margin of the granitoid core of the Vaasa dome
Lithology: Metatexite - Diatexite
Structure: The main foliation S2 (?), subvertical and striking NE-SW, is underlined by calcschist concretions. A new folding/shearing event result into the development of a N145 striking sub-vertical S3 planar fabric where calcshiste concretions are sometimes reoriented. Melt is also collected within this new cleavage.

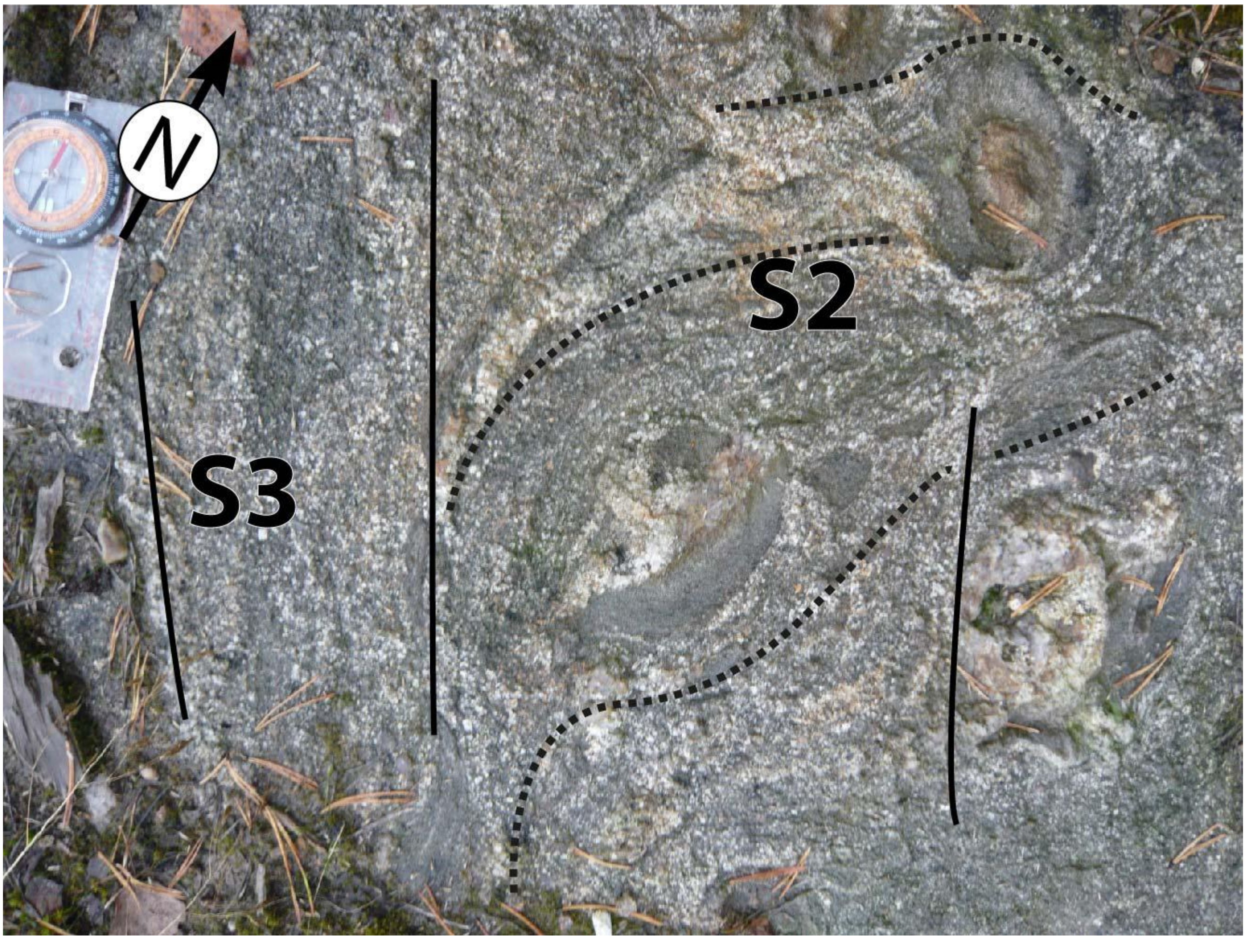


Figure 30 Metatexite/diatexite affected by F3 folds.

Forsby – Polyphased deformation at the margin of the dome core

#STOP 17#

Outcrop name: FJCH-2012-059 (PSH-11-32)
Locality: Pedersöre - Forsby - Kullasberget
GPS coordinates (ETRS-TM35FIN): 295669 E – 7054843 N
General location: Eastern margin of the granitoid core of the Vaasa dome
Lithology: Diatexite
Mineralogy: Bt+Ms+Kfs+Qtz
Structure: Relics of older stromatite/nebulite and calcschist concretions are preserved within diatexite. Original strike of S2 (?) subvertical foliation was probably W-E, whereas the new sub-vertical planar fabric, where melt is finally collected, is roughly N-S. It bears both horizontal (stretching?) and vertical lineation (intersection between S2 and S3).
Microstructure: The neosome is made of a coarse grained granolepidoblastic matrix. The biotite and muscovite laths underlined S3 foliation. Muscovites laths are requilibrated into a fine grained mixture of mucovites+quartz. Feldspars grains are corroded by perthites and myrmekites.

