BARENTS PROJECT 2014

Integrated geological and geophysical field studies in the Liviöjärvi key area, Pajala region

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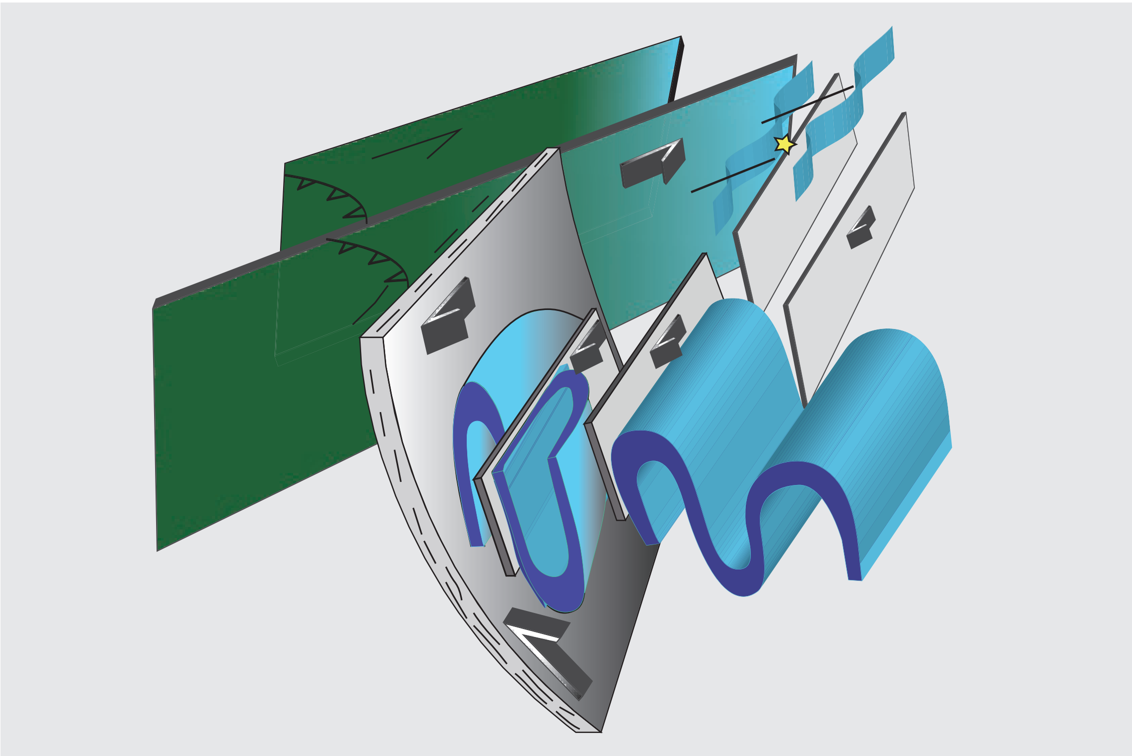

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Cover: Conceptual kinematic model of the Liviöjärvi key area. See Figure 21 for further information.

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CONTENT

ABSTRACT

This report contains data and preliminary results from the geological and geophysical field studies carried out in the Liviöjärvi key area, south of Pajala in northern Norrbotten. The area is one of 15 key areas that are studied within the context of the Barents project, which aims for a better understanding of the ore district's geological history in terms of stratigraphy, tectonic evolution and mineralisations.

SAMMANFATTNING

Denna rapport innehåller data och tolkningar baserat på nya geologiska och geofysiska fältstudier i nyckelområdet Liviöjärvi, söder om Pajala i norra Norrbotten. Området är ett av 15 nyckelområden som valts ut inom Barentsprojektet. Arbetet bidrar till en bättre förståelse av regionens geologiska historia, stratigrafiska uppbyggnad, tektoniska rörelser samt mineraliseringar.

INTRODUCTION

The Pajala shear zone is a north–south striking shear zone located along the border between northern Sweden and Finland, and can be considered as one of Sweden's largest high strain belts. Despite its dimensions (more than 400 km long and a width varying between 50 and 100 km), only little is known about its subsurface geometry and tectonic evolution. The available data is scarce and comprises several geological map sheets with many inconsistencies between them (see Luth & Jönsson 2014 for available data). Previous compilation studies have had a primary focus on geochronology (e.g. Bergman et al. 2006) and stratigraphy (Lahtinen et al. 2015), but detailed studies on the deformation pattern are lacking.

In the summer of 2014, geological and geophysical investigations were conducted in the Liviöjärvi key area located south of the small town Pajala with the aim to further constrain the stratigraphic and tectonic evolution along the Pajala shear zone (Fig. 1). The Liviöjärvi key area is of special interest since several major branches belonging to the Pajala shear zone merge or overprint each other. In this context, the overall north–south striking Pajala shear zone appears to be dismembered by a north-east striking fault system along which iron and sulphide mineralisation of significant economic importance have been found in Sweden but particularly in Finland (e.g. Niiranen et al. 2007). This study aims for a better understanding of the deformation patterns observed in the Pajala region, and may be used to link the occurrence of mineralisations to the tectonic evolution.

In an area measuring approximately 300 km^2, but with less than 1% exposure of the bedrock, we carried out detailed structural mapping and sampling as well as magnetic and electromagnetic (VLF) ground measurements along carefully selected profiles in order to resolve the complex deformation patterns. An attempt to construct 2D and 3D structural interpretations at various scales and to integrate those within the larger-scale 4D tectonic framework will be made.

In this report we summarise our 2014 field results and present a selection of data in terms of measurements and geochemical analyses as well as preliminary structural interpretations. Based on the large amount of collected spatial data, we have chosen to first summarise our main findings before zooming in on more local and detailed examples. In the concluding chapter a conceptual model on the region's tectonic evolution is presented.

NEW FINDINGS

Three major structural domains were defined: the western, central and eastern domains, respectively (Fig. 1). These terrains are characterised by their distinctive lithology (volcanic rocks vs. paragneisses), deformation pattern (brittle vs. ductile), metamorphic grade (low grade vs. high grade) and different geophysical response (gravity, magnetic and electromagnetic). The western fault branch of the Pajala shear zone divides the western domain from the central domain (Fig. 1). The structural relationships within and between those domains were further investigated.

Central domain

In the central domain several dome geometries were observed on a kilometre to metre scale, mainly as magnetic anomalies but also on an outcrop scale. It is unclear whether the dome geometries formed as a result of multiple folding phases (i.e. superimposed folding) or were formed during a single deformation event. However, the lack of observations of *two* well defined foliations combined with the presence of a steeply plunging stretching lineation suggests that most closed fold geometries are the expression of a single event of progressive simple shear. The elongation of the large-scale fold domes seem to increase towards the Western fault branch and is interpreted as a result of vertical shearing associated with reverse faulting along the Pajala shear

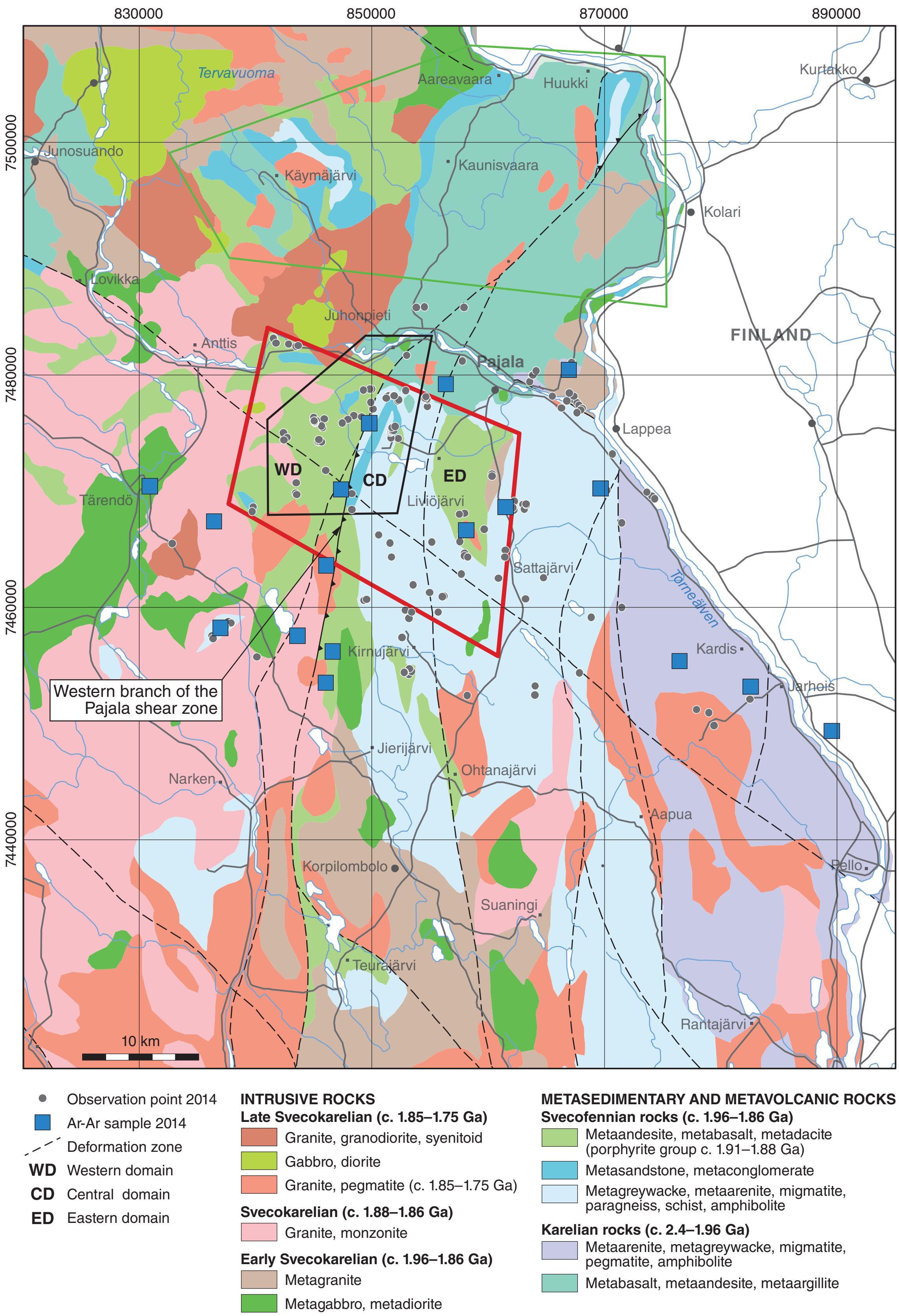

Figure 1. Geological map of the Pajala region showing the main geological units and the main north–south trending fault branches related to the Pajala shear zone. Red polygon refers to the study area and black polygon to the map shown in Figure 7. Green polygon outlines the Käymäjärvi-Ristimella key area as described in Grigull et al. (2014). Background data was extracted from the SGU bedrock database.

zone. This faulting is consistent with eastern-side-up movement and accommodated east–west to north-east–south-west shortening as well as uplift of the central domain.

