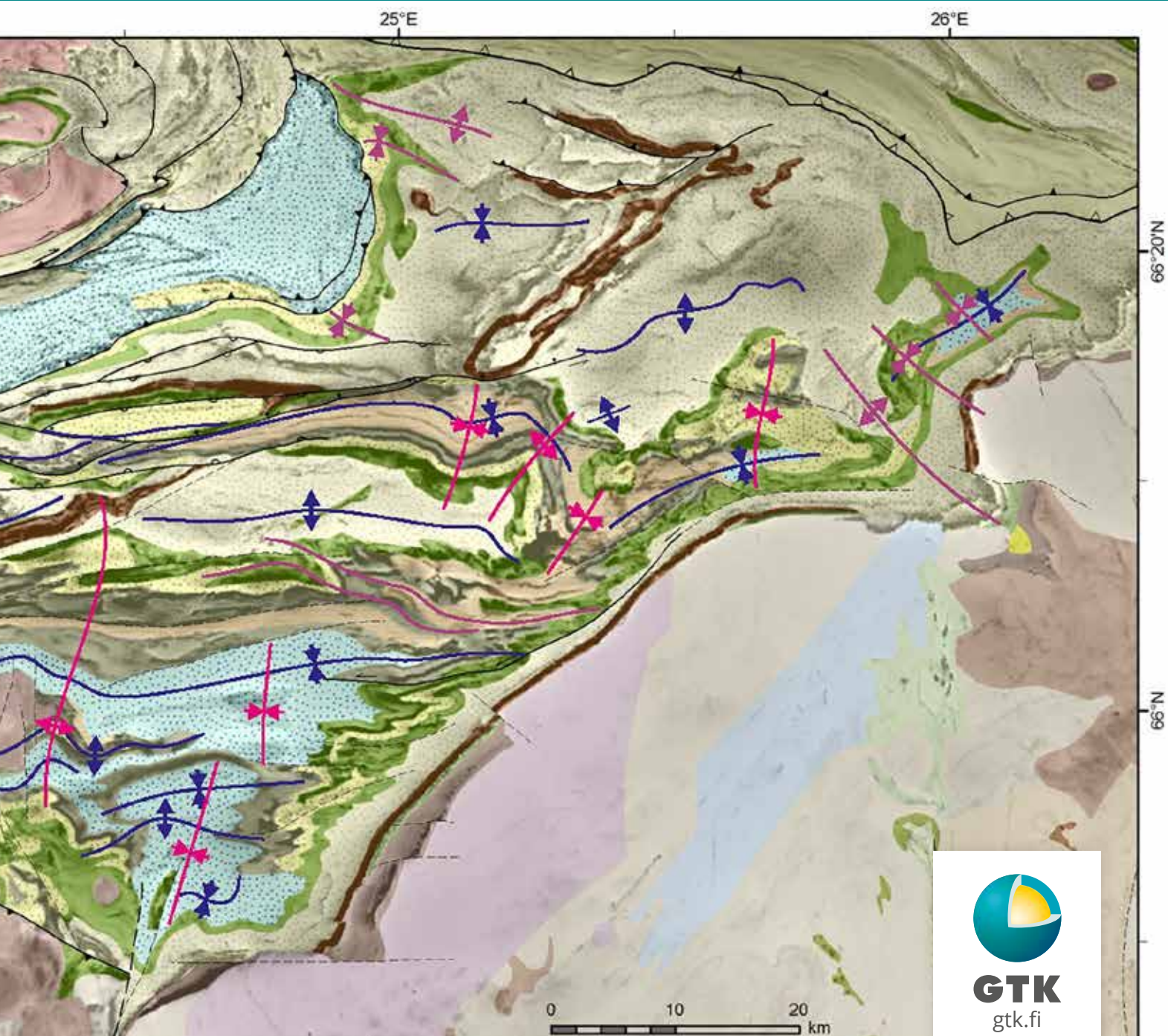# Geological Survey of Finland

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Structural interpretation of the Peräpohja and Kuusamo belts and Central Lapland, and a tectonic model for northern Finland

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This study is based on existing literature, aerogeophysical maps, and the GTK bedrock database. Structural evolution in the Peräpohja and Kuusamo belts was first interpreted, and a tectonic model is presented for both areas. Central Lapland, the largest of the areas and crucial in the interpretation of tectonic evolution in northern Finland, was divided into five domains. The structural evolution in each domain was independently interpreted by studying key areas. Deformation was correlated with metamorphic characteristics, and structural evolution in central Lapland was assessed in the framework of existing age data. Finally, a model is presented for the tectonic evolution in northern Finland by combining models from the three areas. The tectonic model follows some earlier presented models, but is more detailed with respect to the study area. It is based on the concept 'soft' supracrustal rock sequences on the rigid Archean basement, the movement of rigid crustal blocks upon the basement, and the partitioning of strain in the 'soft' rocks between the rigid units. Movement of the blocks controlled much of deformation in northern Finland during the Svecofennian orogeny.

The emplacement of layered mafic intrusions and felsic volcanic rocks occurred at 2.44 Ga in the Archean craton along old shear zones, and the earliest sediments were deposited in a half-graben. The water-filled area widened into an epicontinental basin that covered the present area of northern Finland. Blocks of various sizes were detached from the attenuated Archean continent. The largest of these was the Pudasjärvi block, consisting of the present Pudasjärvi complex, Peräpohja belt and Central Lapland granitoid complex. Continued extension finally led to continental break-up at 2.06−2.05 Ga. The Pudasjärvi block and smaller crustal blocks remained at the continental margin.

Two foreland fold and thrust belts developed in northern Finland during 1.93−1.91 Ga, as a result of two continental collision events: the Kittilä and Uusivirka suite rocks were thrust from the west, and partly simultaneous thrusting from the north−northeast led to the development of a thrust belt (Lapland granulite complex) and a nappe structure. Accretion in the south at 1.89−1.88 Ga caused the movement of the Pudasjärvi block first northeast and subsequently to the north against the Archean continental crust. As a result of the northward movement, the frontal part of the Pudasjärvi block was thickened, the sedimentary-volcanic sequences covering the Archean crust were intensely deformed, and only small areas remained relatively undeformed. The tectonically thickened frontal part of the Pudasjärvi block was uplifted, deeper crustal sections were exhumed at the margins of the block, and the Kumpu group sediments were deposited upon the exhumed rocks during 1.88−1.87 Ga.

Thrusting in western Finnish Lapland at 1.86−1.85 Ga, with tectonic transport towards northeast, also affected some Kumpu group rocks (Ylläs formation). E−W compression at 1.85 Ga caused upright folding that can be found in the Peräpohja and Kuusamo belts and in several localities in central Lapland. E−W compression was followed by NW−SE compression at 1.84−1.83 Ga. Late Svecofennian continental collision in the south caused thrusting from the south, and several shear zones that had developed during 1.89−1.88 Ga, were reactivated at 1.82−1.80 Ga. The extensional event at 1.80−1.77 Ga was part of the orogenic collapse that affected the entire Svecofennian orogen. The tectonically thickened Central Lapland granitoid complex became a thermal center and was uplifted during extension.

Keywords: bedrock, stratigraphy, stratigraphic units, structures, structural analysis, tectonics, tectonic units, Archean, Paleoproterozoic, Proterozoic, Peräpohja Belt, Kuusamo Belt, Central Lapland Area, Finland

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Tutkimus perustuu alan kirjallisuuteen, aerogeofysikaalisiin karttoihin sekä GTK:n kallioperätietokantaan. Peräpohjan ja Kuusamon vyöhykkeiden tektoninen kehitysmalli esitetään ensiksi perustuen alueista tehtyihin rakennetulkintoihin. Keski-Lapin alue, joka on laajin ja tektonisen mallinnuksen kannalta tärkein alue, on jaettu viiteen rakenteelliseen osa-alueeseen. Kunkin osa-alueen rakenteellinen kehitys on tulkittu itsenäisesti tarkastelemalla työn kannalta tärkeimpiä kohteita. Keski-Lapin deformaatio on korreloitu metamorfiseen kehitykseen ja rakenteellista kehitystä on arvioitu olemassa olevan ikäaineiston perusteella. Lopuksi Peräpohjan, Kuusamon ja Keski-Lapin tulkinnat on koottu Pohjois-Suomen kattavaksi rakenteelliseksi kehitysmalliksi. Malli noudattaa eräitä aikaisemmin esitettyjä kehitysmalleja mutta on näitä yksityiskohtaisempi. Mallin perusajatus on se, että jäykän arkeeisen kuoren päällä oli 'pehmeitä' suprakrustisia kiviä sekä jäykkiä kappaleita, jotka olivat irronneet arkeeisesta mantereesta sen hajotessa. Jäykkien kappaleiden liikkuessa kuoren päällä deformaatio kohdistui 'pehmeisiin' kiviin. Suuri osa deformaatiosta svekofennisen orogenian aikana Pohjois-Suomen alueella johtui näiden jäykkien kappaleiden liikkumisesta.

Mafisia kerrosintruusioita ja felsisiä vulkaniitteja purkautui 2,44 Ga (2,44 miljardia vuotta) sitten vanhaa, arkeeista siirrosvyöhykettä myöten, ja varhaisimmat karjalaiset sedimentit kerrostuivat tämän vyöhykkeen avautuessa muodostuneeseen epäsymmetriseen altaaseen. Allas laajeni mantereensisäiseksi altaaksi, joka kattoi nykyisen Pohjois-Suomen alueen. Kuori ohentui ekstensionaalisessa ympäristössä, ja mantereellisen repeytymisen yhteydessä (2,06–2,05 Ga) siitä erkani erikokoisia arkeeisia kappaleita, joista osa jäi passiiviseen mannerreunukseen. Suurin näistä kappaleista oli Pudasjärven blokki, joka koostui nykyisistä Pudasjärven kompleksista, Peräpohjan vyöhykkeestä ja Keski-Lapin granitoidikompleksista.

Litosfäärilaattojen törmäyksien seurauksena Pohjois-Suomen alueelle kehittyi aikavälillä 1.93–1.91 Ga kaksi ylityöntövyöhykettä. Kittilän ja Uusiviran seurueiden kivet työntyivät lännestä itään, ja osittain samanaikainen ylityöntö pohjoisesta–koillisesta aiheutti Lapin granuliittikompleksin työntymisen paikalleen sekä nappe-rakenteen etelämpänä, Sodankylän alueella. Etelä-Suomen aleella tapahtuneiden kaarikompleksien törmäyksien seurauksena Pudasjärven blokki työntyi ensin koilliseen ja myöhemmin pohjoiseen. Pohjoiseen suuntautuneen liikkeen seurauksena Pudasjärven blokin pohjoisosa paksuuntui tektonisesti, ja vulkaanis-sedimenttiset kerrostumat deformoituivat voimakkaasti; vain pienet alueet jäivät heikosti deformoituneiksi. Tektonisesti paksuuntunut kuori kohosi Pudasjärven blokin reunaosissa paljastaen syvemmällä kuoressa metamorfoituneita kiviä, ja Kumpu-ryhmän sedimentit kerrostuivat näiden kivien päälle 1.88–1.87 Ga sitten.

Ylityöntö 1.86–1.85 Ga sitten muokkasi myös Keski-Lapin länsiosassa olevia Kumpu-ryhmän kiviä. Itä-läntinen puristus (1.85 Ga) aiheutti poimutusta, jota voidaan havaita niin Peräpohjan ja Kuusamon vyöhykkeissä kuin eri paikoissa Keski-Lappia. Itä-läntistä puristusta seurasi luode-kaakkoinen puristus (1.84–1.83 Ga). Myöhäis-svekofenninen mannertörmäys etelässä aiheutti puristusta etelästä, ja aikaisemmin kehittyneet hiertovyöhykkeet aktivoituivat uudelleen (1.82-1.80 Ga). Orogeeninen romahdus aikavälillä 1.80–1.77 Ga aiheutti laaja-alaista kuoren ohenemista, ja sen seurauksena aiemmin tektonisesti paksuuntuneesta Keski-Lapin granitoidikompleksista tuli terminen keskus, joka kohosi ympäristöään ylemmäksi.

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CONTENTS

1 INTRODUCTION

Central Finnish Lapland has been subject to mineral exploration for decades, and several mines are presently in operation. Much effort has been put into studying the stratigraphy, and age determinations have revealed that Archean rocks are partly covered (and intruded) by Paleoproterozoic rocks. However, structural studies have only been conducted in rather small areas, generally around mineral occurrences.

Attempts to provide a kinematic interpretation of a major part of Finnish Lapland have previously been made by Gaál et al. (1989), Ward et al. (1989), and Hölttä et al. (2007). The present report is a desk study, mainly carried out during 2012–2014. It is based on existing literature, aerogeophysical maps, and the GTK bedrock database. Structural interpretations are given for three areas Peräpohja, Kuusamo, and central Lapland. On the
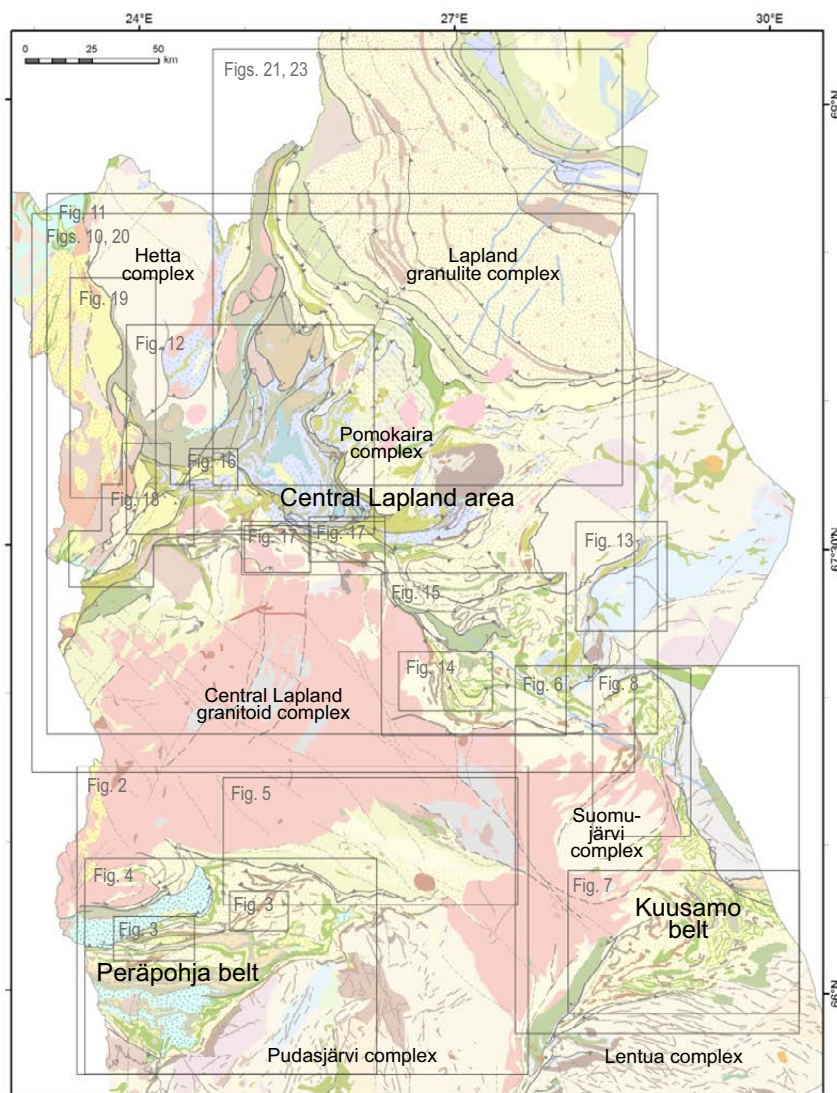

Fig. 1. Bedrock map of northern Finland, showing the main geological units discussed in the text, and the location of the following figures. See Nironen et al. (2016) for an explanation of the rock associations.

basis of these interpretations, a tectonic model is outlined for northern Finland in the framework of collision between the three lithospheric blocks Karelia, Norrbotten and Lapland-Kola, continental collision further south, and finally orogenic collapse (Nironen 2017). Many of the interpretations presented here ended up in the Geological Map of Finland – Bedrock 1:1 000 000 (Nironen et al. 2016). However, rather than presenting definite interpretations, the study aims to provide a template for regional synthesis and show some areas where existing problems could be resolved.

The study area almost entirely covers northern Finland (Fig. 1). The stratigraphic division follows the present GTK stratigraphy (Finstrati),

and the stratigraphic names are considered informal accordingly (formation and group instead of Formation and Group). The compressional/extensional directions given in the text refer to present directions. The study is largely based on the GTK bedrock database. Although the structural observations have their limits (no information on the type of lineation or relative ages of foliations), they are accurate enough for regional studies. It has to be noted that the measurements of foliation strikes and lineation plunges lack declination correction, which is in the order of +10° in central Lapland. The background maps in the figures are generally from Nironen et al. (2016).

2 PERÄPOHJA BELT

2.1 Background

The Peräpohja belt is located between the Archean Pudasjärvi complex and Central Lapland granitoid complex (Fig. 2). The belt is here divided into three parts: the southwestern Tervola area of lower metamorphic grade, the eastern Rovaniemi area of higher metamorphic grade, and the allochthonous Martimo belt. The Tervola area, or parts of it, have also been named as the Kemi area (Härme 1949), Länsi-Pohja (Mikkola 1949), and Peräpohja Schist Belt (Perttunen 1991). Nironen et al. (2002) suggested the Peräpohja belt as a name for the combined Tervola–Rovaniemi area. The Tervola area has been studied more extensively than the Rovaniemi area. The focus in this study is in the Tervola and Rovaniemi areas, and the Martimo belt (previously called the Väystäjä area) is included in structural and kinematic interpretations on the basis of the recent structural study by Lahtinen et al. (2015a).

A NE trending belt of 2.44 Ga layered mafic intrusions, named as the Tornio–Näränkävaara belt (Iljina & Hanski 2005), extends discontinuously along the northern boundaries of the Archean Pudasjärvi and Lentua complexes, from the Peräpohja belt to the Kuusamo belt (Fig. 1). Northwest of the town Tornio (Fig. 2), there is a 25-km-long block of Archean gneiss, elongate in NW–SE direction and extending to Sweden. At the margin of the Archean block there is a gabbroic layered intrusion with a 2.5–2.3 Ga age (Perttunen 1991, Koistinen et al. 2001). The block indicates that the mafic intrusions once extended further south-

west: the Archean crust was fragmented, and the block represents such a (rotated) crustal fragment.