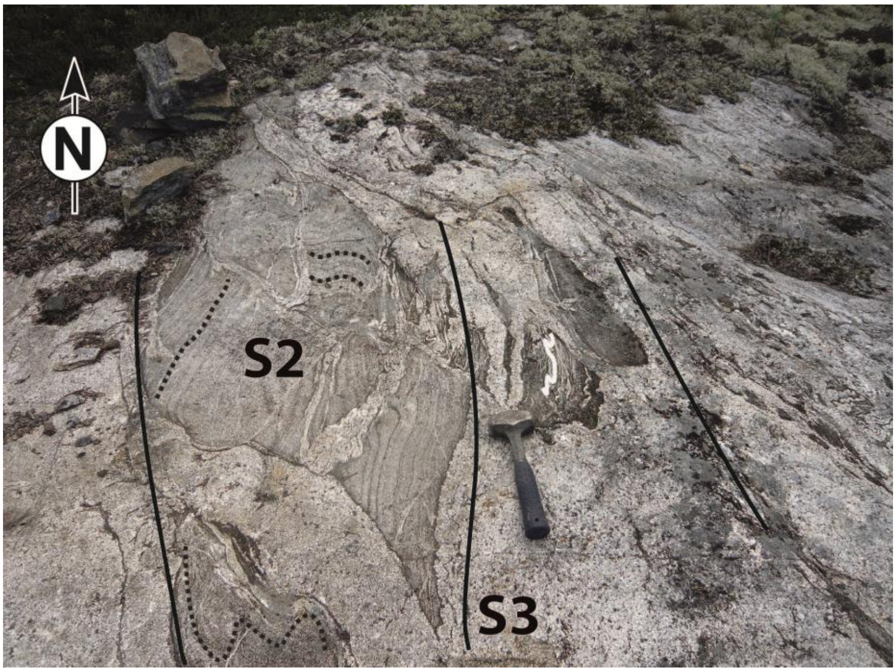


Figure 31 Diatexite at the border of the granitoid core of the dome.

Kokkola outcrop – Polyphased deformation towards the dome core

#STOP 18#

Outcrop name: FJCH-2012-072 (PSH-11-21)
Locality: Kokkola - Pirskeri - Helluskerinnokka
GPS coordinates (ETRS-TM35FIN): 318059 E – 7096495 N
General location: Eastern margin of the Vaasa dome along the Bothnia coastal line.
Lithology: Metatexite – Paragneiss, pegmatite and granitoids intrusions
Mineralogy: Fsp+Qtz+Bt+Ms+Opaque
Structure: This is a very good place to observe interaction between gently dipping S1 metamorphic foliation and S2 W-E striking sub-vertical foliation.

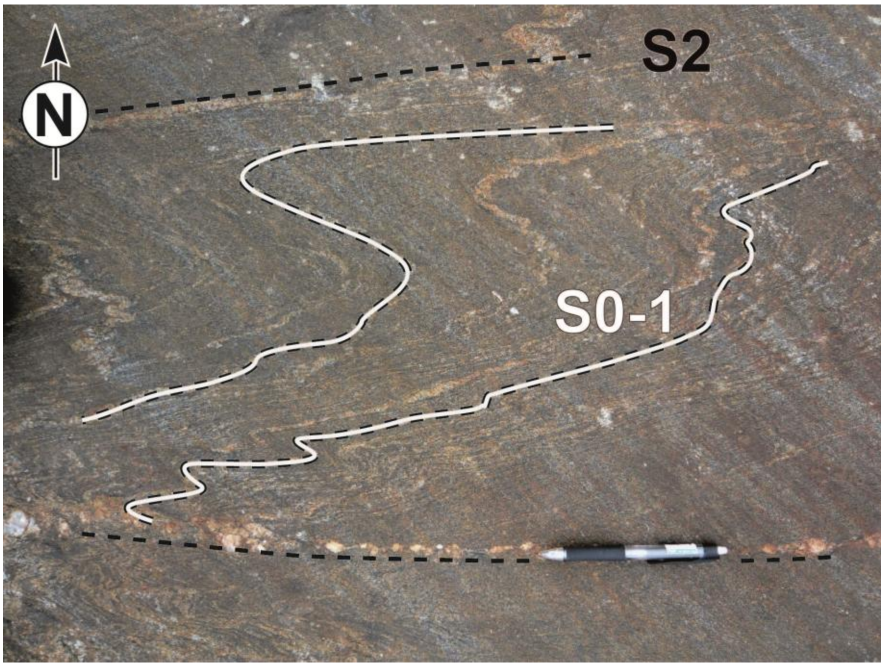
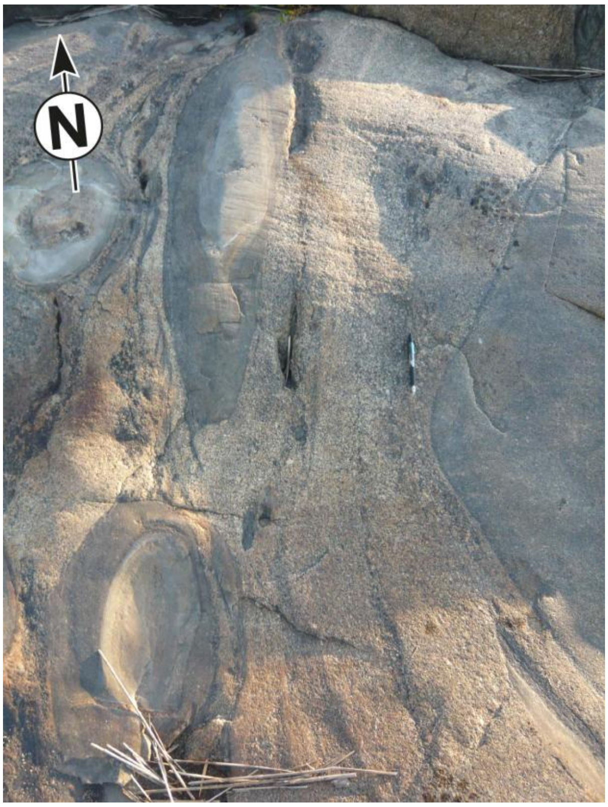