The folding pattern is overprinted and locally disrupted by a strong penetrative, north–south striking foliation (here referred to as S3). This foliation aligns well with the main structural trend observed on the magnetic anomaly maps. Detailed structural analysis revealed that this fabric is well developed throughout the entire central domain and may have formed during a phase of dextral transpression. In the vicinity of some of the major fault branches, the S3 foliation appears as a tight crenulation cleavage.

Locally, a north-east to north-north-east striking S4 fabric developed and this represents a phase of sinistral transpression. Its presence is limited to retrograde shear zones with a maximum width of c. 1 m as well as to sets of spaced cleavages (kink bands) indicating localised brittle deformation.

Western domain

The western domain mainly comprises andesitic lavas and metavolcaniclastic rocks ranging between layered tuffs and volcanic breccias. The geochemical signature of the rocks suggests an affiliation to the Sammakkovaara group (1.91–1.88 Ga, Martinsson 2004), but no stratigraphic relationships with the surrounding units could be determined.

The magnetic response associated with the metavolcaniclastic rocks of the western domain allowed for the interpretation of fault bounded basins (depocentra). Some of these basins are aligned in a north-east direction and their stratigraphic sequence is characterised by rapidly alternating tuffs, volcanic breccias and meta-arenites. The rocks are often highly fractured but lack a clear foliation. Some open, upright folds trend parallel to north-west striking and steeply dipping faults that may have formed during north-east–south-west shortening.

The presence of major north-east striking faults is typical for the western domain. These north-east-striking faults are associated with mylonitisation, intense fracturing, sinistral and dextral strike-slip, alteration (scapolitisation, albite and actinolite veins) and mineralisation (magnetite veins). The fact that some of these faults mark the boundary between metavolcanic and metasedimentary rock sequences may indicate a syn-depositional origin.

Tectonic implications

Based on the above, a main phase of north-east–south-west directed shortening led to dextral transpression along the Pajala shear zone. Locally, strain was partitioned into an east–west shortening component resulting in viscous flow, intense folding and uplift of the central domain. Meanwhile, the cooler and more rigid western domain became faulted along north-east striking strike-slip faults and north-west striking reverse faults. The long-lived Western fault branch acted as a main decoupling horizon and accommodated both dextral and reverse slip.

Implications for mineralisation and ore potential in the area

It is known that the central domain hosts some low grade graphite deposits in the subsurface (e.g. Gerdin et al. 1990, Luth & Jönsson 2014, Bergman et al. 2014). Associated magnetic and electromagnetic anomalies have indicated a north–south ellipsoidal outline of the Liviövaara prospect, which is structurally bounded by an antiform (Johansson 1985). Based on our new structural model, many of the folds within the central domain most likely have tubular geometries and may extend (when extrapolated) to several kilometres in depth. This makes us believe that high graphite concentrations may be traceable to deeper levels than previously assumed.

The volcanic rocks of the western domain have been the target of prospecting mainly for iron and copper (e.g. Kautsky & Frietsch 1971). Here, many of the rocks are indeed rich in copper and iron, but the concentrations are today (2014) too low to be of economic interest. However, our observations indicate that a secondary phase of local enrichment towards higher concentrations occurred probably in relation to fluid flow along several major north-east striking faults. The proposed multi-phase tectonic history for these faults (possibly initiated as normal faults) in combination with a relatively young reactivation as strike-slip faults make these structures interesting targets for further ore potential investigations.

GEOPHYSICAL CHARACTERISATION OF THE DIFFERENT DOMAINS

The Liviöjärvi key area is extensively covered by airborne geophysical measurements. Full coverage is present for magnetic, radiometric and electromagnetic slingram data. Approximately a third of the key area lacks electromagnetic VLF data. Gravity measurements have a sampling density of approximately 1.5 measurements per square kilometre and are well distributed over the area. Detailed ground measurements have been performed in six areas in or in the vicinity of the Liviöjärvi key area. A summary on the existing airborne and ground geophysical data in the Liviöjärvi key area is presented in Luth & Jönsson (2014).

Western domain

The western domain is dominated by volcanic rocks of basaltic to andesitic composition but there are also some occurrences of felsic intrusive and sedimentary rocks (Fig. 1). In general, the high density rocks of the western domain correlates with a positive Bouguer anomaly in the residual gravity map (Fig. 2). The average density of the rocks within the western domain is 2 813 kg/m^3. In the north-western corner of the key area the presence of a pronounced mass deficiency suggests that the sedimentary or felsic intrusive unit mapped within the western domain is more widespread than shown on the current bedrock map (Fig. 1 and marked area in Fig. 2). This area is further discussed below in section Region 4.

The magnetic pattern for the western domain varies considerably. There are areas of high or low magnetic signature, folding patterns and also disruptive anomalies (Fig. 3). The magnetic susceptibility for existing bedrock samples varies considerably within the area from 20×10^{-5} SI units to $34\,000 \times 10^{-5}$ SI units with a log-average value of $1\,318 \times 10^{-5}$ SI units. Within the area of Soursa, a homogeneous, high-magnetic signature is observed. In this area, the bedrock in general has a higher magnetic susceptibility, and 70% of the samples have a magnetite content higher than 3 vol.% and 25% of the samples contain more than 20 vol.% magnetite. The area has been classified as a minor iron deposit (Kautsky & Frietsch 1971). Structural interpretations from this area is presented and discussed in section Region 5.

Central domain

The central domain consists of a quartz-feldspar rich paragneiss unit. This area differs in the geophysical response from the surroundings with regard to gravity, magnetic and electromagnetic slingram data. The residual gravity field show a mass deficit compared to the surroundings which is consistent with the low density rock types found here. The average density of the samples collected within the central domain is 2 741 kg/m^3.

In general, the magnetic field is low and fairly homogeneous although some horizons with higher magnetic response can be distinguished (Fig. 3). The outcrops are few but the existing samples give a low log-average value of 273×10^{-5} SI units for the magnetic susceptibility. A weak, positive magnetic anomaly, interpreted as a dome structure, was investigated in 2014 and a detailed ground magnetic survey and several samples were collected. This area is further discussed and some data is presented in the section *Geophysical and geological 3D modelling of an elongated fold (region 2).*

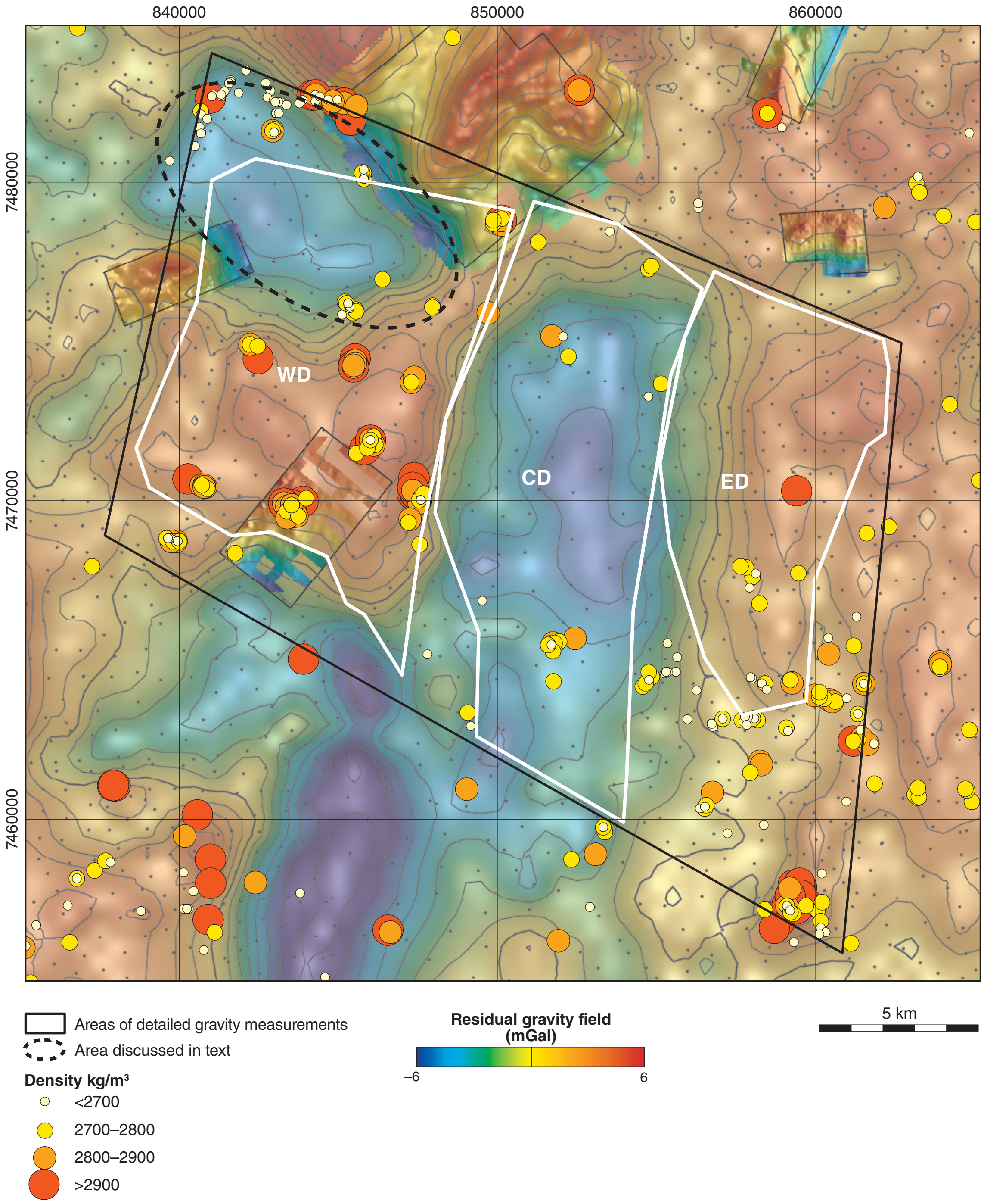

Figure 2. Residual gravity field. Small dots show the gravity measurement sites of regional measurement character. Detailed gravity surveys are also included (without measurement sites). Circles show bedrock samples with the density value (proportional size). The dashed black area in the north-west corner of the key area shows the mass deficient area discussed in the text. The contour lines are at 1 mGal equidistance.