Perttunen (1985, 1991) presented a stratigraphic interpretation of the supracrustal rocks in the Tervola area. At the bottom, there are rare conglomerates of the Sompujärvi formation, in places as basal conglomerates directly upon the Archean crust, but generally unconformably overlying the 2.44 Ga layered mafic intrusions. The estimated age of this 'Sub-Sariola unconformity' is 2.35 Ga (Laajoki 2005). The mafic volcanic rocks of the Runkaus formation overlie the conglomerates, followed by voluminous quartz arenites of the Kivalo formation and mafic volcanic rocks of the Jouttiaapa formation; in the aerogeophysical maps, the Jouttiaapa volcanic rocks show up as a positive magnetic and negative electromagnetic anomaly. On top, there are quartz arenites (Kvartsimaa formation), mafic volcanic rocks (Tikanmaa formation), and dolomites (Rantamaa formation). The stratigraphy has been modified in Finstrati: the former Kivalo formation is now the Palokivalo formation, and the formations in the Tervola area together belong to the Kivalo and Paakkola groups. Perttunen and Hanski (2003) added the Kaisavaara and Santalampi formations which they tentatively correlated with the Palokivalo and Jouttiaapa formations, respectively. Kyläkoski et al. (2012) added the Petäjäskoski formation between the Palokivalo and Jouttiaapa formations, with the depositional age bracketed between 2.22 Ga and 2.14 Ga. The minimum age of
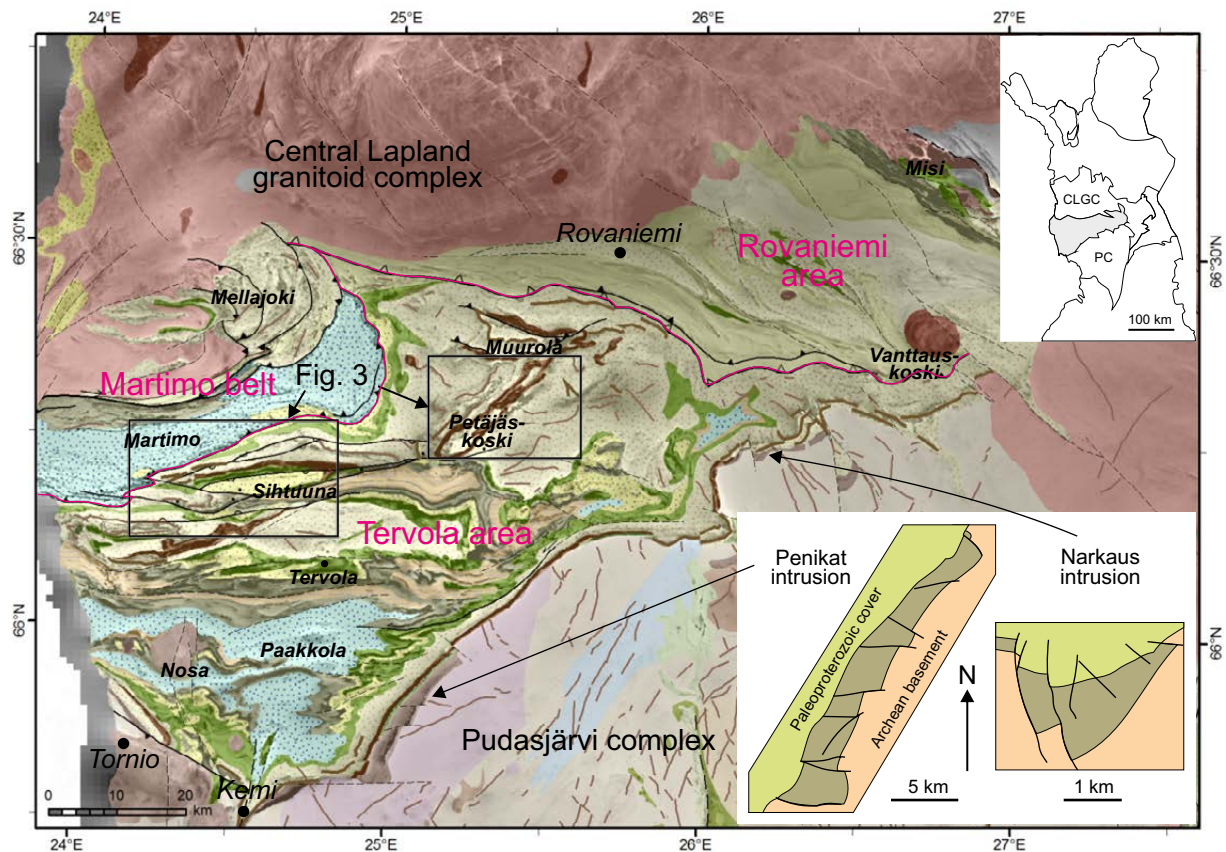
Fig. 2. Aeromagnetic and bedrock map of the Peräpohja belt, divided into the Tervola and Rovaniemi areas and the Martimo belt. Upper inset: location of the Peräpohja belt between the Pudasjärvi complex (PC) and Central Lapland granitoid complex (CLGC). Lower inset: Penikat and Narkaus layered intrusions (brown), displaced into blocks along faults and unconformably covered by Paleoproterozoic supracrustal rocks (simplified from Alapieti and Lahtinen 1986, and Huhtelin et al. 1989 a, b).

the stratigraphically underlying Runkaus formation is given by the 2.25 Ga Pb−Pb age of secondary titanite (Huhma et al. 1990), whereas the age of the plateau basalts of the Jouttiaapa formation is about 2.1 Ga (whole-rock Sm−Nd age, Hölttä et al. 2003). The present understanding of stratigraphy in the Kivalo group is shown by Kyläkoski et al. (2012). The sedimentary rocks of the Paakkola group (Karunki formation) are considered to overlie the rocks of the Kivalo group, and they may represent a different depositional environment ('Kaleva system'; see Lahtinen et al. 2015a). The rocks in the Martimo belt form the Martimo suite in Finstrati.

2.1.1 Tervola area

Mikkola (1949) considered the Tervola area an asymmetric synclinorium, consisting of several synclines with fold axes plunging 30−50° NE. According to Härme (1949), in the eastern part of the Tervola area, lineations plunge fairly regularly W or WNW, irrespective of the strike of foliation. He

also described NW−SE oriented, vertical 'fault-like cleavage' and associated minor folding. In line with earlier interpretations, Perttunen (1991) considered the Tervola area a large synclinorium with a roughly E−W hinge line. The synclinorium consists of alternating synclines and anticlines, especially close to the Archean Pudasjärvi complex; around the Nosa intrusion (Fig. 2), older rock sequences are exposed in the core of an anticline. Close to the Pudasjärvi complex bedding dips are 40−60° NW, whereas further north, south of Sihtuuna (Fig. 2), bedding planes are rather flat (Perttunen 1991). In the axial planes of the syncline−anticline structure, a steeply dipping schistosity is found in fine-grained rocks but is hardly visible in coarser-grained rocks. Perttunen (1991) also described younger symmetric, fairly open folding with N−NNE axial traces that deforms the syncline−anticline structure. These deformation structures can be seen in aeromagnetic maps, e.g. around the Nosa intrusion.

The metamorphic grade in the southern part of the Tervola area is generally greenschist facies but

increases at the western margin where randomly oriented (post-tectonic) cordierite is visible in biotite paraschist and tuffites contain hornblende (Perttunen 1991; see also Hölttä & Heilimo 2017). According to Perttunen and Hanski (2003), further north, biotite paragneisses contain cordierite and andalusite porphyroblasts and thus express lower amphibolite metamorphic grade; these rocks now represent the Martimo suite. According to Lahtinen et al. (2015a), the metamorphic grade in the Martimo belt increases eastwards, from upper greenschist to lower amphibolite facies.

2.1.2 Rovaniemi area

The E−W structural grain of the low grade metamorphic rocks is crosscut by a sequence of cordierite and antophyllite rocks trending WNW (Perttunen & Hanski 2003). A thrust zone has been outlined to differentiate the higher grade rocks of the Rovaniemi area from lower grade rocks of the Tervola area (Korsman et al. 1997, Koistinen et al. 2001, Nironen et al. 2016). In Finstrati, the supracrustal rocks have been divided into the Ounasvaara, Oikarisenvaara, Niemivaara and Olkkajärvi formations of the Kivalo group, all quartzite-dominated and correlative to the Palokivalo formation. Perttunen and Vaasjoki (2001) and Hanski et al. (2005) dated zircons in arkositic rocks of the Korkiavaara formation at 1.98 Ga. Hanski et al. (2005) concluded that the arkositic rocks date felsic magmatism, although the genesis of the rocks remained open. Kyläkoski et al. (2012) interpreted the arkositic rocks and associated amphibolites as tuffs. In Finstrati the supracrustal rocks surrounding the Ounasvaara, Oikarisenvaara, Niemivaara and Olkkajärvi formations form the Oikarila suite, and the Korkiavaara formation was included in the Oikarila suite as the Korkiavaara arkosite.

According to Lappalainen (1994), the penetrative foliation in the western part of the Rovaniemi area is a composite S0-S1 structure in the axial plane of isoclinal F1 folding. The regional synform−antiform structure is F2 folding with fold axes plunging 0−40° NW or SW; the vergence of F2 folding is N−NE. In horizontal section, D2 structures deform D1 structures with a sinistral sense. The E−W trending ductile shear zones are D3 deformation structures. Lappalainen (1994) interpreted that horizontal compression during D1 produced asymmetric folding with almost horizontal axial planes. During

D2, compression was from SW−SSW. Pegmatite dikes generally crosscut D2 structures, but some of the dikes are syn-D2. Migmatites and granites of the Central Lapland granitoid complex crosscut D2 structures but generally developed before D3. Metamorphic isograds trend E−W, crosscut D2 structures and show that the grade of metamorphism increases towards the Central Lapland granitoid complex. Two metamorphic events can be discerned in the area: an older event during D2, with growth of synkinematic garnet and staurolite (3.8−5.5 kbar, 550 °C); and a younger, lower pressure metamorphism, associated with thermal metamorphism of the Central Lapland granitoid complex (3.8 kbar, 650 °C).

The M.Sc. thesis by Salonsaari (1990) from Vanttauskoski (Fig. 2) is the most comprehensive structural study from the Rovaniemi area. According to him, the main foliation is composite S0−S1 foliation. Isoclinal and generally intrafolial F1 folding developed during NNW−SSE horizontal compression. Open to tight folding, with axes plunging 30−60° WNW, produced synformal and antiformal D2 structures, and possibly also overthrusting. Penetrative S2 foliation strikes WNW, indicating maximum compression in NNE−SSW direction. Axial planes of fairly open F3 folding strike WNW and fold axes plunge moderately (30−40°) WNW; S3 crenulation cleavage is found in the axial plane. F4 is open folding with a wavelength of several kilometers, and fold axes plunge moderately north. N-striking axial planes indicate E−W compression. According to Salonsaari (1990), the growth of garnet, andalusite and kyanite in mica schists occurred during D1, and S2 commonly deforms the porphyroblasts; this interpretation is in contrast to the syn-D2 metamorphism presented by Lappalainen (1994).

The studies of Niiranen et al. (2003) on metamorphism, alteration phenomena, and mineral occurrences around Misi (Fig. 2) indicate that the area comprises a block of lower metamorphic grade (greenschist to lower amphibolites facies) within a larger area of upper amphibolite facies rocks. Three deformation phases can be discerned in the area: during D1, N−S compression produced isoclinal folding; during D2, SW−NE compression caused ductile folding and dextral shearing; and during D3, E−W compression caused ductile or ductile-brittle deformation.

2.2 Structural interpretation

Layered intrusions occur at the southeastern margin of the Peräpohja belt (Fig. 2). Their occurrence only there suggests that the belt initiated as a half-graben during extension of the Archean crust. Several faults displace the Archean bedrock and the Penikat layered intrusion but not the overlying conglomerates of the Sompujärvi formation and mafic volcanic rocks of the Runkaus formation (Fig. 2 inset; cf. Alapieti & Lahtinen 1986, Halkoaho 1994, Laajoki 2005), indicating that the conglomerates

were deposited unconformably on the faulted and variably eroded layered intrusion. Laajoki (2005) concluded that faulting occurred before or during erosion and suggested that faulting was related to rift basin inversion. Another explanation, more consistent with the structural pattern, is tilting by sinking of the layered intrusion along normal faults as a result of extension in the (present) NE–SW direction (see Fig. 2 inset). This explanation means extension during 2.44 Ga in two orthogonal
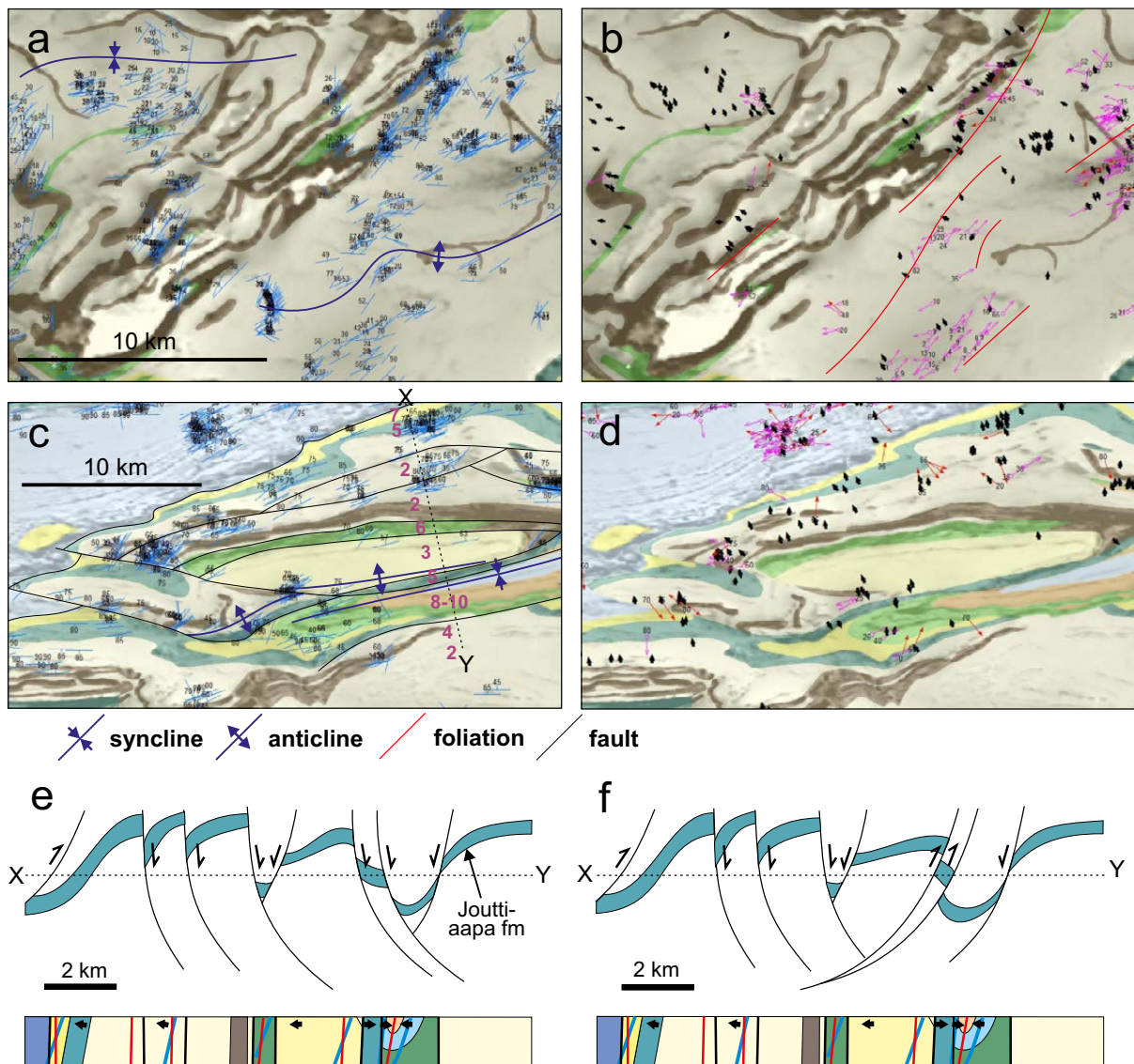
Fig. 3. Structures in selected parts of the Tervola area. a) Bedding observations in the Petäjäskoski–Muurola area, and interpretation. b) Observations of stratigraphic younging (black arrows) and linear structures. Foliation form lines are shown as red lines. c) Bedding observations at Sihtuuna, and interpretation. Cross-section in Figures 3e and 3f is shown by the line X–Y. Numbers in purple denote stratigraphic units seen in the present erosional level (2 = Palokivalo fm, 5 = Jouttiaapa fm, 10 = Rantamaa fm), based on Kyläkoski et al. 2012). d) Observations of stratigraphic younging and linear structures. e) and f) Two interpreted cross-sections of the Sihtuuna area. The lower section shows the dip relationships: blue line = bedding, red line = foliation, black line = fault. The present erosional level is shown by a broken line.

directions, first NW–SE (half-graben) and subsequently NE–SW.

In the Narkaus layered intrusion, faults extend to mafic volcanic rocks and probably have a normal sense of displacement (Fig. 2 inset). This interpretation implies normal faulting after the early faulting at Penikat. Further evidence for several rifting events in the Peräpohja basin is obtained by extrusion of the Jouttiaapa basalts from the mantle (Huhma et al. 1990). Some of the normal faults may have been reactivated and new thrust faults developed during basin inversion.

Bedding planes in the Petäjäskoski–Muurola area dip moderately towards NW, and stratigraphic younging is generally towards NW as well (Figs. 3a and 3b). One syncline and one anticline may be outlined, both with an apparent original E–W hinge direction (Fig. 3a). Further southeast, fold axes plunge shallowly SW or NE and foliation planes strike NE and dip steeply NW, suggesting folding around a subhorizontal, NE trending axis that deforms the anticline (Fig. 3b). The overprinting folding as well as the dolerite dike swarm form the NE–SW structural grain in the Petäjäskoski–Muurola area.

The NE–SW structural grain of the Petäjäskoski-Muurola area is abruptly crosscut by the E–W structural grain of the Tervola area (see Fig. 2). The lithologies in this area trend E–W, and stratigraphic younging directions, primary layering, as well as schistosity around Sihtuuna are consistent with an anticline (Figs. 3c and 3d). In bedrock maps (Perttunen 2002, 2003), the folded rocks are crosscut by E–W trending faults. According to Perttunen (1991) and Perttunen and Hanski (2003), these faults are steeply dipping and have a north-side-up sense of movement, but it is unclear whether they were interpreted as normal or reverse faults. The E–W trending faults in the northern part of Sihtuuna are here interpreted as normal faults; faulting explains why the metamorphic grade does not change much along the limb of the anticline. The normal faults are crosscut by faults that display sinistral displacements of 1–4 km in rock sequences (Fig. 3c). These faults may be interpreted as oblique faults (thrusting + sinistral horizontal displacement), but since the fold axes plunge moderately west (Fig. 3d), the horizontal component is probably small, or the displacement may even be dip-slip faulting. Two possibilities are given for these faults. In the first one the faults are interpreted as normal faults (Fig. 3e); in this case faulting at Sihtuuna was extensional (or

transtensional). The other possibility is that the latest faults are transpressional or compressional (Fig. 3f).

According to Lahtinen et al. (2015a), the oldest structures in the Martimo belt developed during thrusting towards E (D1) that brought the rock package into the present allochthonous position. The boundary between the Martimo belt and Tervola area is shown as the northernmost fault in Figures 3e and 3f. Thrusting was followed by N–S compression; this compression (D2) affected both the Martimo belt and the Tervola area (Fig. 4). Structures in the northeastern part of the Tervola area are interpreted as interference structures caused by E–W synclines and anticlines, and younger NW–SE synforms and antiforms. Structures at Paakkola (see Fig. 2) are interpreted as an interference structure of E–W synclines and anticlines, and younger synforms with a NNE trend. This is considered the youngest fold structure, which is also responsible for the NE–SW structural grain in the Petäjäskoski–Muurola area.

The structural interpretation of the Rovaniemi area (Fig. 5) follows the one presented by Salonsaari (1990) and Kortelainen (1994), with the dominance of WNW trending synforms and antiforms. In contrast to the Tervola area, no undisputed synclines or anticlines can be discerned. Based on the GTK bedrock database, the central part of the Rovaniemi area is characterized by shallowly WNW-plunging lineations and fold axes. At Vanttausjärvi, there is apparently a fold interference structure: linear structures plunge moderately WNW and the foliations are moderately to shallowly dipping as well. The structure at Vanttausjärvi is probably more complex than the interpreted one. The number of observations diminishes towards east; there are so few around Palojärvi that the area was left out of the structural interpretation.