Figure 32 Preserved primary structures affected by N-S shortening D2 within metatexite.

Leucosomes are presents within both foliations, and granitoids are collected within F2 folds hinges or limbs.
Microstructures: The S0-1 layering is underlined by an alternation of Qtz+Fsp and micas rich layers. A second generation of Bt-Ms laths is growing into the S2 cleavage.

Jakobstad/Pietarsaari outcrop – Polyphased deformation within dome core



#STOP 19#

Outcrop name: FJCH-2012-010 (PSH-11-69)
Locality: Pietarsaari - Näsiskatan - Kurudden
GPS coordinates (ETRS-TM35FIN): 279773 E – 7067840 N
General location: Dome core
Lithology: Diatexite with numerous enclaves (calcschists concretions, metavolcanic, pelitic restites, granitoids…)
Mineralogy: Kfs+Bt+Qtz±Ms
Structure: The gneissic sub-vertical planar fabric S3 (?), striking N20, is underlined by the preferred orientation of enclaves.
Microstructures: The leucosomes show coarse grained granoblastic texture.
Ages: 1859 ± 13 Ma (U/Pb monazite)

Figure 33 . N-S striking calcschist concretions within diatexite

Vaasa dome core, Vöyri quarry – Megacrystic Vaasa granodiorite

Stop 20

Outcrop name: 07-AKK-13 (FJCH-2012-54)
Locality: Vöyri – Larven
GPS coordinates (ETRS-TM35FIN): 252965 E – 7010020 N
General location: Dome core
Lithology: Pervasively alkali feldspar-megacrystic biotite granodiorite from the core of the Vaasa batholith. The alkali feldspar megacrysts are disk-shaped or tabular (Carlsbad-twinned), with a maximum diameter/length of about 10 cm. Abundant garnet is found both within the megacrysts and in the surrounding granitoid groundmass. The granodiorite also contains greenish granitic patches (≤ 1 m in diameter) with potential orthopyroxene, as well as small (10-15 cm diameter) metasedimentary xenoliths. A garnet pair from within a megacryst and the surrounding groundmass from a corresponding megacrystic granodiorite (15 km west of this site) implies a circa 1 kb difference in equilibrium pressure and a 150 ^{o}C difference in temperature (both higher in the garnet within the megacryst). The megacryst examined also shows a positively igneous variation in trace element values from the core to the margin [Rämö et al., 2012]

Figure 34 Garnet-bearing alkali feldspar megacryst in garnet-bearing biotite granodiorite matrix at the Vöyri quarry.

Vaasa dome core, Frakaninkalliot – Even-grained Vaasa granodiorite

Stop 21

Outcrop name: 03-AKK-13 (FJCH-2013-06)
Locality: Vöyri – Frakaninkalliot
GPS coordinates (ETRS-TM35FIN): 277568 E – 7006945 N
General location: Dome core
Lithology: Even-grained biotite granodiorite from the Vaasa batholith. The granodiorite is medium-grained (grain size is approximately 3 mm) and contains 5-10% biotite and some garnet. It also contains schist inclusions.

Figure 35 Even-grained granodiorite at Frakaninkalliot.

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