The airborne slingram data show that the central domain area is more conducting than the surroundings (Fig. 4). The Liviövaara slingram anomaly within the central domain is a striking feature in both the in-phase and out-of-phase component and is the only area where more detailed ground slingram measurements have been performed. The highly conductive area is

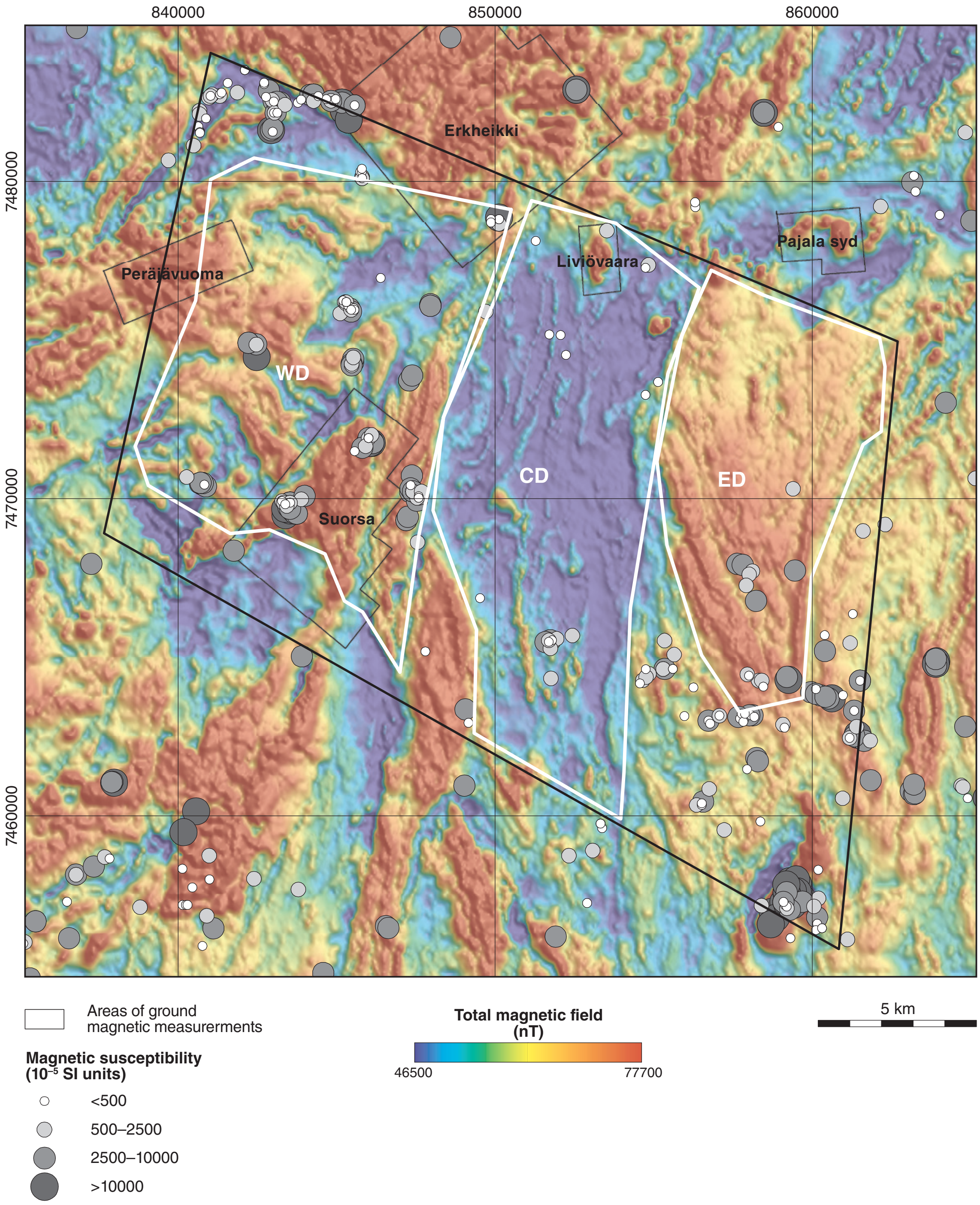

Figure 3. The total magnetic field within the Liviöjärvi key area. The circles show, by proportional size, the susceptibility of samples collected before 2014. The black polygons show the areas of detailed ground magnetic measurements as part of different exploration projects performed before 2014.

explained by the presence of both sulphides and graphite. Additional small, localised anomalies in the key area are present, especially in the central domain. These have not yet been investigated but the source of the anomalies is probably the same as in Liviövaara, i.e. graphite and sulphides.

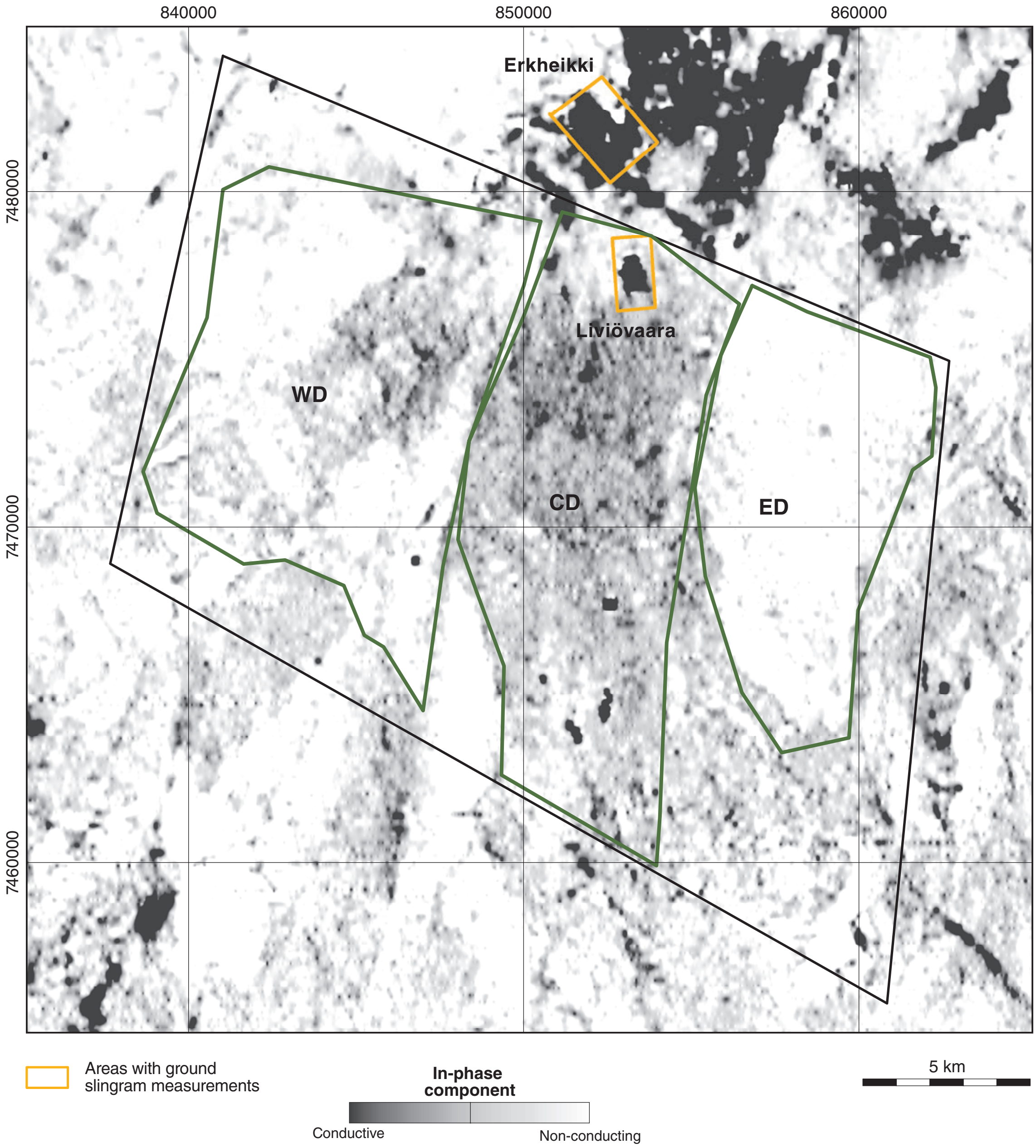

Figure 4. In-phase component of airborne slingram data. Darker areas indicate good conductors. The green polygons show the location of detailed ground slingram surveys in the area.

Eastern domain

The eastern domain is similar to the western domain with regard to lithology and it is dominated by rocks of basaltic to andesitic composition. The magnetic susceptibility has a similar log-average value of $1\,200 \times 10^{-5}$ SI units but the magnetic pattern is different. In the eastern domain, the magnetic field is intermediate and fairly homogeneous compared to in the western domain (Fig. 3). The positive residual gravity field reflects the intermediate density rocks present here (Fig. 2). The domain is also well defined as a non-conducting area in the airborne slingram data (Fig. 4).

GEOPHYSICAL BASIS FOR STRUCTURAL INTERPRETATIONS

The maps of the magnetic field and the apparent resistivity from the airborne VLF measurements constituted the base from which the target areas for the structural field investigations

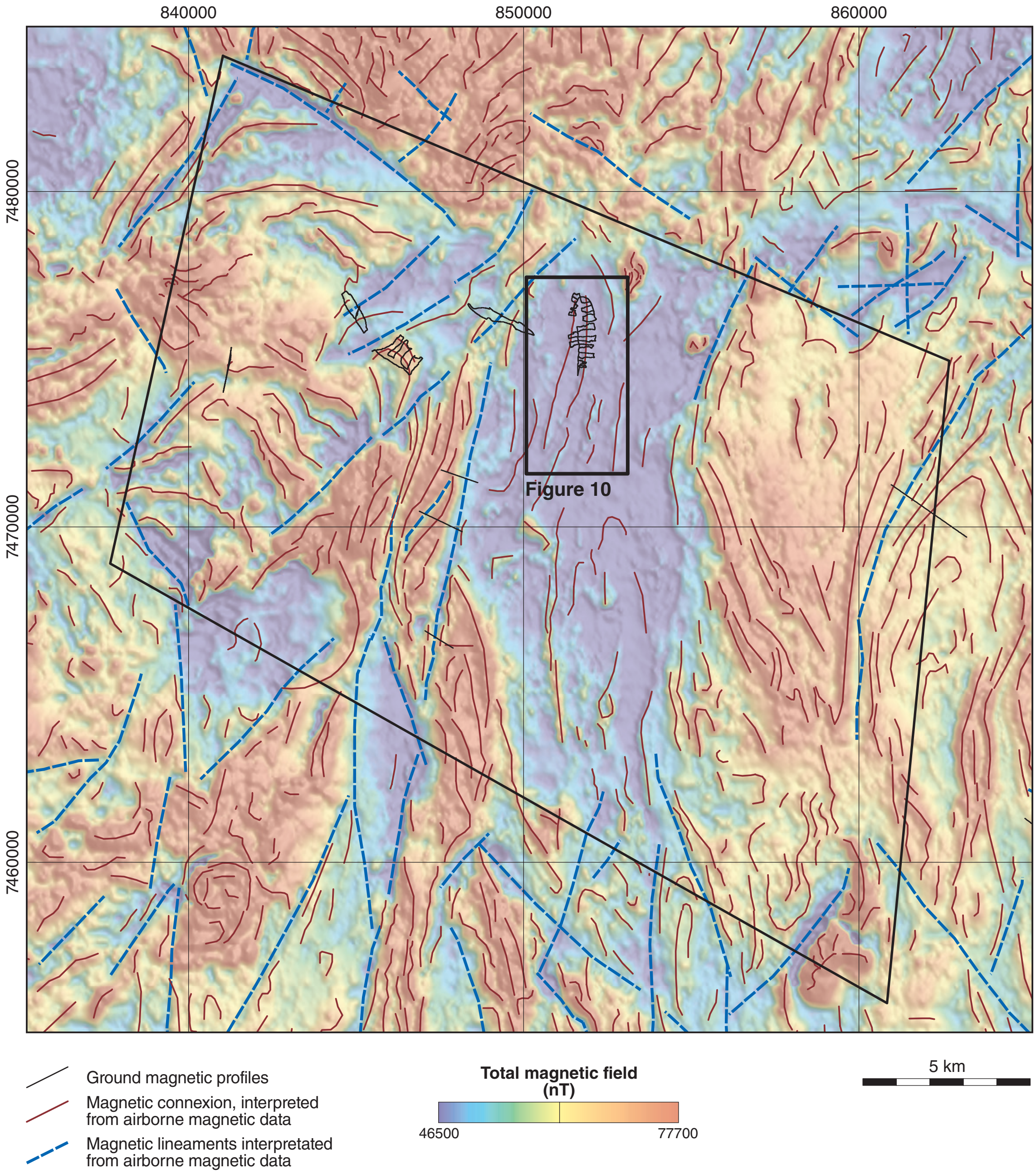

Figure 5. Total magnetic field with structural interpretations and the location of magnetic profile measurements.

were selected. Figure 5 shows the total magnetic field with connexions and lineaments. The connexions facilitate interpretations of ductile structures including folds while the lineaments may correspond to brittle structures such as faults and fractures. In addition, brittle structures were interpreted from the apparent resistivity map produced from the airborne VLF data (Fig. 6). The interpreted brittle structures were compared to structural data from the current bedrock map. Some discrepancies between the two data sets exists and these were target areas for VLF-ground surveys. The location of old and new ground measurements are shown in Figures 5 and 6. We have focused the field work on the north-western part of the Liviöjärvi key area (black polygon in Fig. 1 and Fig. 7) since the most interesting structures and lithological variations on a relative small scale occur there.