Since the Korkiavaara arkosite (or felsic tuff) in the Rovaniemi area is younger than the adjacent quartz arenites of the Palokivalo formation, and probably also younger than the mica gneiss of the Oikarila suite, a thrust zone with displacement towards SW has been delineated on both sides of the Korkiavaara rocks (Fig. 5). A thrust zone has not been identified in the field but Salonsaari (1990) described a 20-m-wide zone of antophyllite-cordierite rock at Vanttauskoski. Another zone of antophyllite-cordierite rock was found at Herajärvi, at the margin between a mica gneiss and an arkosite at Köyry (Fig. 5), which may also mark a thrust zone.
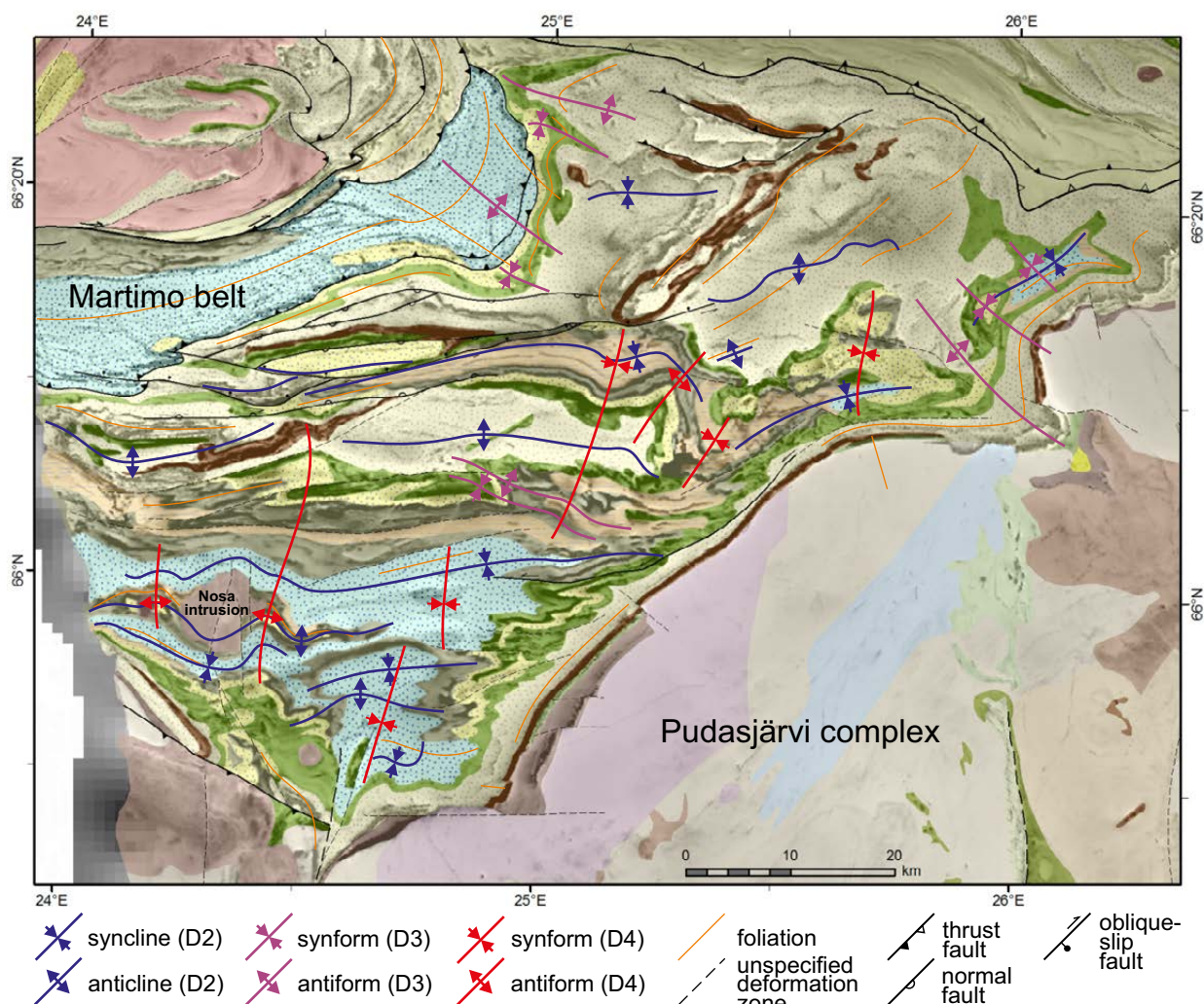
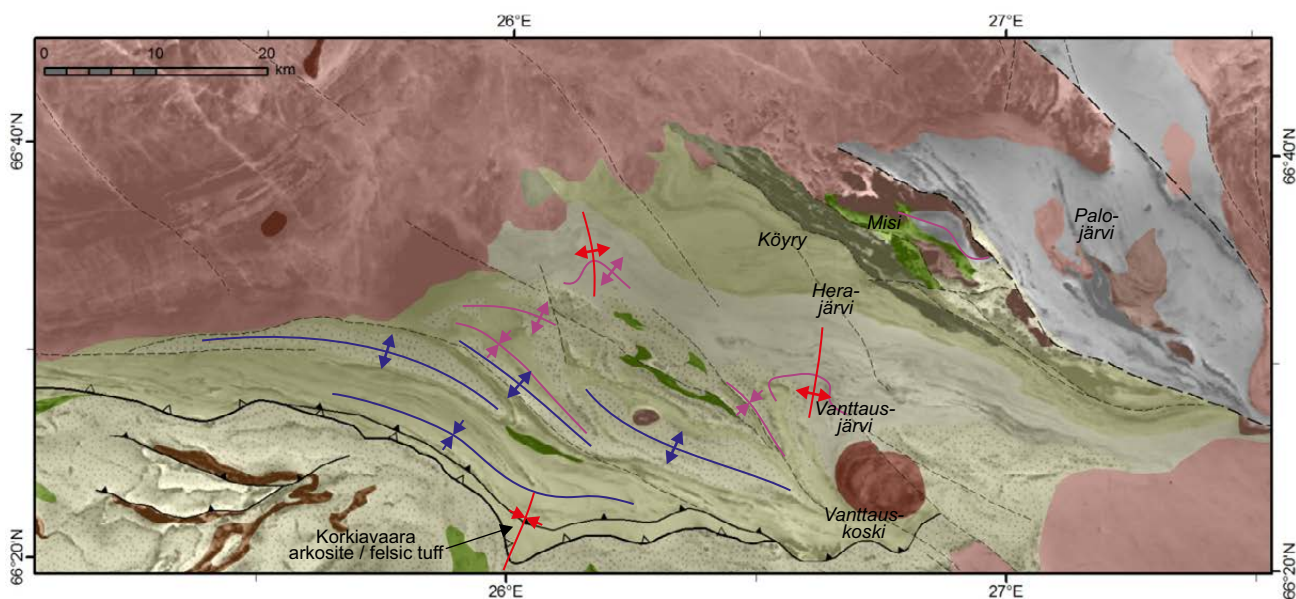Fig. 4. Structural interpretation of the Tervola area.

Fig. 5. Structural interpretation of the Rovaniemi area. Symbols are as in Figure 4.

2.3 Kinematic interpretation

The interpretation of convergent deformation in the Peräpohja belt should explain the three structural grains: E–W in the Tervola area, NE–SW in the Petäjäskoski–Muurola area, and WNW–ESE in the Rovaniemi area. Moreover, interpretation of the Martimo belt (Lahtinen et al. 2015a) should be considered. East-vergent thrusting, visible in the Martimo belt, is considered the oldest deformation event D1. N–S compression caused the development of the E–W trending synclines and anticlines. The event is here interpreted as D2 deformation, which produced steeply dipping S2 axial plane schistosity and flat to moderately plunging F2 fold axes around the synclines and anticlines. At the margin of the Archean block, deformation was transpressional, with NW–SE as the main horizontal compression direction, and production of an asymmetric, en echelon –type syncline and anticline system and faults with oblique slip (dextral horizontal slip). The Nosa intrusion crosscuts the anticline structure in adjacent supracrustal rocks (Fig. 4). Emplacement of the Nosa and Liakka intrusions with ages at 1879 ± 3 Ma and 1885 ± 10 Ma, respectively (Perttunen & Vaasjoki 2001), constrains the minimum age for D2 deformation at 1.88 Ga.

D2 was followed by two compressional events D3 and D4. The direction of the main horizontal compression shifted to NNE–SSW, resulting in D3 refolding of the synclines and anticlines in the Tervola area (Fig. 4). D3 may have been a progressive continuation of D2 deformation. D3 in the Tervola area corresponds to D3 in the Martimo belt (see Lahtinen et al. 2015a).

The structural interpretation of the Rovaniemi area is a modification of the interpretations by Salonsaari (1990), Lappalainen (1994) and Niiranen et al. (2003), with the addition of an earlier deformation event D1 (seen only in the Martimo belt). D2 structures, seen at outcrops as isoclinal F2 folding and composite S0–S2 axial plane foliation, developed as the result of NNE–SSW horizontal compression, and resulted in a syncline–anticline structure with arkositic–quartzitic rocks in anticlines. NE–SW compression during D3 caused deformation of the syncline–anticline structure into an en echelon structure, penetrative S3 foliation as well as dextral shear zones (Fig. 5). The rocks of the Rovaniemi area, with higher metamorphic grade, were partly thrust upon the lower grade rocks of the Tervola area during D3.

Fairly open folding with subvertical N–S axial plane is found around the Nosa intrusion, and N–S trending faults deform the intrusion. These are interpreted as products of horizontal E–W compression during D4 deformation, giving 1.88 Ga as the maximum age for D4. Lahtinen et al. (2015a) described mesoscopic F5 folding in the Martimo belt with N–NNE strikes and steeply dipping axial planes. The style and orientation of this folding correspond with F4 folding in the Tervola area.

The NE-striking foliation in the Petäjäskoski–Muurola area (Figs. 3b, 4) is here considered S4. The interpreted trends of F4 fold axial planes indicate E–W to SE–NW compression. Curiously, NE-striking foliation is common in the quartz arenites of the Petäjäskoski–Muurola area, whereas only a few foliation observations in the Tervola area further southwest can be interpreted as axial plane foliation to F4 folding.

Faulting in the Sihtuuna area probably occurred after the folding events, because the faults do not appear to be deformed. N–S extension (D5) followed the compressional events, producing E–W trending normal faulting (Fig. 4). If the scenario presented in Figure 3e is considered, normal faulting was the last major deformation event. According to the scenario in Figure 3f, N–S extension was followed by NNW–SSE transpression (or N–S compression), with the development of oblique (or reverse) faulting that deformed the normal faults (D6). Since such a late transpressional/compressional event is improbable in the tectonic history of an orogeny, the former possibility is preferred.

2.4 Tectonic model

1) The development of the Peräpohja belt initiated as rifting of the Archean continental crust into a half-graben during NW–SE extension and emplacement of layered mafic intrusions at 2.44 Ga. The intrusions were faulted (normal faulting) soon after emplacement during orthogonal, NE–SW extension. The lowermost stratigraphic sequences (Sompujärvi conglomerates, Runkaus volcanic rocks) were deposited either upon the Archean crust or upon the faulted and partly

eroded layered intrusions, and faulting continued in places after the deposition of these sequences.

2) Collison between the Norrbotten and Karelia lithospheric blocks caused thrusting of the allochthonous units of the Martimo belt (and the Kittilä allochthon further north) from the west to their present position (D1). The inferred timing of thrusting varies from ~1.92 Ga (Hanski & Huhma 2005, Lahtinen et al. 2015b, Nironen 2017) to ≤ 1.91 Ga (Lahtinen et al. 2015a).

3) Basin inversion started with northward movement of the Archean Pudasjärvi block (including the Pudasjärvi complex, the Peräpohja belt and the Central Lapland granitoid complex) as a result of accretion further south. Reflection seismic data (Patison et al. 2006) suggest that bulk shortening in the Peräpohja belt was moderate.

The convergent stage initiated before emplacement of the Nosa and Liakka intrusions (1.88 Ga). Continued convergence resulted in progressive D2–D3 deformation with rotation of the bulk shortening direction from N–S to NNE–SSW. The northern part of the Peräpohja belt (Rovaniemi area) was thrust southwards. Peak metamorphic conditions were attained during D2–D3.

4) E–W to NW–SE compression caused upright F4 folding, with a maximum age of 1.88 Ga.

5) N–S extension caused normal faulting in the northern part of the Tervola area and reactivation of some earlier thrust faults as normal faults. The extension is tentatively associated with the younger metamorphic event in the Central Lapland granitoid complex (Lappalainen 1994).

3 KUUSAMO BELT

3.1 Background

The Kuusamo belt is situated in eastern Finland and has continuations across the national boundary to Russia (Fig. 6). The belt is located between the Lentua complex in the south and granites of the Central Lapland granitoid complex in the northwest. The Kuusamo belt has been divided here in the triangular Kuusamo area in the south and the Salla area in the north. The Kuusamo area has been studied in much more detail than the Salla area, but comprehensive bedrock map coverage at the scale 1:100 000 is lacking from both areas. The eastern part of the Kuusamo area was mapped by Silvennoinen (1972, 1973, 1982, 1991) who also published one bedrock map at the scale 1:100 000 from the central Kuusamo area (Silvennoinen 1989). Only occasional bedrock observations exist from the western part of the Kuusamo area, except for small areas studied in M.Sc. projects (Juhava 1969, Kalliomäki 1985). The southern and northern parts of the Salla area have been mapped by Manninen (1991) and Lauerma (1995), respectively.

The stratigraphic interpretation of Silvennoinen (1972) constitutes a basin sequence with the oldest rock, basal conglomerate, occurring at the southern margin against the Archean basement, overlain by mafic volcanic rocks (Greenstone Formation I). Boulders in the basal conglomerate yielded a 2405 ±

6 Ma age (Silvennoinen 1991). Finstrati is based on Silvennoinen (1972), but has been updated according to the stratigraphic division of Lehtonen et al. (1998; see section 4.1). Both the basal conglomerate and Greenstone Formation I are now considered parts of the Kuusamo group. Both Kuusamo group and Salla group rocks lie directly upon the Archean basement but in places Salla group rocks underlie rocks of the Kuusamo group. In the western part of the Kuusamo belt the Kuusamo rocks are bordered by mafic volcanic rocks, named as Posio greenstone by Räsänen and Huhma (2001); in Finstrati they are included in the Kuusamo group. On top of the mafic volcanic rocks of the Kuusamo group there are Sodankylä group rocks in the following formations: Hukkavaara (quartzite), Petäjävaara (mafic volcanic rocks, Greenstone Formation II), Vaimojärvi, Ruukinvaara (mafic volcanic rocks, Greenstone Formation III), and on top Rukatunturi (quartzite). In addition, there are mafic tuffs, carbonate rocks and paraschists of the Savukoski group, which stratigraphically overlie rocks of the Sodankylä group. According to Silvennoinen (1972), the total thickness of the sequence is more than 2500 meters.

The volcanic rocks in the Salla area occur as a NNW trending belt. In Finstrati, the felsic and intermediate volcanic rocks of the Salla group
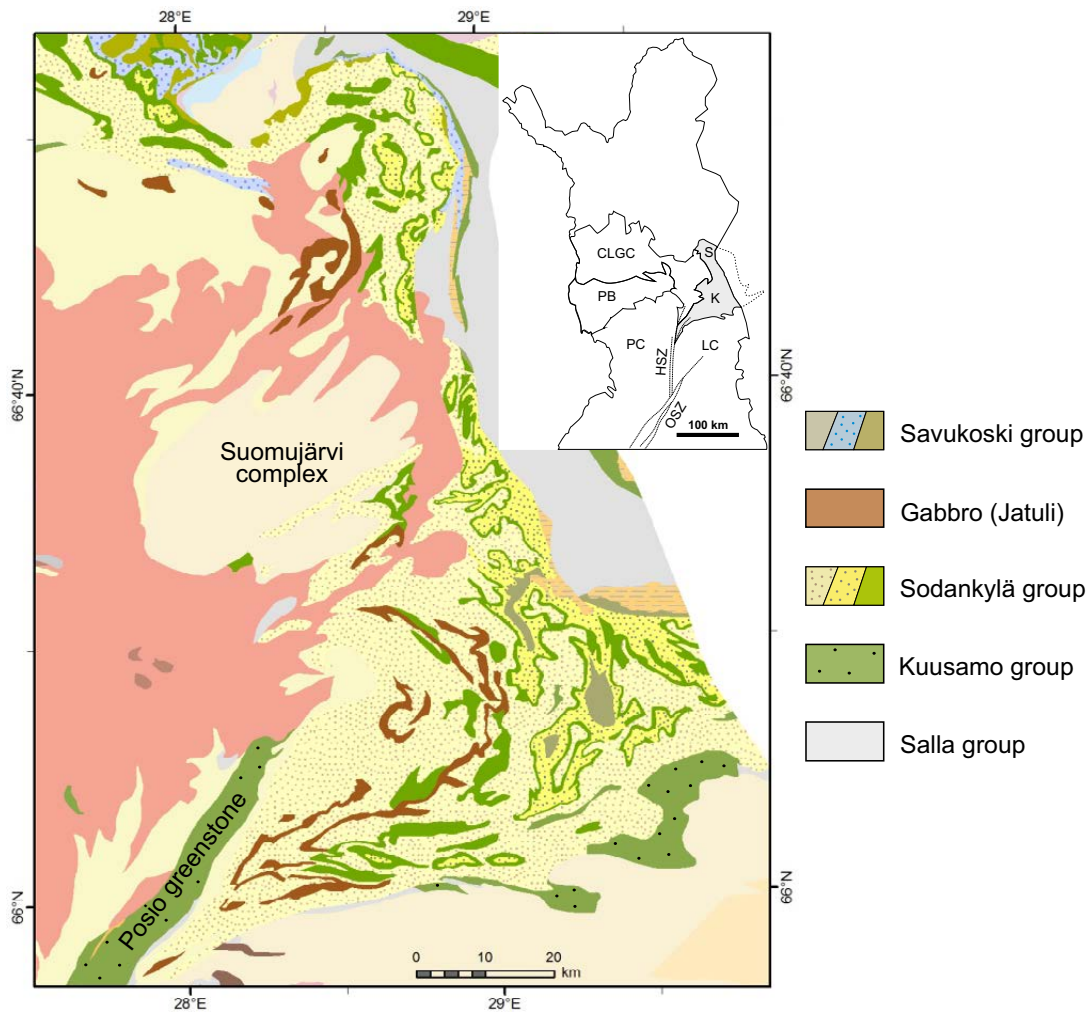
Fig. 6. Bedrock and stratigraphy of the Kuusamo belt. Inset: location of the Kuusamo belt and the Kuusamo (K) and Salla (S) areas within it. CLGC = Central Lapland granitoid complex, PB = Peräpohja belt, PC = Pudasjärvi complex, LC = Lentua complex, HSZ = Hirvaskoski shear zone, OSZ = Oulujärvi shear zone.

(Petservaara formation) and mafic volcanic rocks of the Kuusamo group (Esikkovaara formation) form a package that is separated by faults from volcanic–sedimentary rocks of the Sodankylä and Savukoski groups. Manninen (1991) interpreted that the rocks in the Salla area were deposited 2.5–2.0 Ga ago in a NW trending intracratonic rift zone.

The Salla group rocks at Salla have not been dated. Further north, in central Lapland, felsic volcanic rocks, dated at 2.44 Ga, are considered to stratigraphically underlie mafic volcanic rocks (Räsänen and Huhma 2011, Manninen et al. 2001). These rocks have been correlated with the Salla area as Salla group and overlying Onkamo group rocks (Lehtonen et al. 1998, Hanski & Huhma 2005); however, in Finstrati, the Onkamo group has been merged into the Kuusamo group. The age of the rocks in the Kuusamo area, consisting of rocks of the Kuusamo, Sodankylä and Savukoski groups, is in the range of 2.4–2.1 Ga (Silvennoinen 1991, Hanski et al. 2001). In the western part, a small area is occupied by delta-type deposits with a maximum depositional age of 1.9 Ga (Himmerkinlahti member; Laajoki 2000, Laajoki & Huhma 2006). Laajoki (2005) described another conglomeratic unit, the Kolmiloukkonen formation, in the Kuusamo belt (Fig. 7a). The formation differs from the Himmerkinlahti member by being highly metamorphosed.