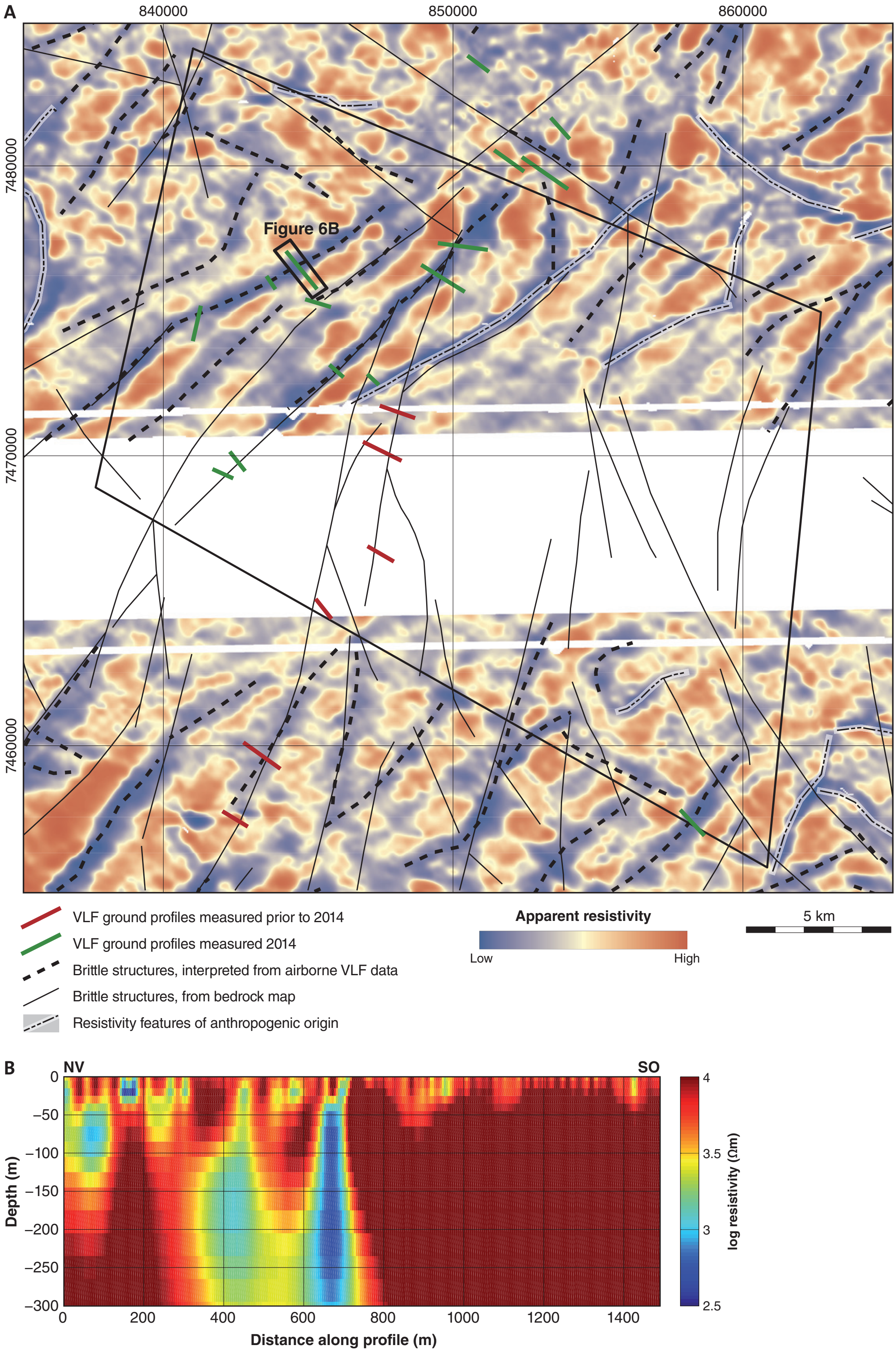

Figure 6. **A.** Apparent resistivity map based on airborne VLF data. Lineaments marked with black dashed lines show low resistivity horizons. Brittle structures are compiled from current bedrock maps. **B.** 2D resistivity model based on ground VLF measurements along profile shown in A. A vertical zone of low resistivity is apparent at 700 m and confirms a brittle conducting structure.

The result from one ground-measured VLF profile measured in 2014 is shown in Figure 7. This profile was measured in order to investigate a lineament interpreted from airborne VLF data, which is not shown as a brittle structure on the current bedrock map. The result from the VLF profile shows that the structure is a steep, nearly vertical low resistivity zone that extends to at least 300 m depth, which confirms that it is a brittle structure.

A NEW STRUCTURAL MAP OF THE LIVIÖJÄRVI AREA

Structural measurements on bedding, foliations, fault planes, fold axes and lineations were obtained from the northern part of the key area and are shown in stereoplots in Figure 7. In the stereoplots, measurements from several outcrops were combined into "regions" and key observations are summarised below for each of these regions.

In general, the central domain is characterised by intense folding and shearing. A north to north-north-east striking, penetrative foliation is commonly observed and it is mainly associated with dextral shearing, but sinistral shear was documented locally. Despite the high grade of metamorphism in the central domain, as revealed by garnet porphyroblasts and migmatisation,

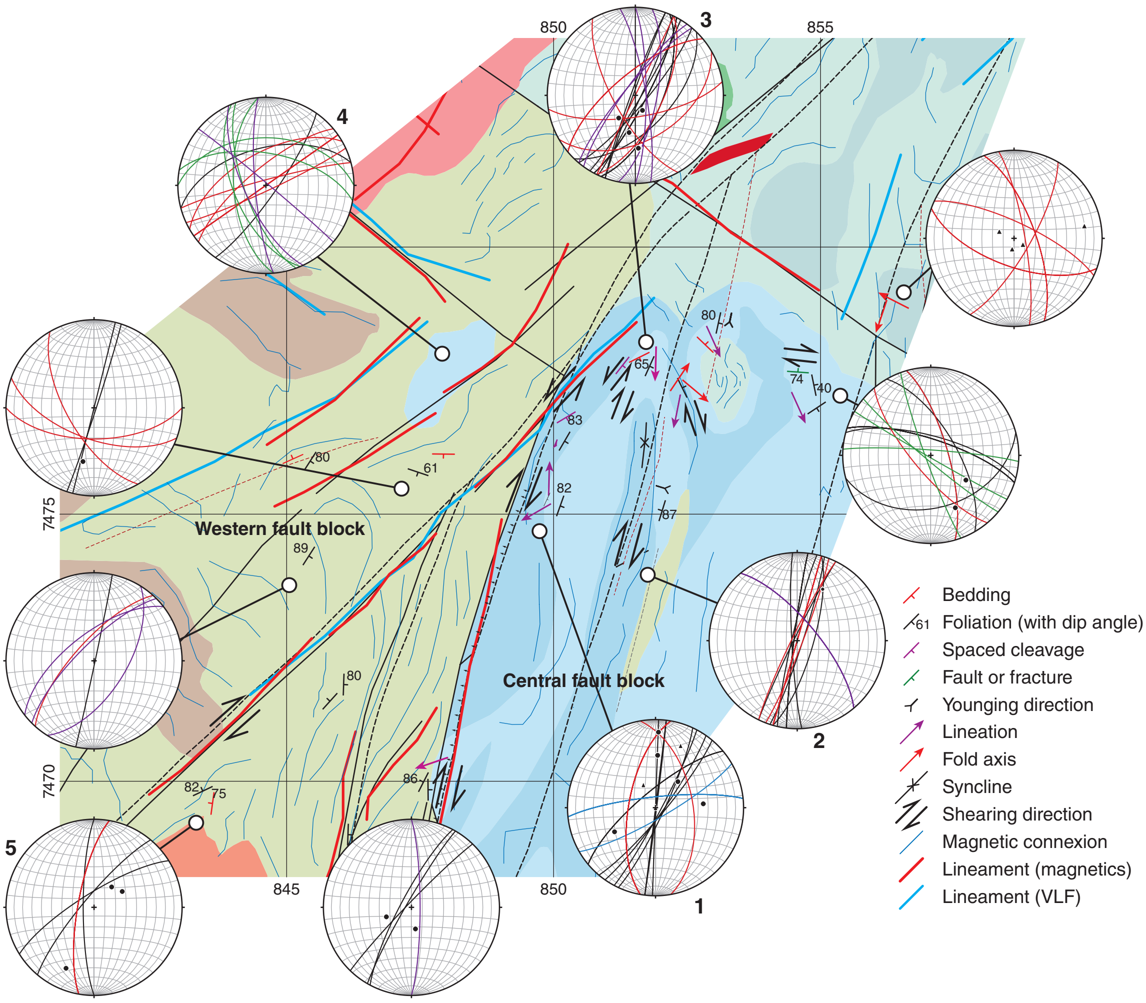

Figure 7. Structural geological map of the north-western part of the Liviöjärvi key area showing magnetic connexions and lineaments. Stereoplots (equal area, lower hemisphere) and shearing directions refer to numbered regions where important structural observations were made. Map colors refer to lithology (see Figure 1 for explanation).

a folded bedding was recognised in several outcrops. The north-striking, penetrative foliation intensifies towards the Western fault branch, but rapidly weakens within the western domain. Here, bedding is only observed in the volcaniclastic rocks, whereas the lavas appear massive and are often strongly fractured. The shear zones in the western domain strike predominantly north-east and are limited in width to a few tens of metres. Lineations and folds were rarely observed within the western domain.

Field observations and interpretations from the central domain of the Pajala shear zone

Region 1

Region 1 is located along the northern segment of the Western fault branch (Fig. 7). It contains a complex folding pattern which is overprinted by a penetrative, north–south striking fabric.

On an outcrop scale, relics of folded bedding (meta-arenites) appear as lenses surrounded and cross-cut by layers comprised of mica schists (Figs. 8–9). The schists are mylonitic and have a penetrative north striking foliation. Shear sense indicators such as C-S fabric, imbricated clasts and mica-fish are consistent with dextral shearing.

The presence of several fold axes in the meta-arenites indicate superimposed folding. The axial plane of F1 is parallel to bedding and is refolded twice (F2 and F3, Fig. 8A). F2 was only observed in a single outcrop and may therefore be only local. F3 is more consistent as its axial plane cleavage strikes parallel to the penetrative north–south fabric, which is therefore named S3 (Figs. 8–9).

In several outcrops, bedding (S0) appears dome-shaped without a clear associated foliation. In cross-section these domes appear to have tube shapes (Fig. 9A–B). For simplicity we refer

Figure 8. **A.** Top view of a refolded F1 dome structure affected by later north-east to south-west trending F2 folding as well as north–south trending F3 folding. The dominant foliation (S3) strikes north–south. Notice that S4 is only locally developed and associated with sinistral shearing (see also Figure 9D). **B.** Cross-section revealing a tight F1 fold with a strongly inclined axial plane which is refolded by F3 with a fold axis plunging gently towards the north.

to theses dome shapes as F1 folds. However, they may actually be the product of an F2 refolding event, but evidence for that is lacking. It is clear, however, that S3 postdates doming since it overprints and locally cuts the dome structures (Fig. 9C). F3 fold axes plunge approximately 60° mainly towards the north but also towards the south. Locally, kink bands (S4) which strike north-east and record sinistral displacement were observed (Fig. 9D).

Andalusite and staurolite have grown mainly in fold hinges and seem to postdate folding and most likely predate S3 (Fig. 9C). Some uncertain outcrops consisted of protomylonites that revealed east-side-up sense of shear. Locally, large blocks of L-stretched conglomerates were found.

Region 2

Region 2 is defined as a large, elongated fold structure within the central domain. A very tight, north–south striking, ellipsoidal fold geometry was observed in the airborne magnetic anomaly map (Fig. 10). After detailed mapping and geophysical modelling the structure was interpreted as a large-scale sheath fold.

Only the fold's eastern limb is exposed and it consists of tightly foliated and partly migmatised, biotite-rich paragneisses and quartzite. The metasedimentary rocks strike north–south and dip towards the east. Bedding and foliation are sub-parallel and rotated clasts and asymmetrical folds indicate predominantly dextral shearing (Fig. 11).

Figure 9. **A.** Top view of a dome-shaped F1 structure with well preserved laminated (S0) metasandstone. The dome is refolded along an F3 axial plane which is parallel to S3. **B.** Cross-section of a comparable dome structure revealing a funnel-shape in 3D. **C.** Top view of highly strained rock in which the dominant foliation (S3) developed as a symmetric crenulation cleavage isolating the hinges of several tight folds. **D.** Top view of kink bands with several splays (S4) causing sinistral displacement and gentle folding of the penetrative foliation (S3).

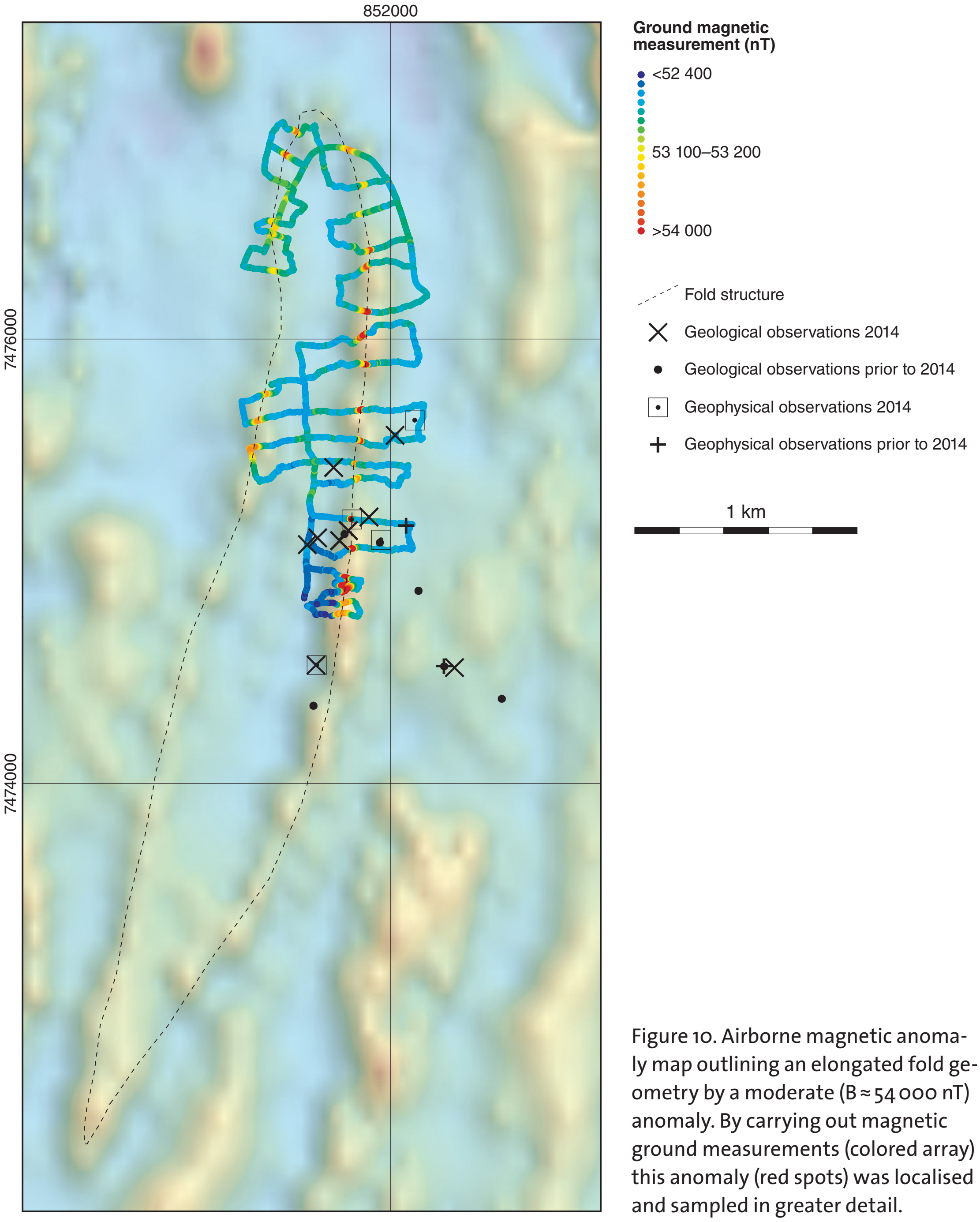

Figure 10. Airborne magnetic anomaly map outlining an elongated fold geometry by a moderate (B ≈ 54 000 nT) anomaly. By carrying out magnetic ground measurements (colored array) this anomaly (red spots) was localised and sampled in greater detail.

Cross-bedding observed within the quartzite is consistent with younging towards the west. Primarily based on this observation, the fold is interpreted as a syncline with an axial plane that dips steeply towards the east.

Region 3

Region 3 is located south of the junction between the north-striking and north-east-striking faults in the central domain (Fig. 7). In this area, four tectonic events were constrained in terms

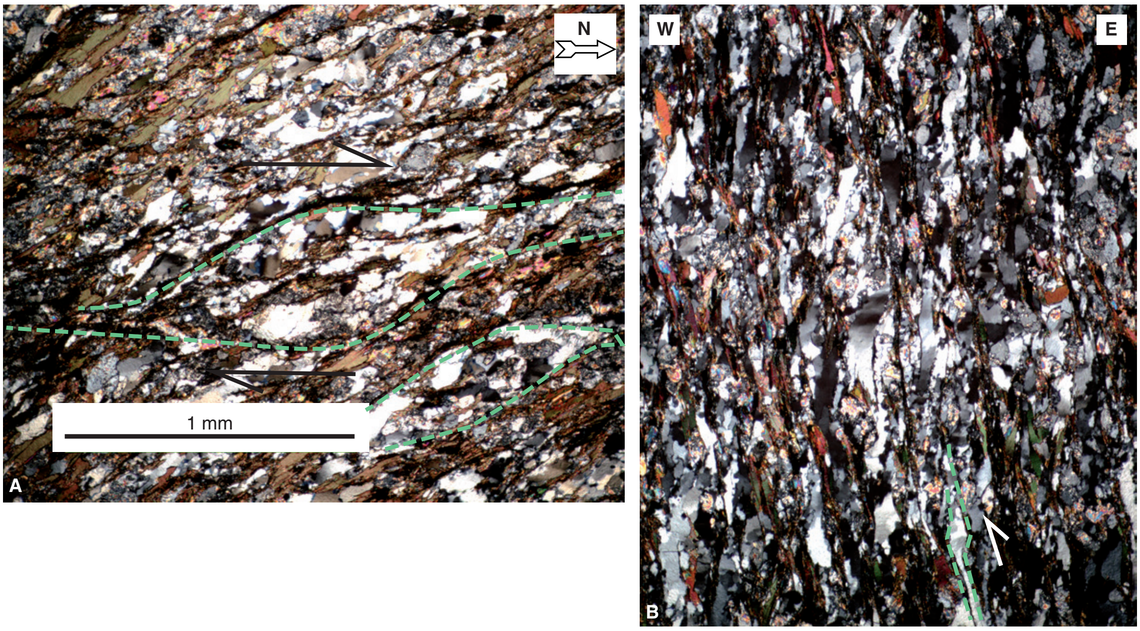

Figure 11. Two orthogonally oriented thin-sections both reveal a mylonitic fabric within a mica schist. **A.** A horizontal section shows a clear CS fabric comprised of mica domains (brownish color) anastomosing around partly recrystallised, lens-shaped quartz grains (white and black colors). **B.** In a vertically oriented thin section, quartz appears mostly as ribbons (elongated bands in the center of the image) with "sweeping" undulose extinction indicating low to medium grade conditions (300–500 °C).

of overprinting relationships: 1) development of foliation or metamorphic banding, 2) north–south folding, 3) dextral strike-slip and 4) sinistral strike-slip.

A sequence of paragneisses, meta-arenites and migmatites has been tightly folded on a kilometre scale (F1). The folded fabric comprises both S0 (thinly laminated arenites) and a metamorphic banding (S1, made out of quartz and biotite-rich layers).

The limbs of the folds are typically bounded by 1–10 m wide, north–south striking shear zones that locally contain garnet and andalusite porphyroblasts and often are rich in biotite (Fig. 12). Both sinistral and dextral shear indicators have been observed parallel to a moderately southward plunging stretching lineation (Fig. 12B–C). Some of the dextral shear indicators are locally overprinted by a north-east striking crenulation cleavage that can be associated with late sinistral shearing. Magnetite-rich veins striking north-east and are associated with a north-east striking crenulation cleavage.