The bedrock in the Kuusamo area has been metamorphosed to greenschist facies in the southeastern part, but the metamorphic grade rises towards northwest (Hölttä & Heilimo 2017): in the Riisitunturi area (Fig. 7a), primary bedding is associated with clear schistosity, in contrast to the Rukatunturi area where foliation is weak (cf. Silvennoinen 1972, Kalliomäki 1985).
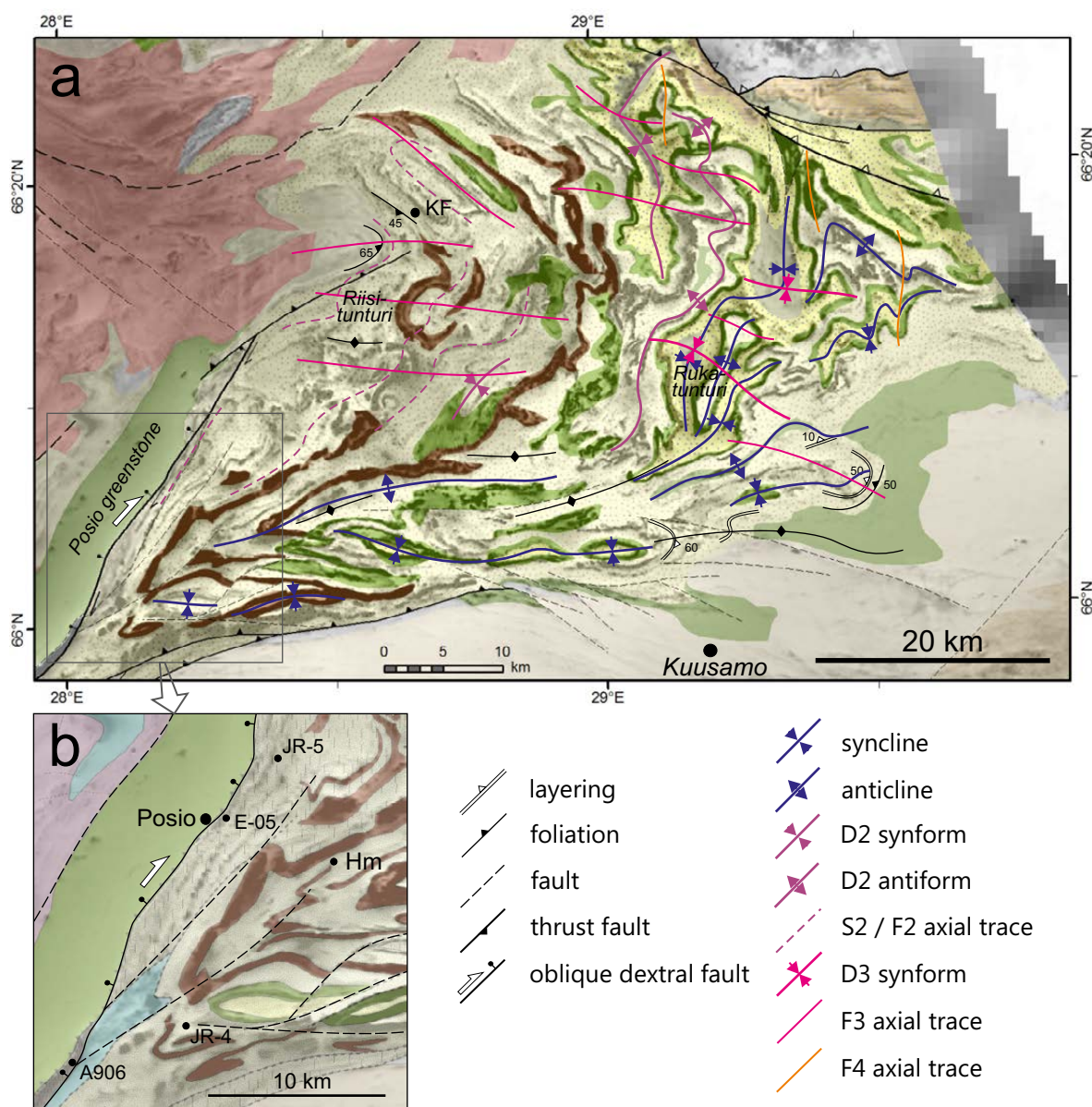
Fig. 7. a) Bedrock and structural interpretation of the Kuusamo area. KF = Kolmiloukkonen formation (Laajoki 2005). b) Posio area. Hm = Himmerkinlahti member (Laajoki 2000). E-05 = study site of Evins (2005), A906 = site of isotope dating, JR-4 & JR-5 = excursion sites.

3.1.1 Structural studies

Silvennoinen (1972) distinguished synclines and anticlines in the Rukatunturi area (Fig. 7a), with two hinge line directions ENE to NE and NW. The age difference between these directions is unclear; Silvennoinen (1972) interpreted that the structure resulted from a single deformation phase, in which 'a force acting from the west pushed the sedimentary-volcanic cover in partly decollement folds and partly fault-controlled folds against two blocks, one to the northeast, the other to the southeast of the area'. The blocks were parts of the Archean basement, and the folding was induced by faulting of the basement.

In the Riisitunturi area (Fig. 7a), lineations and fold axes generally plunge moderately to steeply E (Juhava 1969). Kalliomäki (1985) distinguished three folding phases at Riisitunturi, the oldest occurring as isoclinal folds. The prominent foliation is F2 axial plane schistosity with a NE strike. Fairly open F3 folding, with an E–W axial plane, governs the bedrock structure at Riisitunturi. Kalliomäki (1985) interpreted the prominent lineations as S1/S2 interference lineations.

According to Manninen (1991), the volcanic rocks of the Salla group in the eastern part of the Kuusamo belt (see Fig. 6) are bounded by faults; rocks are strongly deformed in the marginal zones.

Elsewhere in the southern part, the rocks are only moderately foliated and openly folded. The dominant N–S trending fold axes are subhorizontal or plunge gently to the north. In the northern part of the Salla area, the bedrock is poorly exposed. According to Lauerma (1995), the structures are generally flat-lying.

Kärki et al. (1993) associated the NNE trending shear zone, running along the eastern margin of the Posio greenstone (Fig. 7), with the N–S trending, subvertical Hirvaskoski shear zone (see Fig. 6). The Hirvaskoski ductile shear zone separates the two Archean complexes Pudasjärvi and Lentua, with an estimated 70–90 km total dextral displacement

(Kärki et al. 1993). In the nomenclature of Kärki et al. (1993), the Hirvaskoski shear zone developed during D3, and the crosscutting Oulunjärvi shear zone during D4. Dating of undeformed granitoids yielded 1.82 Ga as the minimum age of D4 deformation (Vaasjoki et al. 2001).

Karinen (2010) studied the layered mafic intrusions south of the Kuusamo belt. He concluded that the intrusions were emplaced in an extensional regime during 2.50–2.45 Ga, and that N–S compression caused tilting and duplication of the intrusive blocks, and folding of supracrustal sequences above the intrusions.

3.2 Structural interpretation

3.2.1 Kuusamo and Salla areas

Taken that the Kuusamo belt is a supracrustal sequence with a thickness of ca. 2.5 km and covering an area of ca. 40 km x 60 km, the structural pattern is the result of wrinkling of the sequence upon rigid Archean crust. As Silvennoinen (1972) pointed out, faulting of the underlying crust has had an effect on the overlying sequence, possibly already during deposition.

The structural interpretation is restricted to the Kuusamo belt and is not correlative as such to the Peräpohja belt. In the GTK bedrock database, structural data exist from the western part of the Kuusamo area, but observations around Rukatunturi and further northeast are few. Foliations in the western part generally have E–W to ENE strikes and, steep to vertical dips (Fig. 7a). The structural interpretation of the Kuusamo area is mainly based on low-altitude aerogeophysical (magnetic, electromagnetic) data which indicate a clear fold pattern, especially shown by the strongly magnetic mafic volcanic rocks of the Ruukinvaara formation.The syncline–anticline interpretation of Silvennoinen (1972) is extended in the present structural interpretation. A syncline–anticline pattern with hinge lines in E–W direction follows the southern contact against the Archean basement; these are considered D1 structures. To the north there is a set of NE trending syncline–anticline pairs, including the Rukatunturi syncline with axial plane dipping 50–80° W (Silvennoinen 1972). Considering that the prominent foliation at Riisitunturi is S2, it is difficult to assess whether the structures west of the Rukatunturi syncline are D1 synclines and anticlines

or D2 synforms and antiforms; the foliations in the GTK bedrock database are too few to resolve this.

The structural pattern in the Kuusamo area is here interpreted as the result of northward movement of the Pudasjärvi complex with respect to the eastern Lentua complex. The supracrustal rocks were deformed into a syncline–anticline system in an overall dextral shear. During progressive dextral shear (D2), new NW–SE oriented synclines and anticlines developed, and the D1 synclines and anticlines were reoriented to E–W direction.

Around Riisitunturi the structural pattern is dominated by F3 folding with E–W axial plane (Fig. 7a). The structural grain changes northwards to NW–SE orientation, and this orientation is interpreted as the result of F3 folding. Further north, there is a dome-and-basin structure in the Sodankylä group rocks against the Salla group rocks, and the domes and basins have been deformed into an asymmetric en echelon pattern (Fig. 8). The en echelon pattern is interpreted as the result of E–W shortening, leading to thrusting of the Salla group rocks upon younger rocks, folding with roughly N–S axial traces, and the development of the en echelon pattern during sinistral shear (D4). This interpretation is different from previous interpretations (Korsman et al. 1997, Koistinen et al. 2001), in which the younger rocks were thrust upon the Salla group rocks from the south. Manninen (1991) described graphite schists and dolomites (Savukoski group rocks in Finstrati) in a N–S topographic depression south of Kelloselkä (Aatsinginhauta, Fig. 8), and interpreted that rocks to the west of the depression have been thrust eastwards. Structural observations of Manninen (1991) and in the GTK bedrock database suggest thrusting
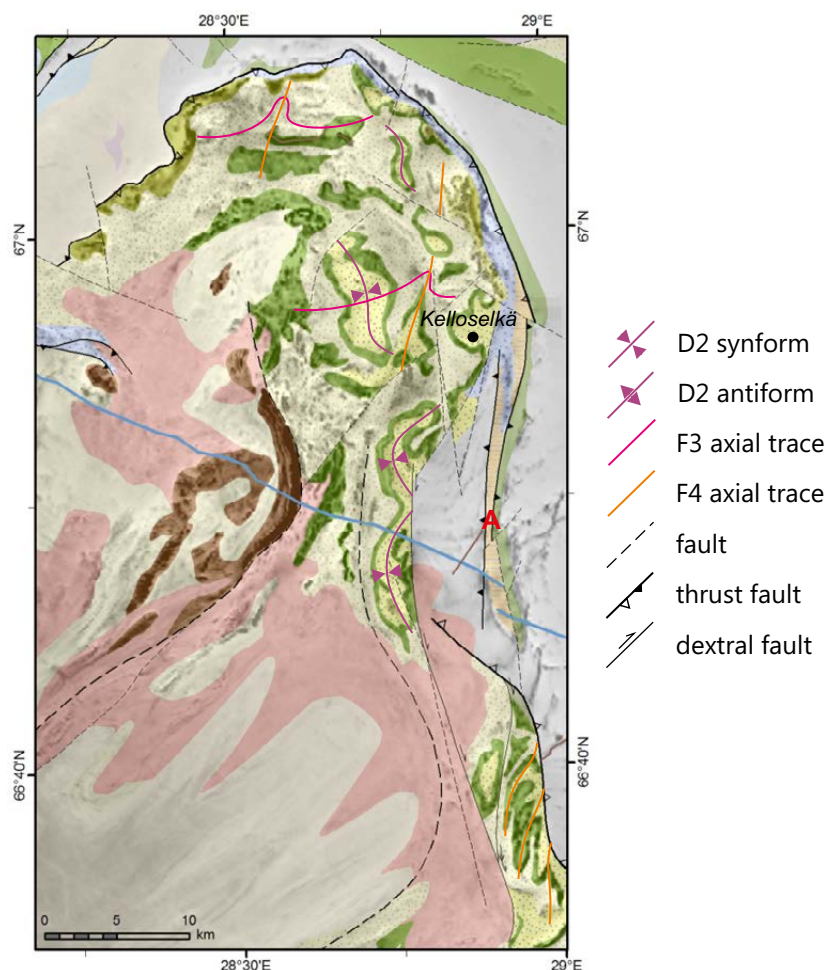
Fig. 8. Bedrock and structural interpretation of the Salla area. A = Aatsinginhauta, light blue line = Mesoproterozoic dike (Salla dike).

from both the east and west towards the depression, i.e. the Savukoski group rocks are squeezed between the Salla group rocks.

The aerogeophysical pattern in the northern Salla area suggest flat-lying structures, as already interpreted by Lauerma (1995). In Finstrati, the rocks in this area have been interpreted as the same Sodankylä group rocks that occupy most of the Kuusamo area. At the margin of the arcuate schist area, there are Savukoski group rocks with a sharp contact to Kuusamo group volcanic rocks that overlie Salla group rocks. The sharp contact is here interpreted as a thrust/transpressional zone with displacement towards the north (Fig. 8). Evidence for thrusting is provided by the foliation in the Salla and Kuusamo group rocks, with dips moderately to steeply towards the younger rocks.

The Archean Suomujärvi complex and Paleo-proterozoic gneisses south of the complex (Fig. 6) contain a NE–SW structural grain. According to Evins et al. (2002), the Archean gneisses were tightly to isoclinally folded during NW–SE com-

pression; this structure is deformed by folding associated with a SW-plunging linear fabric, implying late thrusting towards northeast. The structures in the Suomujärvi complex appear to overprint structures in the Kuusamo belt, and the complex as a whole has truncated the Kuusamo belt (Figs. 7a and 8). This is in line with monazite datings from the Suomujärvi complex (Corfu & Evins 2002), which imply marked deformation and metamorphism at 1.78–1.76 Ga.

3.2.2 Posio

The area around the village Posio is treated separately here because of different opinions about the stratigraphy and structures in the area. Laajoki (1997) correlated the rocks at Posio with Paleoproterozoic rocks further south, in the Paltamo–Puolanka area of the Kainuu belt. He presented a stratigraphic order with the lowermost Posio greenstone (Karkuvaara formation), overlain by turbiditic schists (Ahola formation), quartzites,

and metatempestites (storm deposits; Kirintövaara formation) on top. Airo (1999) presented a geophysical interpretation that supports the stratigraphic interpretation, with the Posio greenstone dipping gently southeast below the schists. Räsänen and Vaasjoki (2001) dated a felsic gneiss immediately southeast of the Posio greenstone (A906, Fig. 7b). They interpreted that the gneiss is a felsic tuff, and that the Archean age (2.80 Ga) disproved the stratigraphy of Laajoki (1997). In contrast, Laajoki and Wanke (2004) considered that the rock is meta-arkose, the age is from detrital zircons, and that the stratigraphy is correct. The question of stratigraphy in the western part of the Kuusamo area is still open.

Kärki et al. (1993) interpreted that at Posio vertical D3 faults with NNE strike (Hirvaskoski shear zone) crosscut the E−W trending D1−D2 structures of the Kuusamo area. Evins (1997) considered that deformation within the Hirvaskoski shear zone involved both dextral horizontal movement and vertical movement with east-side-up displacement. Airo (1999) also interpreted, on the basis of geophysical evidence, that that the eastern Archean block had moved up with respect to the western block. Evins and Laajoki (2001) outlined a fault (Kitka fault) that divides the Kuusamo area into two parts with differing stratigraphy, but geophysical data provide little evidence for such a fault. They outlined another fault (Posio fault) at the eastern margin of the Posio greenstone. Likewise, Räsänen and Vaasjoki (2001) interpreted that the contact between the Posio greenstone and the gneisses to the east is tectonic. Evins (1997, 2005) studied the rocks in and around the Posio fault in detail. He concluded that in a turbiditic schist (Ahola formation), staurolite has overgrown two biotite generations and is truncated by synkinematic garnet (Evins 1997). According to Evins (2005), D1 deformation is visible in the Posio greenstone to the west of the fault as isoclinal folding with subvertical N−S axial plane, and as inclusion trails in garnet porphyroblasts (si = S1). The shear zone developed during D2, with staurolite overgrowing S2 schistosity. On the basis of garnet microstructure, D2 deformation was coaxial NW−SE shortening within the dextral shear zone, in which strain was partitioned into domains of coaxial and non-coaxial deformation.

Geological studies from the Kainuu schist belt 100−150 km south of Posio (Laajoki & Tuisku 1990, Tuisku & Laajoki 1990) are important in order to interpret the structural evolution at Posio. In the Kainuu belt, the allochthonous Puolankajärvi sediments were deposited in a marine environment at the margin of attenuated Archean crust. D1 deformation was recumbent folding, associated with thrusting with tectonic transport towards northeast. The estimated crustal shortening was at least 50 km (Laajoki 2005). During D2−D3, the main principal stress axis was oriented NE−SW, but orientation of the intermediate principal stress axis changed from horizontal to vertical: low-angle structures were first folded into a subvertical orientation and then reoriented during dextral shear in a N−S shear zone (Hirvaskoski shear zone). Growth of garnet already initiated during D1, but staurolite grew after D3. During tectonic thickening of the crust, a thermal antiform developed on the western side of the belt, leading to an asymmetric thermal structure with metamorphic temperatures increasing to the west. The tectono-metamorphic interpretation of the Kainuu schist belt involves the possibility of deformation of Archean rocks as slivers within the Hirvaskoski shear zone.

During a GTK field excursion in 2011, two outcrops were examined at Posio. The southern one (JR-4, Fig. 9a) is rather well-preserved sericite quartzite, with cordierite and scapolite porphyroblasts overgrowing schistosity. The northern outcrop (JR-5) consists of biotite paragneiss with abundant garnet and staurolite porphyroblasts (Fig. 9b). Staurolite exhibits straight inclusion trails whereas in the matrix, differentiation layering that wraps around staurolite is isoclinally folded. These examples show a marked difference in tectono-metamorphic evolution and indicate a fault between the outcrops. Regarding the growth of staurolite, the D2 deformation of Evins (2005) apparently corresponds to the D3 of Laajoki and Tuisku (1990). Isoclinal folding at outcrop JR-5 shows that shear zone activity continued well after the growth of staurolite.

Following the interpretation of Laajoki and Tuisku (1990) and Evins (1997), the interpreted structural evolution starts with movement of the Pudasjärvi block towards ENE, collision with the eastern Archean block (Lentua complex), and subsequent movement towards north along the Hirvaskoski shear zone, with both lateral (dextral) and vertical (east-side-up) components. On the basis of the above interpretations and observations, the orientation of the shear zone at Posio changed to NE−SW, and the vertical component was west-side-up at least between the two
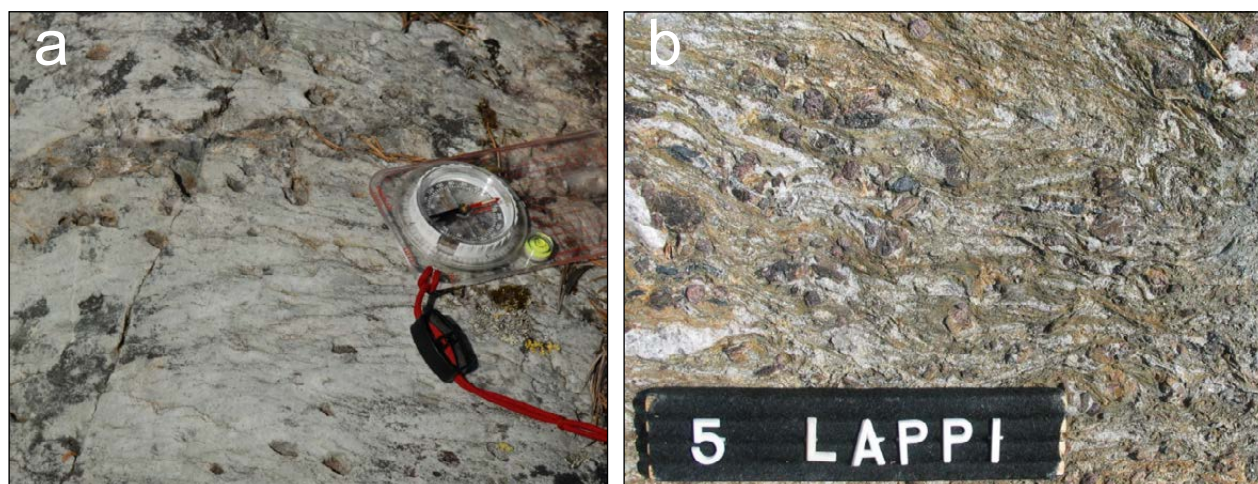
Fig. 9. a) Sericite quartzite with cordierite and scapolite porphyroblasts. Field excursion site JR-4, 7321184/551692 (ETRS-TM35FIN). Length of compass 12 cm. b) Biotite paragneiss with garnet and staurolite porphyroblasts. Field excursion site JR-5, 7335631/556405. Length of code bar 12 cm. See Figure 7b for locations.

examined outcrops. Thus, the 'Posio fault' is a dextral (oblique) shear zone that widens into a horsetail structure around Posio, forming the termination of the Hirvaskoski shear zone.

In the stratigraphic interpretations of Evins and Laajoki (2001) and Laajoki and Wanke (2004), the 'Posio fault' is not a major stratigraphic divider. In contrast, the interpretation presented here corroborates the Posio shear zone as a stratigraphic divider. What about the geophysical interpretation, supporting continuation of the Posio greenstone to the east? Airo (1999) interpreted that a positive gravimetric anomaly was caused by the Posio greenstone. However, the anomaly may also be interpreted so that the greenstone dips gently to the east but is crosscut by vertical faults; the anomaly to the southeast may result from a more regional source such as an Archean granodiorite (Airo, personal communication 2012).

Laajoki (2000) concluded that the <1.9 Ga Himmerkinlahti member signifies a period of significant uplift and erosion before the extrusion of flood basalts (Greenstone Formation III = Ruukinvaara formation). Laajoki and Huhma (2006) tentatively associated the Himmerkinlahti member with post-1.88 Ga molasse-type deposits in Lapland (Kumpu group). Deposition of the delta-type deposits may be the consequence of vertical movements along the northeastern end of the Hirvaskoski shear zone.