Field observations and interpretations from the western domain of the Pajala shear zone

Region 4

Region 4 covers a relatively large area with mainly volcaniclastic rocks within the western domain (Fig. 7). Relatively good exposures allowed for the recognition of a stratigraphic sequence composed of mainly metavolcaniclastic rocks (ranging from volcanic breccia to volcanic tuff) with andesitic to rhyolitic composition (Fig. 13). By integrating the geology and the magnetic anomaly pattern we interpret the area as a fault bounded basin. This is outlined in Figure 14 with an additional area further south also interpreted as a small basin.

Metavolcaniclastic rocks such as laminiated tuffs alternate with layers containing lithic fragments (Fig. 13). Locally, the fragments are large (up to 10 cm) and comprise up to 50% of

Figure 12. **A.** Localised narrow shear zone (dashed lines) comprised mainly of biotite. **B.** Top view of a retrograded porphyroblast composed of mainly biotite and quartz (tails) indicating sinistral shearing. **C.** Well developed stretching lineation (parallel to arrow) plunging towards the south. **D.** North-east striking spaced crenulation cleavage (S4) associated with sinistral shearing.

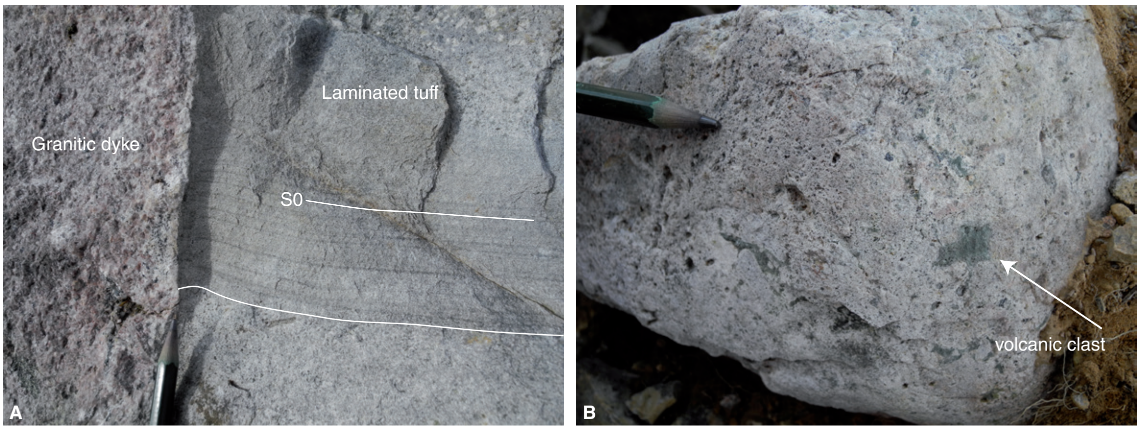

Figure 13. Metavolcaniclastic rocks. Laminiated tuffs (**A**) alternate with porphyritic rocks (**B**) and volcanic breccias containing angular lithoclasts. Note that these primary structures are well preserved indicating a low degree of deformation and metamorphism.

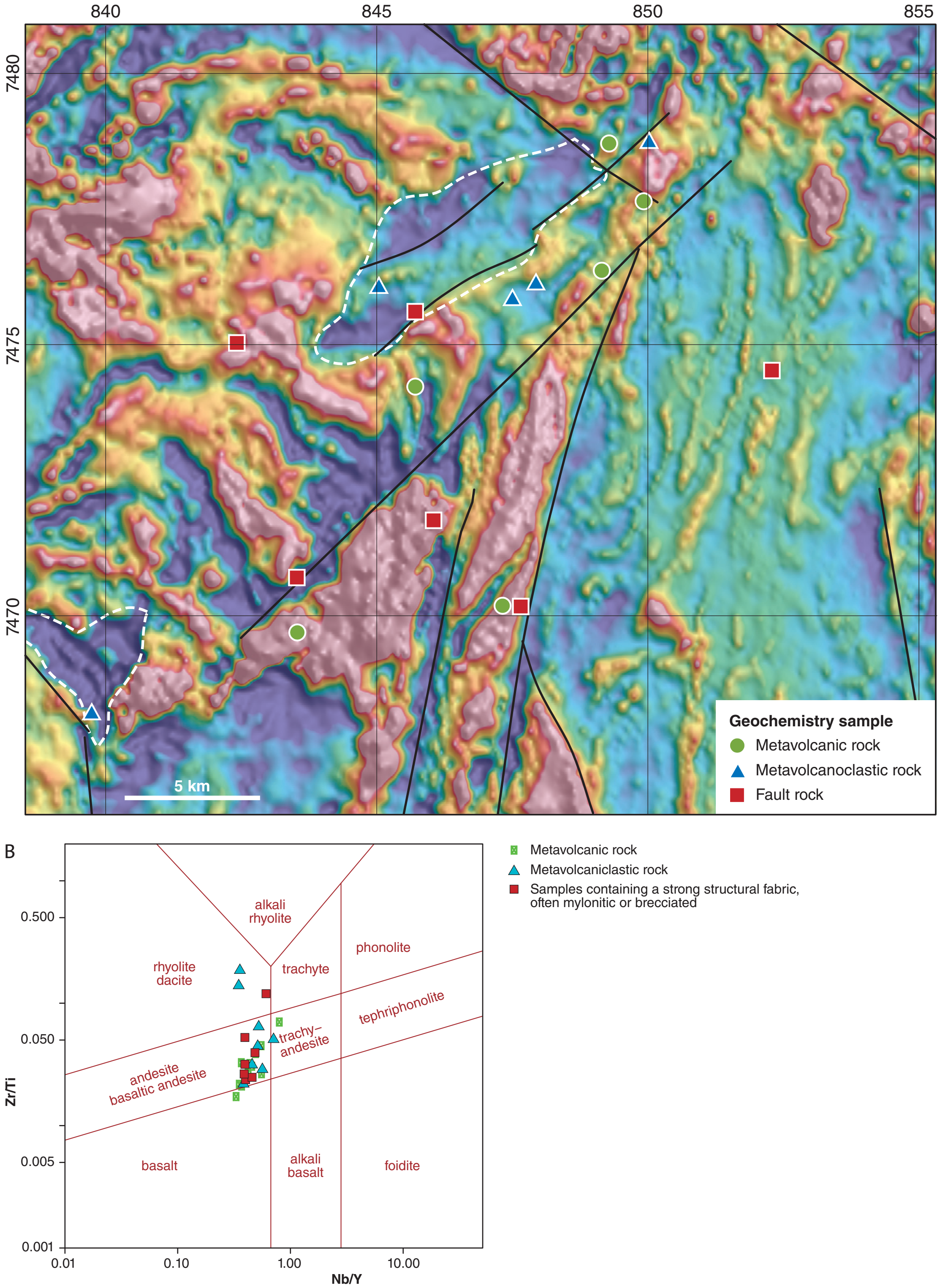

Figure 14. **A.** Detailed map of the western fault block showing the distribution of metavolcanic rocks sampled for geochemistry. Background coloring refers to the magnetic anomaly map shown in Figure 2 and lines to major shear zones. Note that the metavolcaniclastic rocks are associated with magnetic lows, on which grounds two sub-basins were interpreted (white dashed line). **B.** Samples plotted on a Pearce (1996) diagramme. The plot shows that most of the samples taken from the western fault block (Suorsa group) are of andesitic composition.

Figure 15. **A.** Intense alteration of a volcanic rock resulted in compositional banding of mainly epidote (green), magnetite and actinolite (dark gray), and K-feldspar (pink). **B.** Rock primarily composed of magnetite. **C.** Actinolite vein parallel to the axial plane of a drag fold indicating synchronous dextral shearing and vein formation. D. Intense scapolitisation of a basic coherent volcanic rock.

the rock volume making it a volcanic breccia. Granitic dykes cut through the sequence at high angles. The rocks are strongly fractured and faulted (gouge and slickensides), but no penetrative foliation was observed. K-feldspar alteration is intense near the tectonic boundaries of the sequence, but the overall metamorphic grade appears not to exceed upper greenschist facies.

Region 5

Region 5 is located along the major north-east striking fault zone in the western domain (Fig. 7). The fault zone is characterised by mylonitisation, intense fracturing, dextral strike-slip, alteration (scapolitisaton, albite and actinolite veins) and mineralisation (massive magnetite veins).

The eastern side of the fault (footwall) is marked by strongly sheared basic rock (basaltic to andesitic lava) with intense epidote and K-feldspar alteration appearing as bands that alternate with magnetite-rich bands (Fig. 15A–B). Rotated feldspar sigmaclasts reveal mainly dextral shearing. Intense fracturing and albite veins overprint the mylonitic fabric.

The western side of the fault is defined as the hanging wall and is characterised by actinolite veins associated with asymmetric folds formed by dextral shearing. Here, the basaltic host rock is locally intensely scapolitised (Fig. 15C–D).

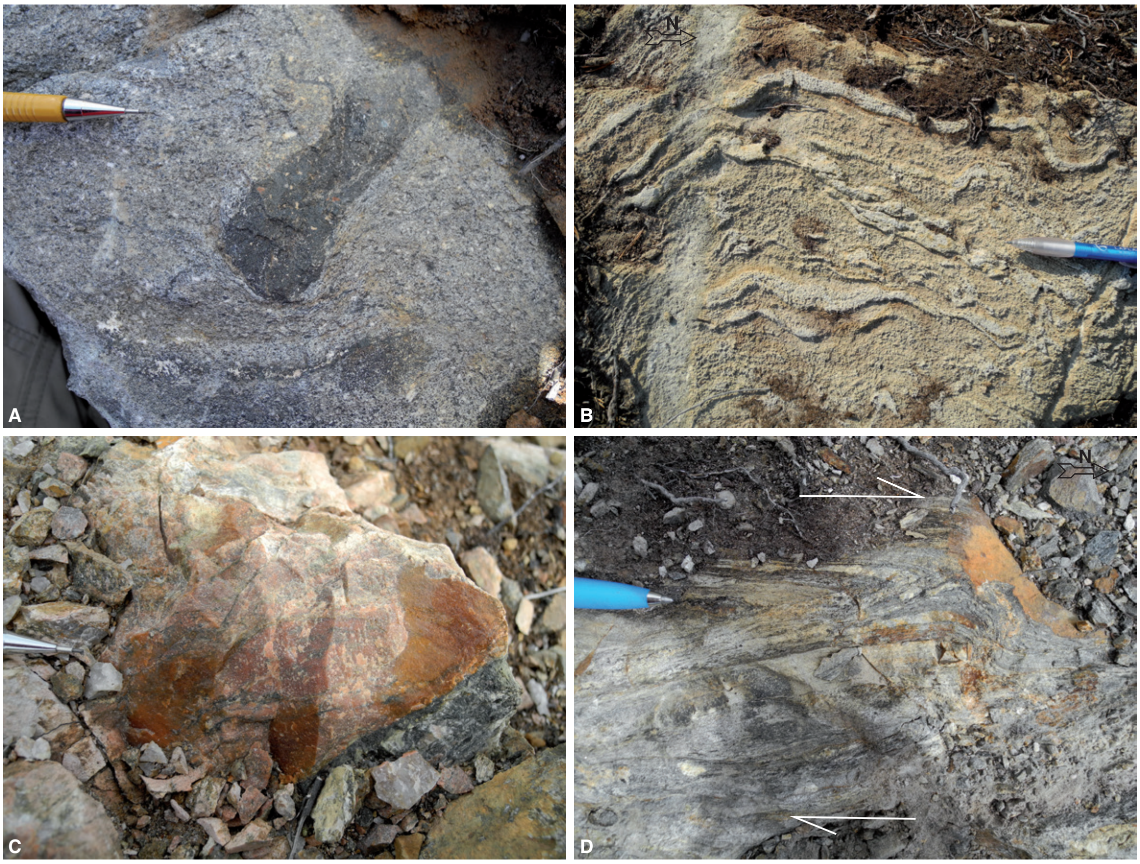

Figure 16. **A.** Porphyritic metavolcaniclastic rock containing large fragments of porphyritic lava (dark gray). **B.** Migmatised and strongly folded metasandstone. Strong alteration (**C**) and intense folding (**D**) along local shear zones (see aslo Figure 17).