3.3 Tectonic model

Based on the existing literature and interpretations presented above, the following model is presented for the Kuusamo belt and partly also for the Kainuu belt. The age of deformation in the Kuusamo belt is unknown. Likewise, the relationship between deformation in the Kuusamo belt and deformation in the Suomujärvi complex is left open.

1) Intracontinental rift zones developed at 2.45–2.44 Ga in the Archean crust along old crustal weak zones. One of these zones was the proto-Hirvaskoski zone and another one had the ENE–WSW direction of the present Archean–Proterozoic boundary. The felsic volcanic rocks of the Salla group were emplaced along the rift zones. A basin developed along the rift zones during continued crustal extension and was gradually filled by volcanic rocks and sediments (Kuusamo, Sodankylä and Savukoski groups).

2) Thrusting from W–SW caused closing of the basin at 1.92–1.91 Ga. The Hirvaskoski shear zone developed between the two Archean blocks Pudasjärvi and Lentua. The supracrustal sequence was squeezed between Archean slivers in the shear zone and was openly folded to form a syncline-anticline pattern upon the Archean basement (D1 deformation) in the Kuusamo area.

3) Accretion in the south at 1.89–1.88 Ga caused northward displacement of 70–90 km of the Pudasjärvi block with respect to the Lentua block. Both lateral (dextral) and vertical movements occurred within the Hirvaskoski shear zone, and the rocks in the Kuusamo area were

progressively folded during dextral transpression into a synform-antiform pattern (D2 deformation). In the Salla area, rocks of the Sodankylä and Savukoski groups were thrust northwards.
4) N−S compression caused deformation of the syncline-anticline (D1) and synform-antiform (D2) patterns, and the development of WNW−ESE synforms and antiforms (D3 deformation).

5) E−W compression caused thrusting of the Salla group rocks from the east, squeezing of the Sodankylä group rocks into a sinistral en echelon system between the Salla group rocks and the Archean Suomujärvi complex, and squeezing of the Savukoski group rocks between the Salla group rocks (D4 deformation).
6) NW−SE compression caused tight to isoclinal folding in the rocks of the Suomujärvi complex.

4 CENTRAL LAPLAND AREA

4.1 Background

The central Lapland area, as defined here (Fig. 1), consists of Proterozoic supracrustal rocks intruded by plutonic rocks, spanning from 2.06 Ga mafic intrusions to 1.77 Ga granites of the Nattanen suite (Hanski & Huhma 2005, Heilimo et al. 2009). It covers a larger area than the Karasjok–Kittilä Greenstone Belt of Gaál et al. (1989), also including supracrustal rocks of the Tana/Tanaelv Belt (Vuotso complex in Finstrati). Lehtonen et al. (1998) presented the stratigraphy of the 'Kittilä greenstone area', covering much the same area as the central Lapland area of this study, but defined the 'Paleoproterozoic volcano−sedimentary succession of the Central Lapland Greenstone Belt', i.e. a stratigraphic domain. They divided the belt lithostratigraphically, from oldest to youngest, into the Salla, Onkamo, Sodankylä, Savukoski, Kittilä, Lainio, and Kumpu groups (for earlier stratigraphic divisions, see Hanski and Huhma 2005). The meta-arkoses and quartzites of the Lainio group were considered to be deposited disconformably on rocks of the Kittilä or Savukoski groups and deformed during the main stage of the (Svecofennian) orogeny, whereas the arkoses and conglomerates of the Kumpu group discordantly cover older, folded rocks and were only deformed during the late stage of the orogeny. Because detrital zircon studies (see Hanski et al. 2001) have shown that both the Lainio and Kumpu group rocks were deposited after 1880 Ma, the Lainio group has been merged into the Kumpu group in Finstrati. Part of the volcanic rocks in the Kittilä group may be parautochthonous (passive margin sequences) and part allochthonous oceanic rocks (Hanski & Huhma 2005), and the stratigraphy is therefore unclear; in Finstrati the Kittilä rocks are considered to form the Kittilä suite (see Luukas et al. 2017).

Recently, Lahtinen et al. (2015b) introduced three supersuites (Vuojärvi, Rovaniemi, Uusivirka) within or fringing the Central Lapland granitoid complex, and these were included in Finstrati after modification (Luukas et al. 2017). The rocks of the Vuojärvi suite are either Neoarchean or early Paleoproterozoic in age, rocks in the Rovaniemi supersuite are 1.99−1.97 Ga in age, and rocks of the Uusivirka suite are younger than 1.92−1.91 Ga.

The tectonic evolution of the rocks in central Lapland has been outlined in a few publications from the late 1980's onwards, based on seismic studies as well as field studies in relatively small areas (Gaál et al. 1989, Ward et al 1989, Evins & Laajoki 2002, Lahtinen et al. 2005). Ward et al. (1989) presented the first tectonic (or geodynamic) interpretation for the Lapland Greenstone Belt. According to them, basin evolution on a cratonic substrate spanned from 2.4 Ga to 1.9 Ga, with the deposition of shallow marine to fluvial sediments in a basin that extended along a set of listric normal faults and transfer faults. Basin inversion during the Svecofennian orogeny resulted in a foreland fold and thrust belt, with coeval thrusting from NE and S−SW. Thrusting initiated a regional clockwise torque, and transfer faults were reactivated as N−NE trending dextral shear zones. Ward et al. (1989) suggested that the Kumpu group rocks may represent late-stage synorogenic sedimentation in small strike-slip basins.

A few structural interpretations have been made of the central Lapland area, or of a smaller area within it. Lehtonen et al. (1998) presented the stratigraphy, petrology and geochemistry of central Lapland, including a structural interpretation that was mainly based on detailed studies in western Finnish Lapland (Koistinen 1986). According

to Lehtonen et al. (1998), D1 deformation in central Lapland was weak and is locally visible as the preferred orientation of micas parallel to primary layering, as well as incipient folding and thrusting; Koistinen (1986) described pre–D2 slip planes sub-parallel to bedding. D1 was followed by 'static' (post–D1) mineral growth during an increasing temperature. Mineral growth progressed towards the D2 'main deformation stage' with generally tight, asymmetric F2 folding with penetrative S2 axial plane schistosity and commonly also L2 mineral lineation; axial planes were originally inclined and possibly even shallowly dipping. Regional metamorphism culminated during D2. Subsequent horizontal E–W compression resulted in open D3 folding with S3 crenulation or segregation cleavage in N-striking vertical axial planes. D3 was followed by exhumation, and the Kumpu group sediments were deposited discordantly on top of the metamorphosed rock sequence. F4 folding with E–W trending axial planes but variable dips also deformed the Kumpu group rocks. S4 is seen as weak muscovite orientation in Kumpu group rocks and as weak crenulation in older rocks. The effects of D4 deformation appears to diminish towards the east. D5 deformation is seen as conjugate folds, kink folds or fracturing with subvertical axial planes generally striking N; the effects of D5 deformation also appears to diminish towards the east.

Evins and Laajoki (2002) conducted a detailed structural study in the area around Sodankylä and discerned three deformational events, of which D1 is the strongest. According to them, a set of partly overlapping F1 folds with subparallel, subhorizontal E–W trending axes and kinematic indicators are consistent with south-vergent folding and thrusting along several sheets. D2 is represented as upright F2 folding with NE-striking, subvertical axial planar crenulation cleavage, and F2 was progressively folded upon itself during continued compression, similar to F1 folding. D3 is expressed as NW trending folds and sinistral faults. Evins and Laajoki (2002) modeled the tectonics in eastern Lapland as the development of a foreland fold and thrust belt, with transport from the north during D1 and development of nappe structures (Kelujärvi and Pyhätunturi nappes), and the Lapland granulite belt as the core of the thrust system (similar to Ward et al. 1989).

Nironen and Mänttäri (2003) studied structures in the Vuotso area and interpreted that the prominent D2 deformation is seen as recumbent F2 folding with shallowly dipping S2 schistosity that deforms primary layering of the metavolcanic rocks and layer-parallel S1 schistosity. At the mapscale, the prominent structure is tight F3 folding with an axial plane striking N–NNE. N–S compression produced a D4 dome-and-basin interference pattern, and thrusting from northeast, associated with development of the Lapland granulite belt, deformed the D3 structures and probably also the D4 structures.

Hölttä et al. (2007) carried out regional structural-metamorphic mapping in central Lapland, in almost the same area as Lehtonen et al. (1998) had done, and ended up with three ductile deformation stages: D1 and D2 are much similar to those described by Lehtonen et al. (1998). According to Hölttä et al. (2007), kinematic indicators in the central and southern parts of the study area indicate northward transport, but close to the southwestern border of the Lapland granulite belt the sense of transport may have been the opposite. All post–D2 deformations are collectively treated as D3 deformation; the vergence of F3 folds varies considerably, and D3 includes tectonic transport from several directions. Hölttä et al. (2007) interpreted that in the Sodankylä area, the vergence of F3 folding was towards the north (cf. Evins & Laajoki 2002).

Patison (2007) focused on the structural control of gold deposits in central Lapland and grouped the first major thrust deformations as D1/D2. Strike-slip shear zones with NW, N and NE strikes developed as a late event of D3 deformation, presumably in older crustal weak zones. According to Patison (2007), D4 involved discontinuous zones of brittle deformation. In a similar study from essentially the same area, Saalmann and Niiranen (2010) studied two gold-bearing shear zones in western Lapland and discerned five deformational episodes (not to be confused with D1–D3 of Hölttä et al. 2007). D1 deformation is associated with early alteration and may be seen as layer-parallel foliation. The metamorphic peak was attained during D2, and during D3, NE–SW compression caused partitioning of deformation into N–S shear zones with dextral horizontal component. During D4, after the deposition of the Kumpu group, NW–SE compression caused semi-brittle deformation, including locally crenulation folding with NE trending axes, whereas during D5, NNW–SSE compression caused brecciation and other kinds of brittle deformation

4.2 Deformation in rocks of the Kumpu group

The Kumpu group consists of the sedimentary formations Ounastunturi, Ylläs, Levi, Kumputunturi, Kaarestunturi, and Pyhätunturi (Fig. 10a), as well as the volcanic formations Latvajärvi and Tuulijoki. In the division of Lehtonen et al. (1998), the formations Ylläs, Latvajärvi and Tuulijoki form the Lainio group, with rocks deformed during D2 and D3 events; the rest form the Kumpu group records only post-D3 deformation. The structural interpretations, given in the M.Sc. theses of Räsänen (1977), Haimi (1977), and Kortelainen (1983), as well as in the report by Ristimäki (1969), are introduced here. More detailed descriptions and interpretations are presented in Section 4.3.

In western central Lapland, the Ylläs and Aakenustunturi fells consist of the quartzites and conglomerates of the Ylläs formation. The rocks have a reddish tint typical of molasses, and the polymictic conglomerates contain clasts from rocks of the Sodankylä and Savukoski groups. The rocks are deformed: according to Lehtonen et al. (1998), both foliation and mineral lineation are visible, and the conglomerate clasts are elongate. A z-shaped fold pattern, clearly visible in the aeromagnetic map (at Aakenustunturi, see Fig. 18), has not been interpreted; in the only study in which the regional structure of western Finnish Lapland is considered (Väisänen 2002), the structure is unexplained. According to Ristimäki (1969), stratigraphic younging at Kesänki (Ylläs) is towards W, indicating occurrence along the eastern, subvertical limb of a syncline.

The Levi formation, with maximum thickness exceeding 2 km, consists of quartzite at the bottom, the polymictic Sirkka conglomerate, quartzites, and siltstone on top. The clasts in the Sirkka conglomerate are similar to those in the Ylläs formation, but undeformed. Lehtonen et al. (1998) interpreted that vertical movements resulted in the deposition of talus, now represented by the Sirkka conglomerate, whereas the overlying quartzites were deposited in a fluvial environment. Around the Levi fell, quartzites and conglomerates of the Levi formation are deformed into a syncline with an almost horizontal E–W axis (Kortelainen 1983). The synclinal structure is openly folded into a synform with a steeply dipping axial plane trending NNE. The Sirkka conglomerate ends in the north in a shear zone (Sirkka shear zone; see Fig. 12a).

The quartzites of the Kaarestunturi formation have been folded at least twice, with the older fold axis plunging moderately NW (Räsänen 1977). Räsänen (1977) reported a younger, NNE–NE striking and steeply SE dipping foliation, which is associated with younger folding. The aeromagnetic map and field observations suggest a NW trending fault with a sinistral sense of shear, deforming the older fold pattern (Räsänen 1977).
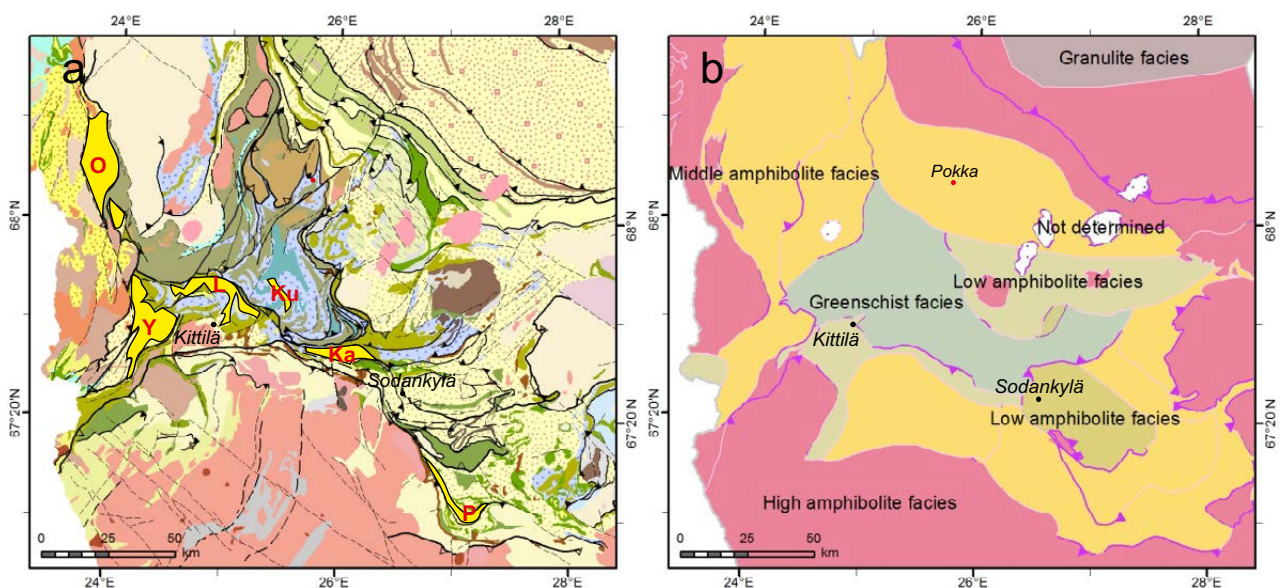

Fig. 10. a) Bedrock map of the central Lapland area. Formations of the Kumpu group: O = Ounastunturi formation, Y = Ylläs formation, L = Levi formation, Ku = Kumputunturi formation, Ka = Kaarestunturi formation, P = Pyhätunturi formation. b) Metamorphic map of the central Lapland area (see Hölttä & Heilimo 2017).

In the area of the Pyhätunturi and Luosto fells, the quartzites of the Pyhätunturi formation sharply crosscut fold structures of older rocks, but themselves form a curving structure. According to Haimi (1977), well-developed schistosity is only visible at Pyhätunturi, where it is bedding-parallel and dips 30−60° NE−N−NW.

The quartzites and conglomerates of the Kumputunturi formation are at the Kumputunturi fell and Mantovaara hill, within the area of the Kittilä suite rocks. These rocks differ from the other occurrences in being virtually undeformed (Mikkola 1941, Hanski & Huhma 2005).

4.3 Interpretation of regional variation in deformation

The modeling of evolution in central Lapland is challenging because during 1.90−1.77 Ga there were several deformation events, and at least two metamorphic events; correlation of deformation events in time and space becomes more difficult towards the end of the age range. Moreover, it has to be borne in mind that the deformation events are not necessary correlative. The modeling presented here is based on the structural interpretations outlined above, interpretation of the reflection seismic FIRE 4 profile (Patison et al. 2006), the metamorphic map of central Lapland (Fig. 10b; see also Hölttä et al. 2007), and structural data from the GTK bedrock database, especially the structures in the Kumpu group rocks. In central Lapland, rocks that have been metamorphosed under greenschist facies peak conditions and were thus never buried deep in the crust, occur adjacent to migmatitic rocks that were metamorphosed at mid-crustal levels, indicating that a crustal-scale shear zone or fault must exist between these rocks. These important crustal zones must be taken into account in the tectonic/kinematic modeling.

The central Lapland area has here been divided into five domains in which structural evolution has been interpreted independently (Fig. 11). At the end
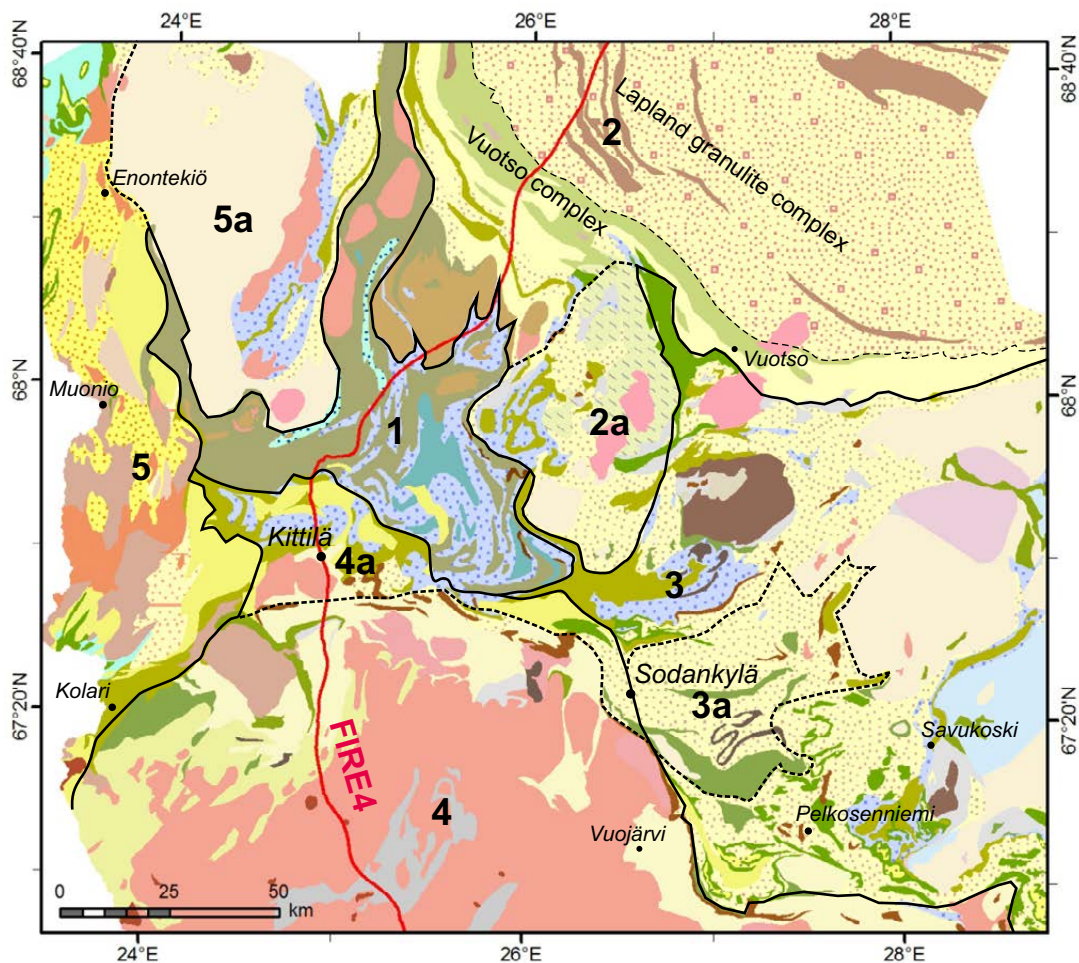

Fig. 11. Structural domains in the central Lapland area.

of each description, the sequence of ductile deformational episodes as well as the inferred stress fields are outlined; late brittle deformation is not considered in this study.

4.3.1 Domain 1

Domain 1 predominantly consists of the volcanic rocks of the Kittilä suite. The suite includes oceanic and within-plate type mafic volcanic rocks (Vesmajärvi and Kautoselkä lithodemes, respectively), mafic tuffs and banded iron formations (Porkonen lithodeme), and quartzites (Pyhäjärvi lithodeme; Fig. 12a). The genetically distinct rocks are considered to form a package of allochthonous and parautochthonous rocks, thrust eastwards to their present position during collison between the Norrbotten and Karelia lithospheric blocks (Hanski & Huhma 2005, Lahtinen et al. 2005, Lahtinen et al. 2015b).

The area is seen in the aeromagnetic gravity map as a positive Bouguer anomaly that is strongest in the center; in a recent 3D model, the rocks form a keel-shaped unit with a maximum thickness of 9.5 km in the center (Niiranen et al. 2014a). A positive Bouguer anomaly is not found in the narrow part that extends north towards Norway, suggesting that the package of Kittilä suite rocks thins northwards. At the base of the Kittilä suite rocks there are strong, subhorizontal reflectors (Patison et al. 2006), consistent with the interpretation of a unit that has been thrust to the present location. Since there is little field or drill core evidence of the boundaries of the Kittilä suite, the boundaries have mainly been interpreted from aerogeophysical data as thrusts with vergence towards the east (Lehtonen et al. 1998). In the GTK database, foliations are generally steeply dipping and define curving patterns (Fig. 12a). In the eastern part (at Rajala), fold axes plunge west (10–20°), consistent with thrusting towards the east, but fold axes and lineations generally have several plunge directions, as already noted by Väisänen (2002). Väisänen (2002) interpreted that further north, at Lauttaselkä, thrusting had been from the east, and ground geophysical studies and drilling (Karinen et al. 2011) have confirmed this interpretation. The change in thrust vergence is discussed in Section 4.3.2.

The Sirkka shear zone (also named as Sirkka thrust or Sirkka Line) defines the southern boundary
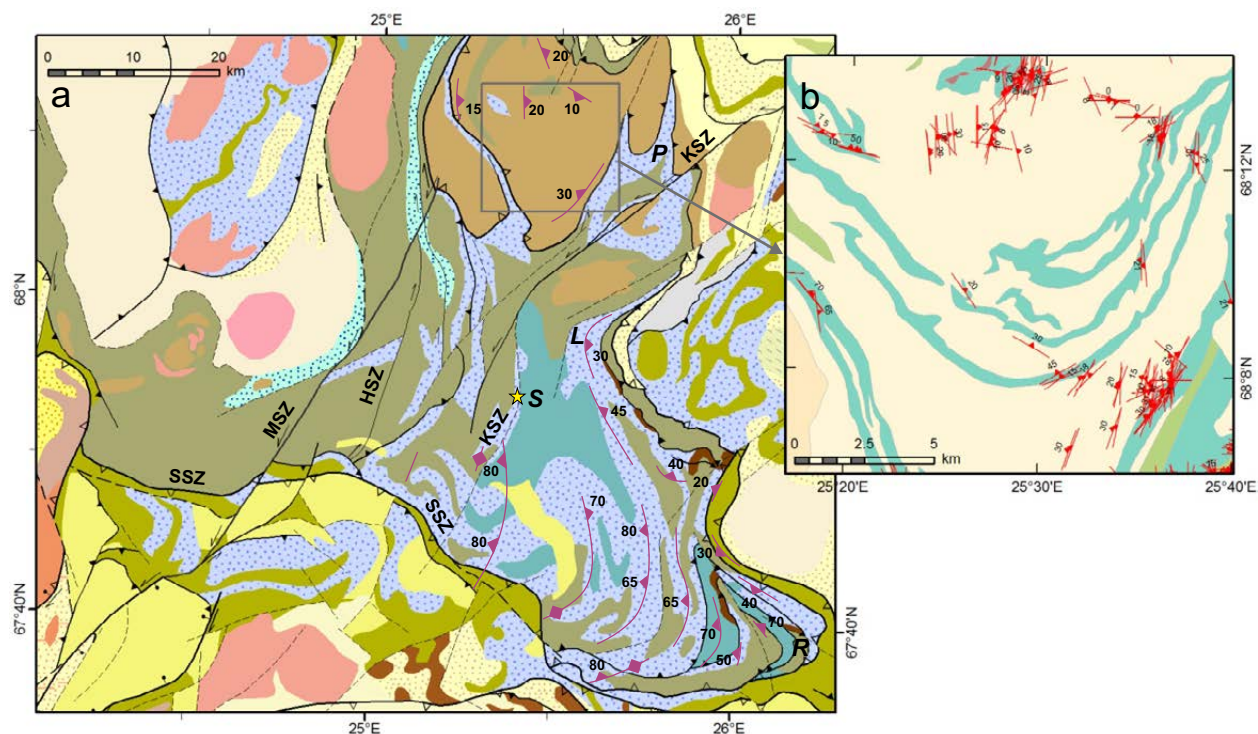
Fig. 12. a) Bedrock and structures in the area of Kittilä suite rocks (in domain 1). Brown-green = mafic volcanic rocks (Kautoselkä lithodeme), blue-green = mafic volcanic rocks (oceanic, Vesmajärvi lithodeme), stippled blue = mafic graphite tuff (Porkonen lithodeme), stippled light green = sericite quartzite (Pyhäjärvi lithodeme). The foliations from GTK bedrock database are shown by form lines (violet). KSZ = Kiistala shear zone, HSZ = Hanhimaa shear zone, MSZ = Muusa shear zone, SSZ = Sirkka shear zone. P = Pokka, L = Lauttaselkä, S = Suurikuusikko (gold mine), R = Rajala. b) Foliation observations (red) in the Taatsi granodiorite (located in domain 2).

of Domain 1 (Fig. 12a). The shear zone is a complex structure, consisting of several steeply S-dipping thrusts and fold structures that have been subject to post-thrusting deformation (Patison 2007). Continuation and character of the zone southeastwards is poorly constrained. The vergence of thrusting is to the south in the maps of Korsman et al. (1997) and Lehtonen et al. (1998), but to the north in Saalmann and Niiranen (2010), in the 1:1 million GTK bedrock map of Nironen et al. (2016), and in the GTK bedrock database.

In the aeromagnetic map, large-scale folding with a N–S axial plane and a wavelength of 6–10 km can be seen in the center of domain 1, and the rock distribution follows this fold pattern (Fig. 12a), classified as F3 folding by Lehtonen et al. (1998). On the basis of the GTK bedrock database, there appears to be a single foliation in the axial plane of this folding, with the following characteristics: the foliation crosscuts the thrust zones; and curving of the foliation increases towards E–SE, giving an impression that the large-scale folding is undeformed in the center of the domain and increasingly tightens towards the E–SE. However, there are several aspects that indicate more than one foliation generation: 1) the Kumpu group rocks crosscut the folding but the foliation crosscuts the Kumpu group rocks; 2) the fold pattern is crosscut by the Sirkka shear zone but the interpreted axial plane foliation crosses the thrust; 3) curving of the foliation follows the interpreted thrusts in the SE but crosscuts the frontal thrust; and 4) the foliation with vergence towards the east changes into foliation with vergence towards the west (at Lauttaselkä). The last point was briefly discussed by Väisänen (2002) who concluded that the 'Nolppio thrust', with opposite thrust directions, was the result of two competing tectonic forces operating simultaneously, as outlined by Sorjonen-Ward et al. (1989).

Several N–NE -trending shear zones crosscut the large-scale fold pattern with N–S axial plane. The shear zones appear to be strike-slip zones, associated with thrusting from NNE–NE as transfer faults. One of these is the Kiistala shear zone. The zone has two branches, the eastern one hosting the Suurikuusikko gold mine (Fig. 12a). This branch, with N–NNE trend, is crosscut by the western branch, trending NNE–NE and continuing to the Vuotso complex. According to Patison (2007), movement within the shear zone was first sinistral and subsequently dextral during dextral rotation of maximum principal stress from NW–SE to NE–SW. Saalmann and Niiranen (2010)

studied gold occurrences in another shear zone, the Hanhimaa shear zone, and concluded that the zone shows a component of dextral shear as well as an oblique dip-slip component. In contrast, the Muusa shear zone displaces the Sirkka shear zone with an apparent sinistral sense. These examples indicate that it may not be correct to group the shear zones into a single deformation event.

The relative age of large-scale folding is crucial in assessing the temporal succession of structures in domain 1. In a first alternative the oldest foliation, parallel to the thrust sheets, developed during thrusting towards the east, and because the large-scale folding tightens towards east, the thrust-related foliation is axial planar to the large-scale folding. The second alternative is that the large-scale folding deforms the early thrust sheet pattern. In both alternatives folding preceded thrusting from the N–NE.

Interpreted order of ductile deformation in domain 1 (the order between 2 and 3 is unclear):
1) Thrusting from W (collison between the Norrbotten and Karelia lithospheric blocks) => stacking of parautochthonous (passive margin) and allochthonous (oceanic) sequences to form a thrust package (Kittilä suite);
2) E–W compression => large-scale folding with a N–S axial plane;
3) Thrusting from N (collision between the Lapland-Kola and Karelia lithospheric blocks) and S (northward movement of the Pudasjärvi block) => deformation of the thrust package;
4) clockwise rotation of compression from N–S to NE–SW (more than one event?) => N–S foliation, N–NE trending shear zones;
5) NW–SE compression => crenulation folding with NE-striking axial plane.

4.3.2 Domain 2

Domain 2 consists of the Lapland granulite complex in the northeast, the fringing Vuotso complex, and rocks of the Sodankylä and Savukoski groups and the Kittilä suite, sliced between the rocks of the Vuotso complex (Fig. 11). The most conspicuous structural feature is the foliation, dipping rather consistently NE. West of the village of Pokka (Fig. 12b), the dips in penetratively foliated granitoid rocks are 0–25°, whereas northeast of Pokka they steepen to 30–50°. The foliated granitoid is here named as Taatsi granodiorite, after an ancient

Lappish sacrificial site in the area of the intrusion. There is also an abrupt change in the grade of metamorphism towards the northeast, from greenschist to mid-amphibolite facies (Fig. 10b). Based on the FIRE 4 reflection profile and its explanation (Patison et al. 2006), this change can be explained by a subhorizontal thrust sheet that is the frontal part of the Vuotso complex and has been overthrust by the package of rocks in the northeast (see also Väisänen 2002, Hölttä et al. 2007).

In subdomain 2a, in the area of the Archean Pomokaira complex, the foliations are generally shallowly dipping and the lineations plunge SW or NE; the aeromagnetic map shows folding with N-striking axial plane in the northern part. The southeastern part of the subdomain consists of Archean granodioritic-tonalitic gneisses, arkositic gneisses of the Vuotso complex, and arkose quartzites of the Sodankylä group, crosscut by granites of the Nattanen suite. An undeformed weathering layer on top of the Archean gneisses is locally visible (Tuore-Naakinselkä; Räsänen 1977), and a deformed contact was found elsewhere between an Archean gneiss and overlying Proterozoic volcanic rocks (at Möykkelmä; Räsänen et al. 1989). Because the preservation potential of a weathering layer during deformation is poor, intensive deformation such as is found around Pokka probably did not occur in the area of subdomain 2a. Rocks of the Savukoski group are squeezed between rocks of the Kittilä allochthon and quartzites overlying Archean rocks, and in all these rocks foliations dip SW. This can be interpreted so that subdomain 2a is an autochthonous Archean core, elevated with respect to the surrounding Archean basement, and the rocks of the Savukoski group were squeezed upon the Archean core, either during emplacement of the Kittilä allochthon or during later compression from the south.

The northwestern part of the subdomain 2a consists of rocks of Salla, Sodankylä and Savukoski groups, with Archean rocks in the core. Around Lauttaselkä (Fig. 12a), in rocks of the Kittilä suite foliations dip moderately E–NE, and the margin is interpreted as a thrust zone. The change in thrust vergence along the boundary of subdomain 2a may be explained by the movement of the northwestern part, with a sliver of Archean rocks, during thrusting towards SW.

At Vuotso, in the Vuotso complex (Fig. 11), an antiformal (D3) structure, with axial plane striking N–NNE, is crosscut by a thrust sheet which in turn is overthrust by the rocks of the Lapland granulite complex (Nironen & Mänttäri 2003). A clockwise rotation of thrust vergence may be outlined: first from the NNE (Vuotso complex), and subsequently from the NE (Lapland granulite complex).

Interpreted order of ductile deformation in domain 2:
1) Thrusting with progressive rotation, from N to NE (collision between the Karelia and Lapland-Kola lithospheric blocks) => thrust-sheet structure in the Vuotso complex and Lapland granulite complex, metamorphic culmination;
2) Horizontal E–W compression => tight folding with N–S axial plane (at Vuotso).

4.3.3 Domain 3

Domain 3 mainly consists of the arkositic rocks of the Sodankylä group. These rocks lie upon Archean rocks in the eastern part of the domain (Fig. 11), but the boundary is probably tectonic. Volcanic rocks of the Sodankylä group occur as curving but approximately E–W trending belts in the southern part of the domain, whereas rocks of the Savukoski group occur as ENE trending belts in the central part. Discontinuities in the aeromagnetic map imply that the belts are bordered by shear zones.

In the northern part of domain 3, southwest of Vuotso (Fig. 11), Paleoproterozoic volcanic rocks exhibit a fold interference pattern with a dome- and basin structure (Nironen & Mänttäri 2003). The older, upright folding (F3) trends N–NNE, and the axial trace of the younger folding (F4) is E–ESE.

At Savukoski, a strip of Paleoproterozoic supracrustal rocks, with a maximum width of 5 km, is located in an area dominated by Archean gneisses (Fig. 13a). The distribution of rocks is symmetric: the Savukoski group rocks are in the center and older Sodankylä group rocks are at the margins. Foliation observations suggest a structural basin, and foliation in the Archean gneisses is generally low-angle but steepens towards the Paleoproterozoic rocks. Two possibilities are given for the structure. In the first one a graben structure developed during extension of the Archean basement and deposition of the Paleoproterozoic supracrustal sequence (Fig. 13 b1); subsequent horizontal compression caused tightening of the graben and folding of the supracrustal rocks. In the other possibility, the Archean basement was thrust upon the supracrustal sequence (Fig. 13 b2). In both cases the Archean gneisses were
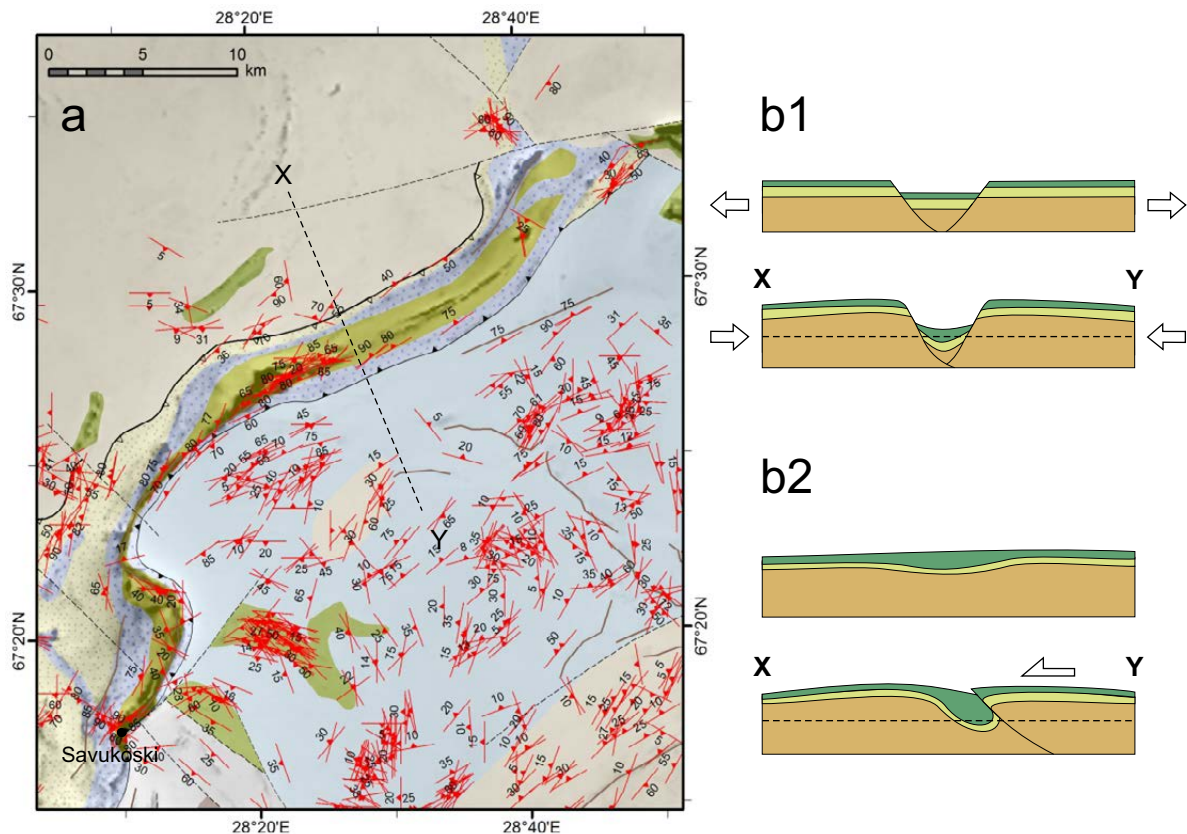
Fig. 13. Structures in the area NE of Savukoski. a) Bedrock map and foliation observations. Ligth brown, light blue = Archean gneisses. Light grey = rocks of the Salla group. The rocks bordered by thrusts are rocks of the Sodankylä and Savukoski groups. b) Schematic structural interpretations, vertically exaggerated. Brown = Archean rock, yellow and green = Paleoproterozoic rocks. b) Structural models across the X–Y line. b1: a graben structure is folded during horizontal compression. b2: folding in the footwall of a thrust or transpression zone. The broken line indicates the present erosion level.

covered by Paleoproterozoic rocks, and most of these have been eroded. At Savukoski, the Savukoski group rocks are bounded against rocks of the older Salla group (Fig. 13a), suggesting a thrust with vergence towards the west (note that the interpretation in Fig. 13a has a vergence to the opposite direction). Therefore, the second alternative is favored in modeling of the tectonic evolution.