Region 6

Region 6 is located further south along the major north-east striking fault zone. Competent volcaniclastic rocks alternate with intensely sheared meta-arenites. Faulting seems to be related with gentle folding which may have formed during a phase of basin inversion.

Gentle folding of the metasedimentary sequence of mainly porphyritic volcaniclastic rocks did not lead to the development of a foliation (Figs. 16A, 17). Folds are associated with north-west striking faults and alteration and sulphide mineralisation occur along these faults up to a distance of 5 m from the fault (Fig. 18). Local shearing resulted in more intense folding revealing a dextral shear sense (Fig. 16D).

Nearby, strongly sheared and partly migmatised metaarenites may have accommodated much of the strain along the major north-east striking fault zones (Fig. 16B).

GEOPHYSCIAL AND GEOLOGICAL 3D MODEL OF AN ELONGATED FOLD (REGION 2)

A first attempt was made to create a 3D model of the elongated fold geometry apparent in the magnetic data from region 2 (Fig. 10). An inverse modeling routine was executed with the magnetic data from airborne measurements as input. The model space measures approximately

5.5 × 2.5 × 1 km and consists of volume pixels (voxels) of 100 × 100 m in the horizontal direction and 25 m in the vertical direction. The inverse modeling assigned a magnetic susceptibility value to each voxel. In Figure 19 an iso-surface of 700×10^{-5} SI units is shown outlining an ellipsoidal distribution.

Interpretation

Structural field observations on the eastern limb of the fold revealed that both bedding and foliation strike north–south and dip subvertically towards the east. Another important field con-

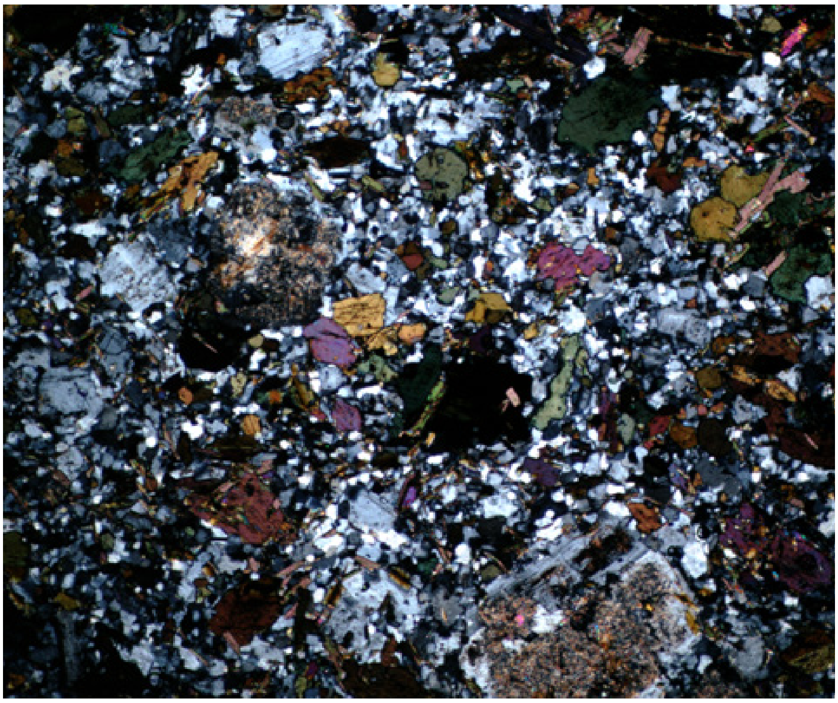

Figure 17. Thin-section of a porphyritic metavolcaniclastic rock (Figure 16A), revealing mineral clasts (mainly amphibole, green and yellow colors) and angular feldspar-rich lithic clasts (below). Note the absence of a foliation. Width of photograph is 10 mm. Crossed polars.

Figure 18. North-west trending open folds (**A**) cut by subparallel listric faults (**B**) along which alterations and sulphide mineralisations were found (Figure 16c).

straint is the observed cross-bedding in meta-arenites which indicates a stratigraphic younging towards the west.

The fold is interpreted to be a syncline with a subvertical axial plane. Nearby field observations on steeply plunging stretching lineations and quartz ribbons (both north and south plunging) and tube-like geometries on an outcrop scale may indicate a sheath fold geometry (Figs. 9B, 20).

IMPLICATIONS ON THE TECTONIC HISTORY OF THE PAJALA SHEAR ZONE

Depositional environment

The volcanic and metasedimentary rocks observed in the western and central domains were most likely deposited during a stage of crustal extension. Associated faulting and subsidence may then have produced multiple basins of variable size, which became filled by volcaniclastic matrial (e.g. pyroclastic flows) as well as clastic sediments derived from the hinterland. On a more regional scale, volcanism and crustal extension may imply deposition in a back-arc setting. The geochemical signature of the metavolcanic rocks found in the eastern domain are consist-

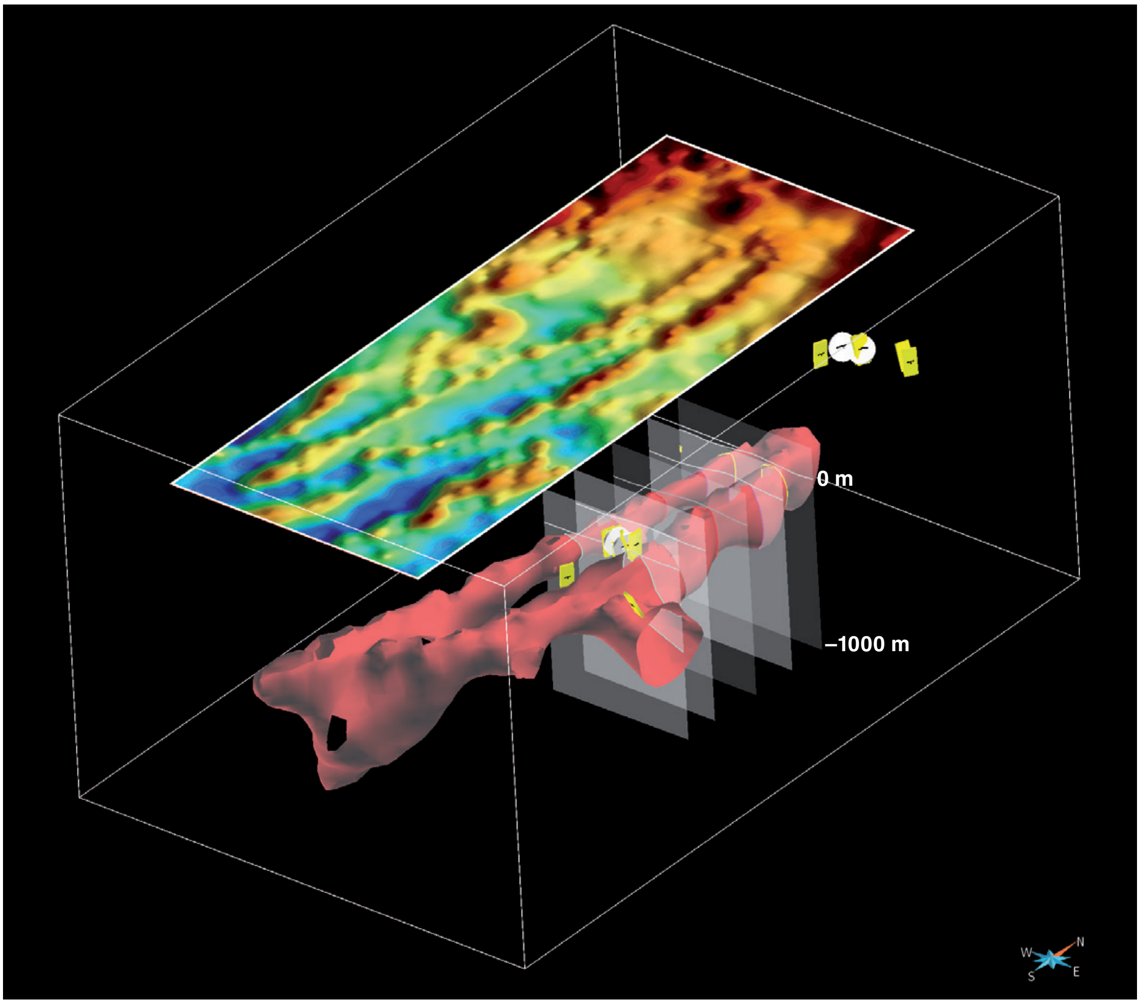

Figure 19. 3D view of the modelled fold geometry looking towards the north-west (see also Figure 10). The red isosurface equals a susceptibility value of 700x10-5 SI-units. The model is derived from inverse modeling by using airborne magnetic data. Structural measurements are shown as tablets (white: bedding, yellow: foliation). No vertical exaggeration applied.