In the southern part of domain 3, at Vuojärvi (Fig. 11), there is a sequence of rocks that are part of the Vuojärvi suite. In the western part there are biotite paragneisses and quartz-feldspar gneisses but the main part consists of fuchsite-bearing sericite quartzite. Räsänen and Huhma (2001) considered that the quartz-feldspar gneisses are Archean (ca. 2.77 Ga) and that the quartzites overlie the gneisses; in Finstrati, the quartzites are also considered Archean. The aeromagnetic anomaly pattern in the rocks of the Vuojärvi suite suggests two folding events (Fig. 14a). In the quartzites, strati-

graphic younging is consistently towards the east whereas bedding dips moderately to steeply west. Consistent with field observations, geophysical modeling across the sequence suggests steep dips towards the west (Fig. 14b). Abrupt terminations of magnetic anomalies by other anomalies may be explained by thrust faults that were originally moderately to shallowly dipping and subparallel to the axial plane of an anticline (Fig. 14 c1) or synform (Fig. 14 c2). Geophysical modeling (Fig. 14d) supports the interpretation that the structure is an anticline. A gabbroic body of the Haaskalehto suite, occurring between the Vuojärvi suite rocks and rocks of the Kuusamo and Sodankylä groups, is seen as a strong positive anomaly in the aeromagnetic map (Fig. 14a). In the geophysical model (Fig. 14b), the gabbro is almost vertical. In the Kuusamo and Sodankylä group rocks bedding and foliation dip steeply east. On the basis of structural data and geophysical modeling, it is difficult to assess
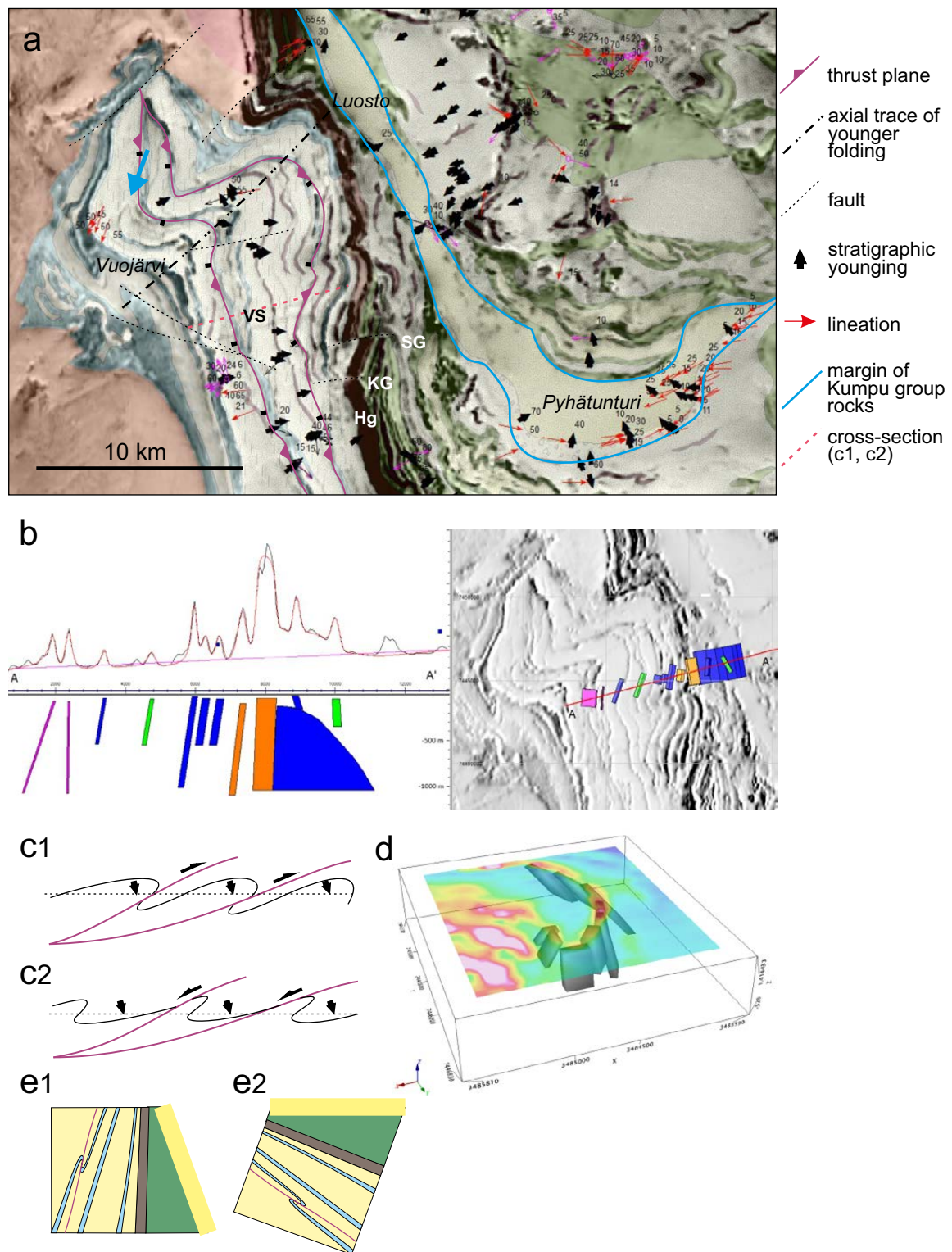
Fig. 14. a) Bedrock and aeromagnetic map of the Vuojärvi-Pyhätunturi area. VS = Vuojärvi suite, KG = Kuusamo group, SG = Sodankylä group, Hg = Haaskalehto gabbro. b) Geophysical interpretation of a section crossing the general foliation trend. c) Schematic cross-section (location shown in Fig. 6a) of the rocks of the Vuojärvi suite before steepening of structures during subsequent deformation: c1 = anticline, c2 = synform. d) Geophysical modeling of the fold closure shown in Figure 6a, blue arrow indicates the view direction. e1) Vertical section of rocks and structures along the cross-section in b. e2) Restoration by rotation of 70° to directions during deposition of the Kumpu group sediments (bedding in the Kumpu group rocks dips 70° east on average). Geophysical modeling by Hanna Leväniemi, GTK. Forward modeling of aeromagnetic flight profile data. Data collected in 1984, inclination 76.6°, declination 7.3°.

whether there is an angular discordance between the Vuojärvi suite and Kuusamo/Sodankylä group rocks; if there is, the angle is small.

The Kumpu group rocks (Pyhätunturi formation) crosscut rocks of the Sodankylä group and form a continuous, curving belt that opens to the north (Fig. 14a). What kind of structure is it? Haimi (1977) described a hematite–bearing schist, with black schist and jaspilite interbeds, and with a gradational contact to Kumpu group conglomerate immediately north. However, according to Räsänen (personal communication 2012), the conglomerate contains clasts of hematite–bearing schist, indicating a discordance between the schist and the conglomerate. The bedding planes in the Kumpu group rocks dip moderately to steeply (30–85°) NE−N−NW along the curving structure, with steepening of structures towards the south and west; this is also the stratigraphic younging direction. According to Haimi (1977), a bedding-parallel schistosity can be seen in the Kumpu group rocks at Pyhätunturi. She discerned a third folding phase with NW−WNW -striking, steeply dipping axial planes and moderately to steeply NW−WNW -plunging fold axes that also deform the Kumpu group rocks. The conglomerate clasts are strongly elongate, but the elongation is not parallel to the fold axis; Haimi (1977) did not provide an explanation for the elongate clasts. In the GTK bedrock database, lineation directions grossly follow the curving structure. The lineations plunge towards the center of the curving structure (Fig. 14a), indicating that the Kumpu group rocks are at the southern rim of a structural basin. Considering the evidence and interpretations given above, the curving structure may be interpreted as a thrust sheet in which the leading edge is foliated and the conglomerate clasts are elongate parallel to the edge.

In the aeromagnetic map, domain 3 is dominated by arcuate, approximately E−W trending anomalies. Evins and Laajoki (2002) interpreted that these anomalies express nappe structures (Kelujärvi nappe and Pyhätunturi nappe) that cover most of the Proterozoic supracrustal rocks in domain 3. According to metamorphic studies (Hölttä et al. 2007), an area can be discerned in which the grade of metamorphism increases eastwards (subdomain 3a, see Figs. 10b, 11). Evins and Laajoki (2002) performed a detailed study on subdomain 3a, within the Kelujärvi nappe, and concluded that low-angle, south-vergent D1 deformation with E and W plunging folds was followed by upright D2 folding with NE-striking axial planes. They suggested that a basal thrust continued southwards to the Pyhätunturi area and that the Pyhätunturi nappe is delimited by this thrust; the Kumpu group sediments were deposited in a thrust-sheet-top basin in front of a thrust.

Two possibilities are considered in the structural interpretation of the Pelkosenniemi area (Fig. 15). The first follows the concept of Evins and Laajoki (2002) that the rocks represent a nappe (Pyhätunturi nappe; Fig. 15a), with continuation of the thrust system characterizing the Kelujärvi nappe in the north; these structures developed during D1. Evins and Laajoki (2002) proposed an age of ca. 1.87 Ga for thrusting. The folding at Vuojärvi, which produced the anticlinal structure (Fig. 14), is the oldest folding and predated nappe emplacement because the Haaskalehto gabbro and dolerite dikes parallel to the gabbro, with ages around 2.2 Ga (see Section 6 for a more detailed explanation), occur parallel to the axial plane of the anticline (shown by green lines in Fig. 15a). The dark blue lines correspond to F1 folding of Evins and Laajoki (2002). The younger, upright folding at Vuojärvi, with NE-striking and steeply dipping axial plane foliation (violet; GTK bedrock database), is tentatively correlated with F2 folding of Evins and Laajoki (2002). The steeply NW-plunging fold axis at Vuojärvi (from equal area projection; Haimi 1977), compared to steep to subhorizontal axes in subdomain 3a, tests the validity of this correlation. The third folding, with approximately N-striking axial plane (light green), also deformed the Kumpu group rocks. This folding is interpreted to explain the structural basin in the Pyhätunturi area and the overall dome-and-basin structure that appears from the aeromagnetic map. The problem with this interpretation is that the dominant planar structure in the nappe (i.e. at Vuojärvi) is older than the nappe.

In an alternative, favored interpretation the rocks in the Vuojärvi-Pyhätunturi area are (par)autochthonous (Fig. 15b). The original orientation of the inclined anticline at Vuojärvi is taken to be approximately NNW, with vergence towards ENE (Fig. 15 c1). The Haaskalehto suite gabbro intruded along a fault between the Vuojärvi suite rocks and Kuusamo/Sodankylä group rocks. Tight, upright folding with NNE-striking and steeply dipping axial plane developed during NNW−SSE compression (Fig. 15 c2); this folding is different from F2 folding in the Kelujärvi nappe (axial trace shown in light blue in Fig. 15b). The Kumpu group sedi-

ments were deposited after the development of the structures described above (Fig. 15 c_3). The original orientation of the Kumpu sequence is NNW (preserved at Luosto). The whole package, including the Kumpu group rocks, was folded around N-plunging axis, with the generation of a dome-and-basin structure (Fig. 15 c_4). A thrust, now represented by the hematite-bearing schist at the base of the sediments, developed at the margin of the Kumpu group sediments. Subsequent thrusting from the south caused folding of the supracrustal sequence, and the development of a foliation in the Kumpu group rocks (Fig. 15 c_5). Evidence for thrusting from the south is that the two southern blocks crosscut

the fabric in the Vuojärvi suite rocks (see bottom of Fig. 15b). The problem with this explanation is the deposition of the Kumpu group sediments: deposition was probably associated with vertical displacement along a fault but the sense of movement and position of the fault is unknown.

The original orientation of structures in the Vuojärvi–Pyhätunturi area may be assessed by rotation (70°) of the inclined Kumpu group rocks into a horizontal position (Fig. 14e). In the restored position, the structures in the Vuojärvi suite rocks, as well as the Haaskalehto suite gabbro, dip moderately east. Structural discordance between the Vuojärvi suite rocks and the Kuusamo/Sodankylä
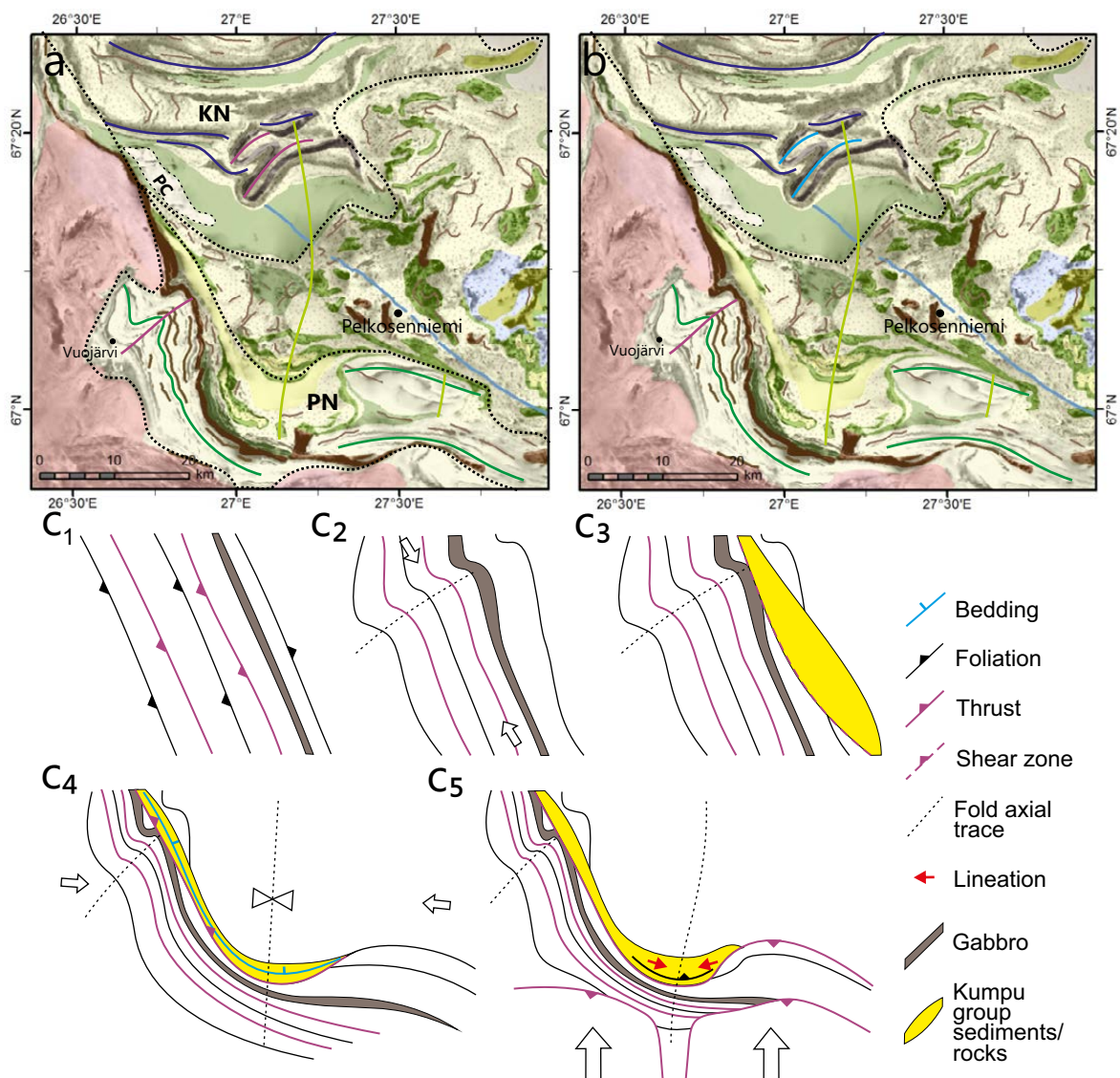
Fig. 15. Two alternative explanations for the structures in the Pelkosenniemi area. a) First alternative with two nappe structures as outlined by Evins and Laajoki (2002), indicated by broken lines: KN = Kelujärvi nappe, PN = Pyhätunturi nappe, PC = Porttikoski complex. Fold axial traces: green (oldest), dark blue, violet, light green (youngest). b) Second alternative in which the southern part is (par)autochthonous. Fold axial traces: green (oldest), violet, dark blue (order unknown), light blue, light green (youngest). c) Development of the present structure according to the second alternative. See the text for details.

group rocks is intuitively plausible, considering that it offers a path for the gabbroic magmas to spread extensively; the length of the Haaskalehto suite gabbro in the present erosion level is about 100 km.

Evins and Laajoki (2007) concluded that in subdomain 3a andalusite, kyanite and staurolite porphyroblasts grew after F1–F2. Andalusite porpyroblasts in places exhibit a curving inclusion pattern, interpreted as S2 crenulation by Evins and Laajoki (2002, Fig. 14) and S3 crenulation by Hölttä et al. (2007, Fig. 15d). Hölttä et al. (2007) concluded that the growth of andalusite and staurolite was syntectonic with S3. They proposed that the eastward progade increase in metamorphic grade around Sodankylä (in subdomain 3a) may reflect an oblique section of the crust, or heat input from granitoids.

Within the western Kelujärvi nappe, there is an area of migmatitic rocks, interpreted to be of Archean age (the Porttikoski complex, Fig.15). Little is known about this complex, and there are no age data to prove the Archean age. The Archean rocks may be exposed in a tectonic window within the nappe structure.

Interpreted order of ductile deformation in domain 3 (the order between 2 and 3 is tentative):
1) Early (Archean?) folding (at Vuojärvi);
2) NNW–SSE compression => open to tight upright folding (at Vuojärvi);
3) Thrusting from N–NNE (collision between the Karelia and Lapland-Kola lithospheric blocks) => nappe structures, folding in subdomain 3a;
4) E–W compression => open upright folding, dome-and-basin structure;
5) NW–SE compression => thrusting (at Savukoski);
6) Thrusting from S => thrusting (SE of Vuojärvi), late folding (at Vuotso).

4.3.4 Domain 4

Domain 4 consists of the Central Lapland granitoid complex (CLGC) and supracrustal rocks to the north of the complex (subdomain 4a; Fig. 11). In the aeromagnetic map the CLGC is characterized by NE to N trending linear anomalies as well as some ovoidal structures. (Fig. 16a). According to the GTK bedrock database, in the center of the CLGC fold axes and lineation plunge shallowly (0–30°) SW, and further north lineations are subhorizontal with a N–S orientation. The foliations are flat-lying (dips 0–30°) with highly variable strike directions. Foliations in

one ovoidal structure dip shallowly outward, indicating an antiform.

The reflectivity pattern in the FIRE 4 profile in the northern part of the CFGC was interpreted by Patison et al. (2006) to indicate several shear zones with apparent dip to the south: the Meltaus shear zone is exposed in the center of the complex, and the Venejoki shear zone and Sirkka shear zone are exposed at the northern margin. There is no field evidence for the Meltaus shear zone, mainly because of the poor outcrop density. The Iso Pirttivaara–Kurtakko and Venejoki shear zones (Patison et al. 2006) have here been combined to form the Venejoki shear zone (Fig. 16a). The eastern part of the Venejoki shear zone consists of a series of N-verging thrusts, and the northernmost of these, the Venetjärvi thrust, defines the northern margin of the CLGC. Since the shear zone is defined on the basis of aerogeophysical data, its exact position and especially extension to the southeast is poorly constrained. The Venetjärvi thrust and the Sirkka shear zone delineate subdomain 4a (Fig. 11). In the interpretation of the POLAR refraction seismic profile (Luosto et al. 1989), the Sirkka and Venejoki shear zones dip 40° south but in the FIRE 4 profile, the dip appears to be shallower (15–20°; Fig. 16b).

In subarea 4a, around the Levi fell, primary bedding in Kumpu group quartzites trend roughly E–W trend (Fig. 16c). Kortelainen (1983) interpreted the E–W structure as a syncline, with conglomerate overlain by quartzite. Is the structure really a syncline? In an alternative interpretation, presented in Figure 16d, the rocks are deformed by two sets of thrusts, and the resulting structure, with quartzite between two units of conglomerate, only resembles a syncline. According to Kortelainen (1983), the syncline is openly folded, with a subvertical axial plane striking NNE. The upright folding implies horizontal, roughly E-W compression.