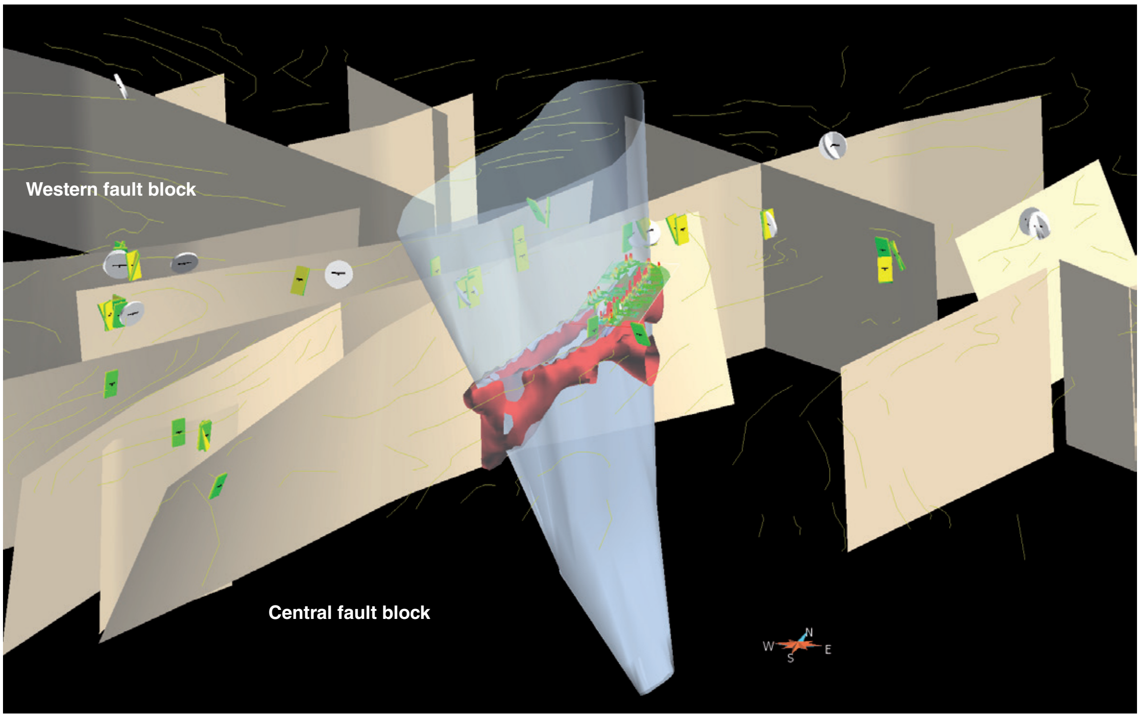

Figure 20. 3D overview of the modeled fold geometry (red surfaces). Based on field observations on steeply plunging stretching lineations, shearing in a vertical sense may have produced a sheath fold. Surfaces in the background represent faults within the western domain. Thin yellow lines are magnetic connexions. View is towards the north-west. Total depth of the sheath fold in this interpretation is approximately 4 km, but this may be an overestimation. No vertical exaggeration applied.

ent with such an interpretation. With ongoing subduction the active margin may finally have switched to a stage of crustal shortening, which induced crustal thickening, deformation, regional metamorphism and crustal melting.

Tectonic evolution

The classification of the observed foliations up to S4 may indicate multiple deformation phases. Several difficulties, however, arise from the lack of observations of overprinting foliations as well as the only local appearance of some fabrics. For example, evidence of a north–south striking S3 foliation is derived only from observations along the Western fault branch in region 1. It is therefore uncertain if the dominant north–south striking penetrative foliation observed in other places throughout the central domain represents an S1, S2 or S3 foliation.

In order to explain the variety of structures observed we must take into account the different physical environments (e.g. pressure and temperature) which prevailed in the western and central domains as well as their difference in composition. At similar depth and temperature the western domain, which consists mainly of basic metavolcanic rocks, may have deformed in a brittle way, whereas the metasedimentary rocks of the central domain may have deformed in a ductile manner. This contrast is further enhanced if we take into account that the rocks of the central domain may actually come from deeper crustal levels compared to rocks of the western domain.

The semi-ductile crenulation cleavage (S3) observed along the Western fault branch in region 1 may have formed at the same time as, but under different PT conditions than the main, penetrative north–south striking foliation of the central domain. The determination of PT con-

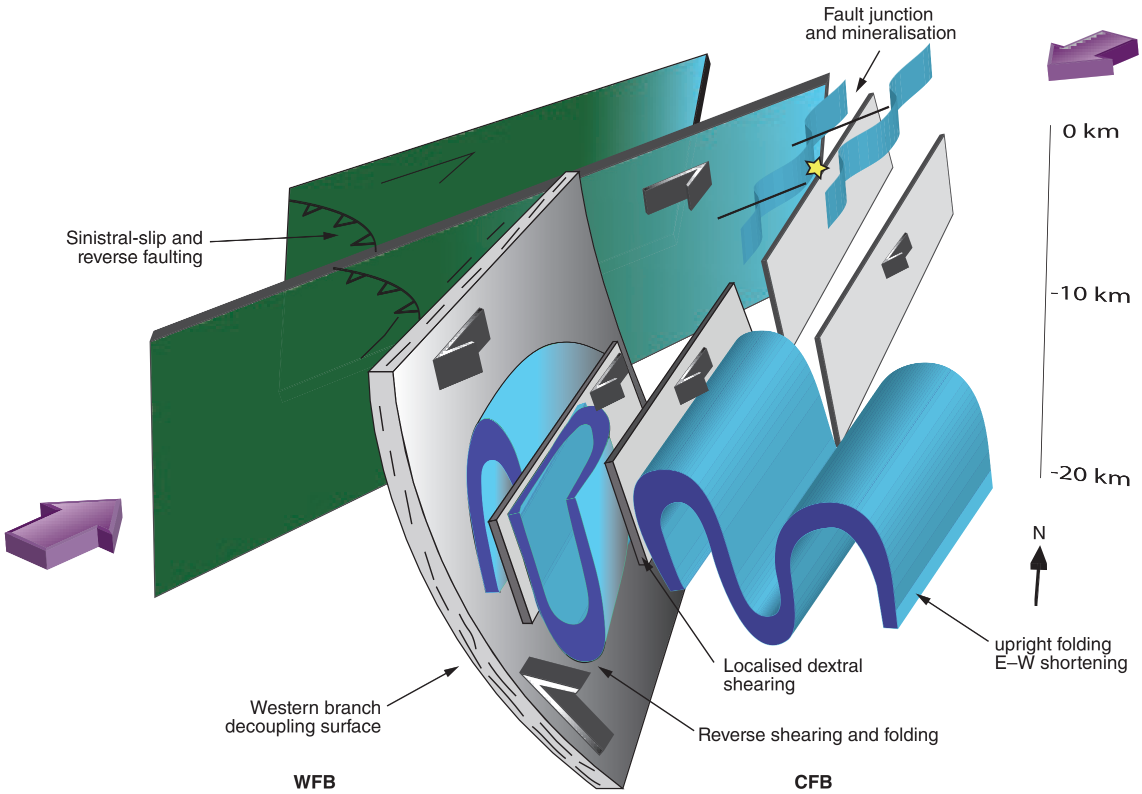

Figure 21. 3D visualisation of the north-western part of the Liviöjärvi key area (see also Figure 7). Folding and faulting of the central and western domains was primarily the result of north-east south-west bulk shortening around or slightly after 1800 Ma (see text for more details).

ditions based on mineral assemblages is still ongoing at the time of writing. However, if we assume that the Pajala shear zone juxtaposed crustal units that were deformed at different crustal depths, then the arising rheological competence contrast may not only have caused the different modes of deformation (brittle versus ductile), but could also have induced local stress fields and strain partitioning.

The more rigid western domain deformed mainly through localised faulting along several north-east striking strike-slip faults and north-west striking reverse faults (Fig. 21). Despite some rotation and deflection of preexisting fabrics (S0) near these faults, no penetrative foliation was developed in the western domain. The hotter and somewhat weaker central domain, on the other hand, accommodated an east–west shortening component mainly through upright folding of bedding and possibly older foliations around north–south striking axial planes. The dextral component was mainly accommodated by vertical shear zones parallel to the fold limbs (Fig. 21). Decreasing temperatures further enhanced strain localisation along the faults, and preexisting fabrics steepened further. The probably preexisting north–south striking Western fault branch acted as a main decoupling horizon and accommodated most of the bulk shortening through reverse shearing at depths below the brittle–ductile transition. At shallower levels, the fault's steep orientation also allowed for the accommodation of the dextral component.

Explaining crustal deformation patterns and strain heterogeneity trough a rheological competence contrast, as proposed above, is not uncommon and has been studied in several active orogens as well as by analogue and numerical modelling (e.g. Handy et al. 2005, Robl et al. 2005, Leever et al. 2011).

Note that in the proposed scenario, the north-east-striking faults of the western domain can be treated as conjugate to the Western fault branch, where the former accommodated sinistral slip and the latter dextral slip (Fig. 21). One of the main north-east striking faults in the western domain continues north of the study area and accommodated a dextral offset displacing the north–south trending Pajala shear zone for tens of kilometers (see also Fig. 1). More work on this fault is needed and an integration with the results obtained from the Käymäjärvi-Ristimella key area are necessary (Susanne Grigull, pers. comm. 2015).

To summarise the above, the number of deformation phases can be significantly reduced if we assign an important role to strain partitioning in the Liviöjärvi key area. Moreover, basically all structural elements observed in the study area may be explained as a result of north-east to south-west directed bulk shortening. The more rigid western and eastern domains locally acted as ramps indenting the central domain in which the interplay between folding, dextral shearing and east-side-up kinematics can be considered as the expression of ongoing shortening during a period of continuous uplift and cooling.

Timing of deformation in the Liviöjärvi area

The timing of deposition of the studied metasedimentary rocks is not well constrained, but is bracketed between 1.96 and 1.88 Ga for both the western and central domains (see Luth & Jönsson 2014, Jonsson & Kero 2013). Depostion was followed by an early phase of the Svecokarelian orogeny which affected northern Sweden and many parts of Finland. This is constrained to the interval 1894–1872 Ma (e.g. Bergman et al. 2006, Lahtinen et al. 2014). Most of the available geochronological data for the Pajala region, however, reflects a late-orogenic phase with deformation and metamorphism at around 1800 Ma (Bergman et al. 2006). The high-grade metamorphic imprint as well as the main north–south striking structural fabric observed in the central domain is most likely associated with this later phase. In addition, a preliminary zircon U-Pb age of 1800 Ma was obtained from a foliated granite sampled for this study, and this placed an upper limit for ductile shearing in the central domain. Similar ages obtained by Bergman et al. (2006) have already shown that metamorphism around this period was associated with zircon overgrowth and the growth of metamorphic monazite. In contrast to some less deformed areas in northern Sweden, we postulate that the emplacement of the 1800 Ma granitic intrusions in the Pajala area may well have supplied heat and locally caused migmatisation, but that their overall structural context and elongated geometry suggest that their paths were strongly controlled by the presence of large, steeply-dipping shear zones. Both metamorphism and plutonism around 1800 Ma may have resulted from shortening and crustal thickening during orogenesis (see also Lahtinen et al. 2014).

CONCLUSIONS

Detailed structural mapping and modelling in order to unravel the complex faulting and folding patterns observed in the Liviöjärvi area shed light on the tectonic history of the Pajala shear zone. The Western fault branch can be considered as a major structural boundary which accomodated large vertical and lateral displacements during oblique, east-side-up shearing. Vertical and north–south directed shearing was associated with intense folding and uplift of the hanging wall (central domain) during which large, steeply plunging sheath folds formed. The produced fold and dome geometries were then further flattened by east–west shortening. In addition, the dominant brittle deformation patterns observed in the footwall (western domain) indicates a rheological competence contrast, which probably induced strain partitioning within and between the two fault blocks. In a regional context we therefore suggest that most of the structures in the Liviöjärvi area can be explained by a main phase of north-east to south-west bulk shortening around or slightly after 1800 Ma. The progressive formation of multiple steeply dipping fabrics (foliations, folds and shear zones) was important for the creation of conduits for granitic melts and hydrothermal fluids.

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