Structures along the northern boundary of the CLGC, southeast of Sirkka, are shown in Figure 17. The aeromagnetic pattern (Fig. 17a) is dominated by strong positive anomalies caused by gabbroic and doleritic bodies of the Haaskalehto suite, including the Haaskalehto gabbro proper (cf. Fig. 14). At the Kaarestunturi fell, aeromagnetic anomalies indicate a clear, asymmetric fold pattern (Fig. 17b). Bedding and top-of-strata observations indicate that the Kumpu group rocks are folded into a syncline with the hinge in the northern part. Foliation observations indicate bedding-parallel foliation in places, overprinted by another foliation,
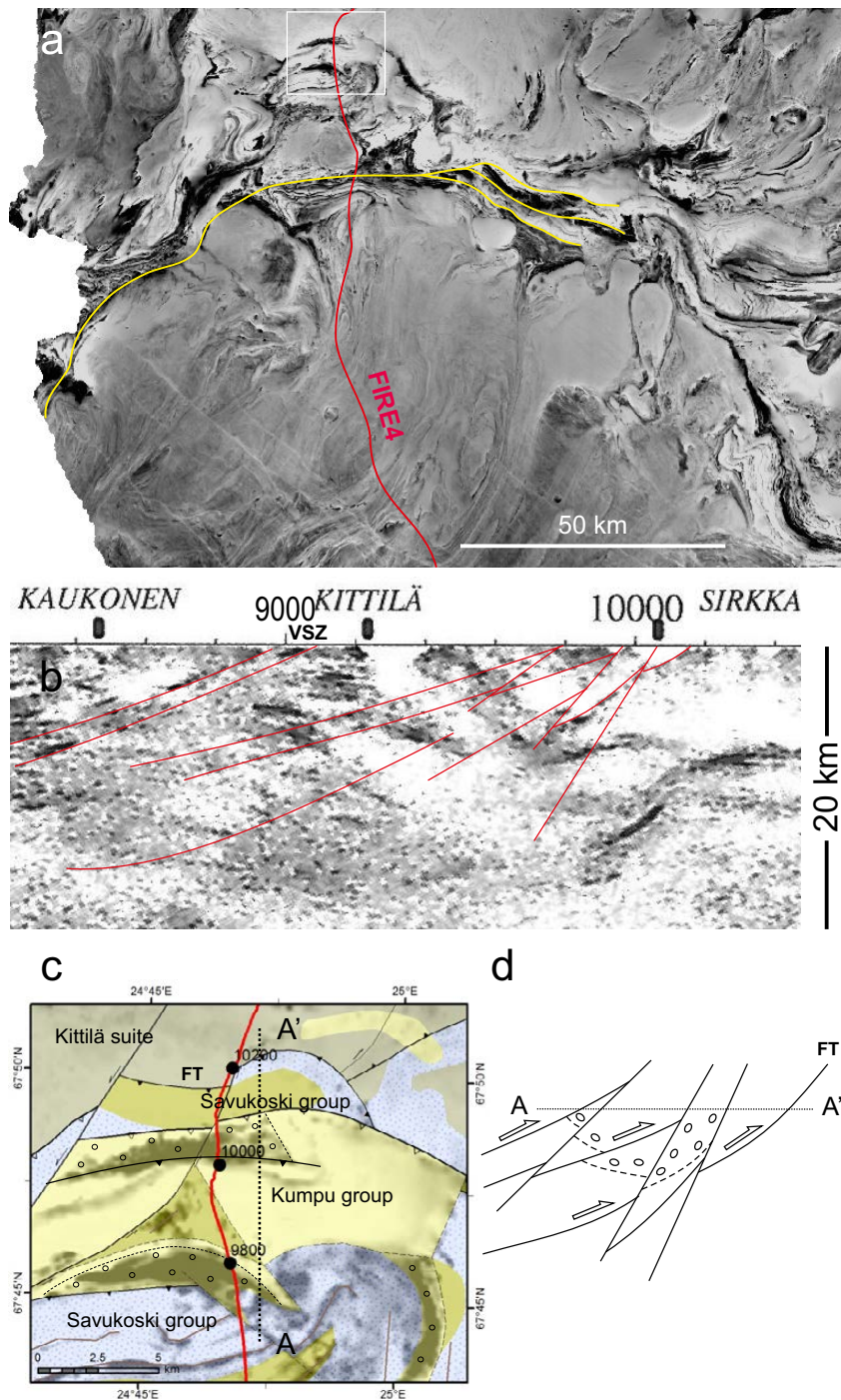
Fig. 16. a) Aeromagnetic map of the area of domain 4. The Venejoki shear zone is shown by a yellow line and the location of Figure 16c by a white rectangle. b) Grayscale smoothed section of the FIRE 4 profile from the northern part of the Central Lapland granitoid complex, and interpretation of structures (see Patison et al. 2006, Fig. 13). VSZ = Venejoki shear zone. c) Interpreted structures at Sirkka. FT = Frontal thrust in the Sirkka shear zone. FIRE 4 / FIRE 4A profile shown as a red line, with three common mid-points (see Patison et al. 2006). Sirkka conglomerate is marked by open circles. Note that the Kumpu group rocks of the Levi formation are surrounded by Savukoski group rocks. d) Interpretation of structures along profile A–A' (shown in Fig. 16c). Base of the Kumpu group rocks (with conglomerate at bottom) is shown by a broken line.

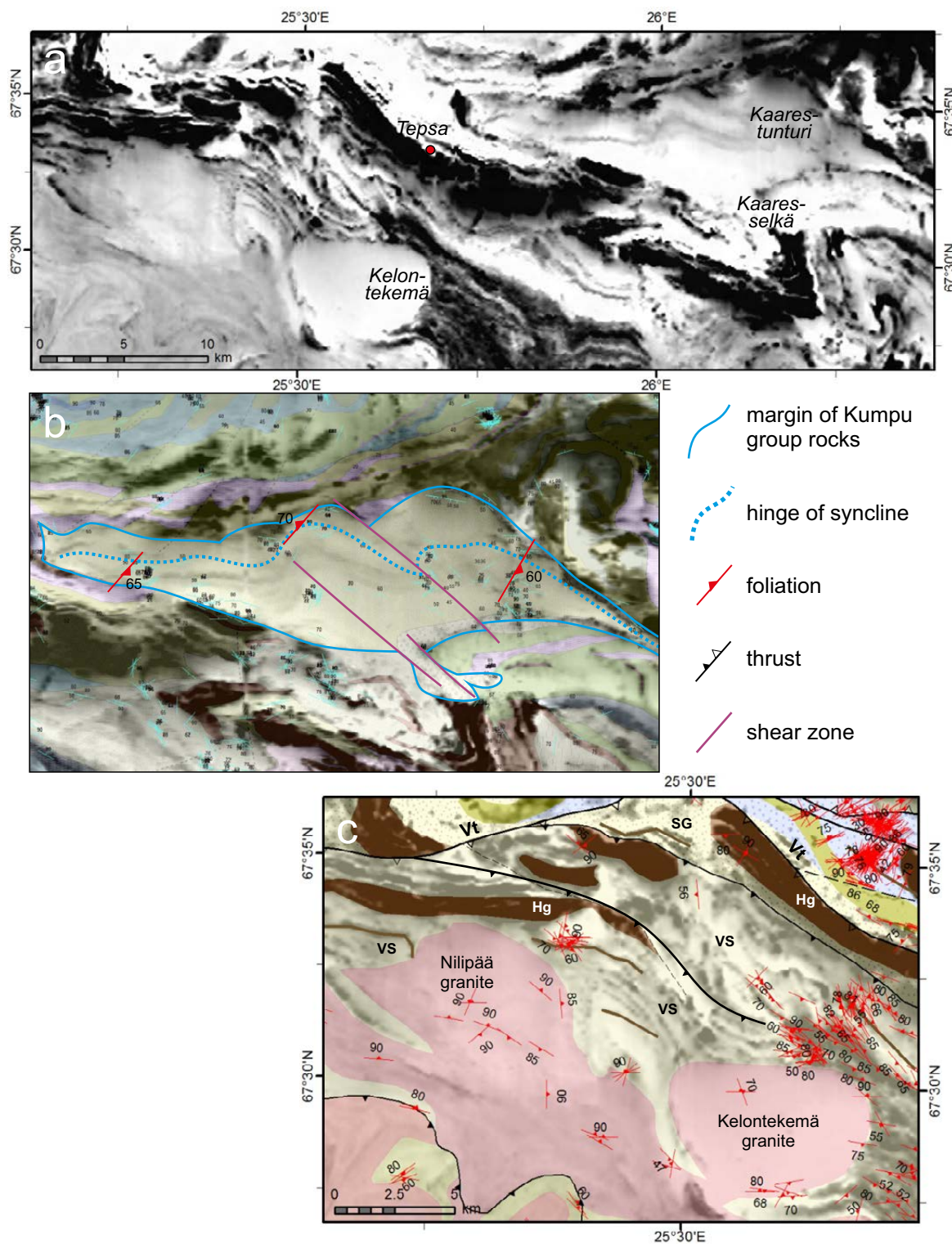Fig. 17. a) Aeromagnetic map of the Kelontekemä–Kaarestunturi area. b) Primary layering and interpreted syn–clinar structure at Kaarestunturi. c) Foliation at Kelontekemä. VS = quartzite and mica gneiss of the Virttiövaara suite, SG = quartzite of the Sodankylä group, Hg = Haaskalehto gabbro, Vt = Venetjärvi thrust.

striking NE and dipping steeply SE or NW, as already noted by Räsänen (1977). The syncline is sinistrally folded with NW-striking axial plane. Räsänen (1977) reported moderately NW plunging fold axis which may be associated with this folding (the fold axis directions in the GTK bedrock database are much more variable). The easternmost shear zone in Figure 17b suggests dextral displacement of the northern margin (interpreted as a thrust), but sinistral displacement of the southern margin; the shearing probably had a major vertical component. Patison (2007) reported gold-bearing, WNW-striking, subvertical, sinistral strike-slip shear zones at the southern margin of the Kumpu group r ocks (at Kaaresselkä). In the Geological Map of Finland – Bedrock 1:1 000 000 (Nironen et al. 2016), the northern margin of the Kaarestunturi formation is interpreted as S-dipping thrust fault zone.

There are (at least) two possibilities to interpret structural evolution in the Kaarestunturi formation. In the first one, the sediments were deposited in front of the Venejoki shear zone. Deformation initiated by development of a thrust fault at the northern margin of the Kaarestunturi formation during thrusting from the south, and the rocks were folded into a syncline. A sinistral shear couple developed as the result of progressive, slightly rotated NNE–SSW compression, causing sinistral folding with NW striking axial plane and shear zones along the axial plane. Anorther interpretation is that the Kumpu group rocks were deposited in a pull-apart basin that formed principally during a single N–S extension event, and deformed during basin inversion (Basha 2017). Neither of the interpretations explain the NE-striking foliation.

At Kelontekemä, elongate gabbroic bodies and dolerite dikes of the Haaskalehto suite appear to have intruded the supracrustal rocks of the Archean Virttiövaara suite along foliation planes that are subvertical at present and follow the orientation of the Venetjärvi thrust and the Venejoki shear zone in general (Fig. 17c). Two granitic bodies, the Nilipää granite and another one, named here as the Kelontekemä granite, crosscut the foliated supracrustal rocks. The consequence of this crosscutting relationship is discussed later (Section 6).

Interpreted order of ductile deformation in domain 4:
1) Thrusting from S (northward movement of the Pudasjärvi block) => thrust zones in the northern part of domain 4;

2) E–W compression => open to tight upright folding (at Levi);
3) NW–SE compression => open folding (synforms and antiforms) in the CLGC;
4) Thrusting from S => folding in subarea 4a.

4.3.5 Domain 5

In the southern part of domain 5, the rocks are mainly quartzites and arkosites of the Kumpu group (Lainio group in the division of Lehtonen et al. 1998). In addition, southwest of the Ylläs fell (Fig. 18), there are quartzites and arkosites of the recently identified Uusivirka (super)suite (Lahtinen et al. 2015b). The areal extent of these rocks is still unknown: the quartzites at Äkäskero were considered by Lahtinen et al. (2015b) to be part of the Kumpu group, whereas in Finstrati they belong to the Uusivirka suite; the former interpretation is followed in this study. In the northern part of domain 5, the quartzitic rocks of the Olostunturi suite are considered older although no age data exist of them. The lithology of subdomain 5a, the Hetta complex, is poorly known as well. The few datings from the complex (Huhma 1986, Ahtonen et al. 2007) show strongly negative ε_{Nd} values, indicating a major Archean component in the source. The Hetta complex is probably Archean in age, partly covered by Proterozoic supracrustal rocks.

The southern part of domain 5 is considered to be part of the wide Pajala shear zone, trending approximately N–S, west of the national boundary between Finland and Sweden (Bergman et al. 2006). The prominent structure in this area is a strong stretching lineation plunging moderately to shallowly SSW–SW, and the fold axes in supracrustal rocks are parallel to this lineation (Fig. 18). Hiltunen and Tontti (1976) outlined an antiform with a quartz monzonitic intrusion of the Haparanda suite (Lakkavaara quartz monzonite; Väänänen 1998) in the core of the antiform. They interpreted that the quartz monzonite intruded syntectonically during NW–SE compression of the main deformation phases (F1, F2) and peak metamorphism; S2 foliation in the axial plane of the antiform overprints an older foliation (S1?) that is conformable with the margins of the quartz monzonite. These deformations were followed by at least one deformation phase.

Lehtonen et al. (1998) described D2 structures in general but gave only a few localized examples. One of these is the occurrence of a prominent, moder-

ately to shallowly SW–plunging L2 mineral lineation and boudinage structure around Äkäsjokisuu. Koistinen (1986) studied the area northwest of Kittilä and suggested that thrusting may have occurred in a late stage of D2 deformation or later, but before D3 deformation.

Väisänen (2002) presented evidence (e.g. recumbent folding) of thrusting towards the NNE and subsequent reverse movement towards the east

in an overall transpressional system. Hölttä et al. (2007) associated the development of SW–plunging lineation and fold axes at Äkäsjokisuu with thrusting from SE during D3. Niiranen et al. (2014b) assigned the Äkäsjoki shear zone to the axial plane of an open fold structure, but left open whether the structure at Äkäsjokisuu is F2 folding and associated shearing, or F2 folding deformed by D3 thrusting. Considering that partitioning of strain into shear
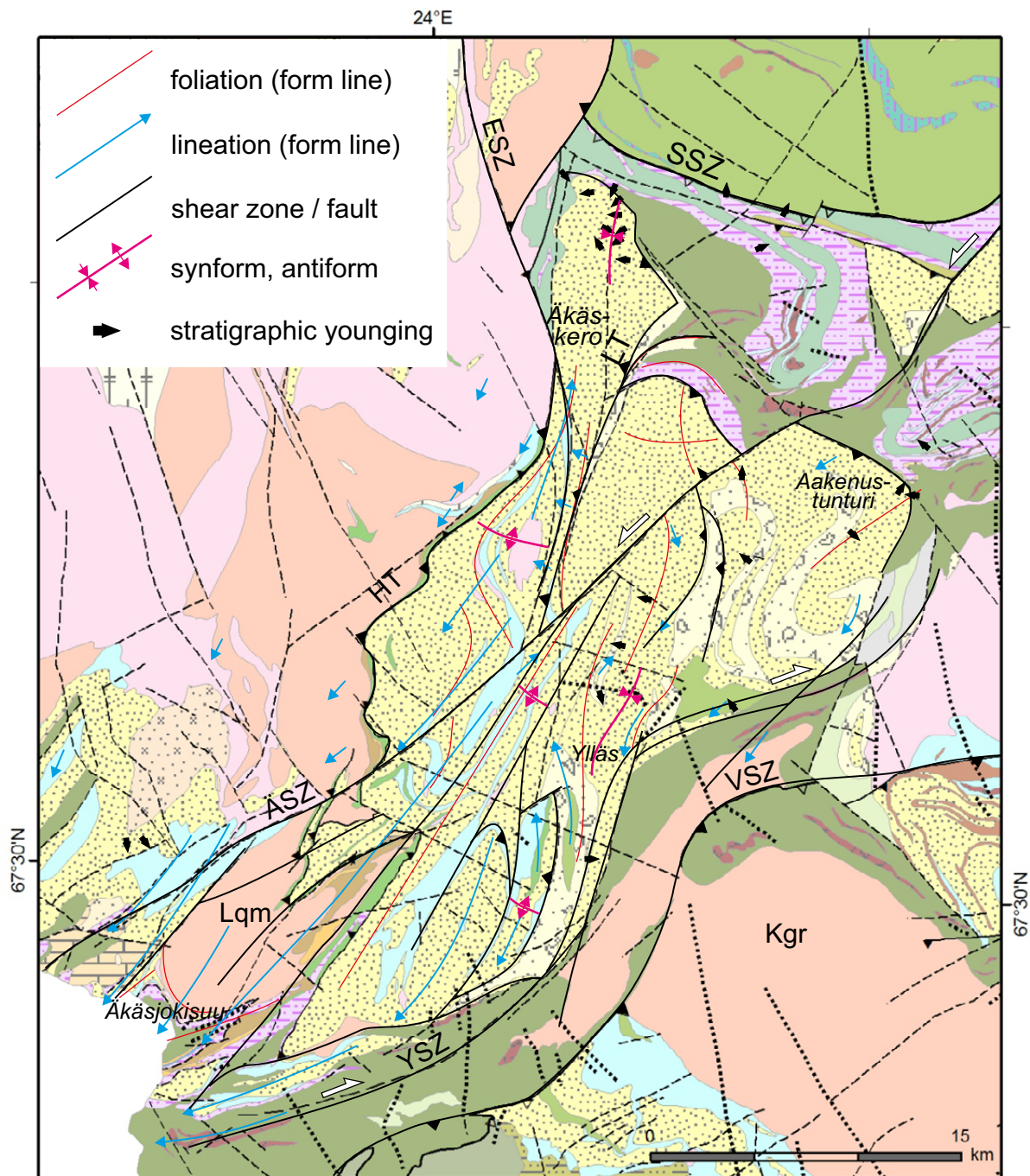

Fig. 18. Structural interpretation of the Äkäsjokisuu–Aakenustunturi area. VSZ = Venejoki shear zone, YSZ = Ylläs shear zone, ÄSZ = Äkäsjoki shear zone, ESZ = Enontekiö shear zone, HT = Hannukainen thrust, LT = Linkukero thrust, SSZ = Sirkka shear zone, Lqm = Lakkavaara quartz monzonite, Kgr = Kallo granitoid.

zones during open folding is not typical, the second alternative is here considered more probable. The sense of shear in the Äkäsjoki shear zone is also obscure: near Aakenustunturi, the offset suggests a sinistral horizontal component, whereas closer to Äkäsjokisuu vertical displacement appears more probable.

In the Kumpu group rocks and older rock assemblages, the structural pattern is characterized by a fold structure overprinted by NE-trending shear zones (Fig. 18). Based on Rastas (1984) and the GTK bedrock database, primary layering and prominent foliation are generally steeply dipping to vertical, whereas lineations and fold axes are moderately to shallowly plunging; moderately dipping layering is found around Äkäsjokisuu, but around the Ylläs and Aakenustunturi fells layering is invariably steeply dipping. Primary layering must have been folded into a steep position during an early folding but evidence of this folding is only found locally. Further southwest, the structure is increasingly dominated by subvertical shear zones, e.g. the Lakkavaara quartz monzonite is bounded by shear zones.

The z-shaped structure at Aakenustunturi is bordered by the Äkäsjoki shear zone and another shear zone, named here as the Ylläs shear zone. These shear zones may be interpreted as a shear couple, folded around a steeply plunging fold axis, but since fold axis observations are few in the Aakenustunturi area, this interpretation is speculative. Overall, the structure in the southern part of domain 5 is interpreted as a thrust system with vergence towards NE: the Kumpu group rocks were thrust from southwest upon the rocks of the Savukoski group, and the Ylläs shear zone acted as a transfer zone during thrusting. Further southwest, older rock sequences were imbricated upon the Kumpu group rocks as thrust sheets. The Äkäsjoki shear zone, which displaces the synform–antiform pattern, was reactivated during thrusting.

A set of thrusts and shear zones are here interpreted to delimit the Uusivirka suite rocks southwest of Ylläs (Fig. 18). A thrust, here named as the Linkukero thrust, is outlined close the eastern margin of the Kumpu group rocks at Äkäskero and further south, between quartzite and a strip of conglomerate. Immediately west of the Linkukero thrust, lineations plunge moderately (50–60°) WNW. The rocks containing the lineations were previously considered part of the Sodankylä group, but were re-interpreted as part of the Uusivirka

suite (Lahtinen et al. 2015b). Taking this interpretation at face value, the evidence suggests that the older (≤ 1.92 Ga) Uusivirka suite rocks were thrust eastwards upon younger (≤ 1.88 Ga) Kumpu group rocks.

In previous interpretations (Korsman et al. 1997, Koistinen et al. 2001) the plutonic rocks of the Haparanda suite have been thrust E–NE upon the supracrustal rocks, along a zone named here as the Hannukainen thrust (Fig. 18). Moderately to shallowly SW plunging lineations on both sides of the thrust zone (GTK bedrock database) suggest a dextral shear component during thrusting. The Hannukainen thrust is crosscut by another structural zone, named here as the Enontekiö shear zone, which is well defined in the aeromagnetic map. In the terminology of Väisänen (2002), the Enontekiö shear zone and Hannukainen thrust belong to a complex structure which he called Kolari shear zone. The Enontekiö shear zone appears to have a sinistral horizontal component but since the foliation to the west of the shear zone is shallowly WSW dipping, dip-slip faulting can result in a similar pattern. The order of overprinting between the shear zones appears to be the following: the NE-vergent thrust system is crosscut by the E-vergent Linkukero thrust, which also deforms the Enontekiö shear zone; and the Äkäsjoki shear zone crosscuts the Linkukero thrust.

In the Ounastunturi–Äkäskero area, the aeromagnetic map exhibits three structures that together resemble a thrust ramp structure, crosscut by the Enontekiö shear zone (Fig. 19). The structures consist of different lithologies, including Kumpu group rocks (Ounastunturi) and plutonic rocks of the Haparanda suite, but all were interpreted to have been thrust towards the east by Korsman et al. (1997). There are not many structural measurements of the Ounastunturi–Äkäskero area in the GTK bedrock database, but for example the lineament plunge directions are not as consistent as in the Äkäsjokisuu–Aakenustunturi area. Thrusting was possibly first towards the NE (thrust ramp system) and subsequently towards the E (Enontekiö shear zone), as in the southern part of domain 5. The Enontekiö shear zone may have been reactivated during NW–SE compression.

Subdomain 5a consists of the Hetta complex, poorly known in age, lithology, and structure. The allochthonous parts of the Kittilä suite may have been thrust over the Hetta complex.
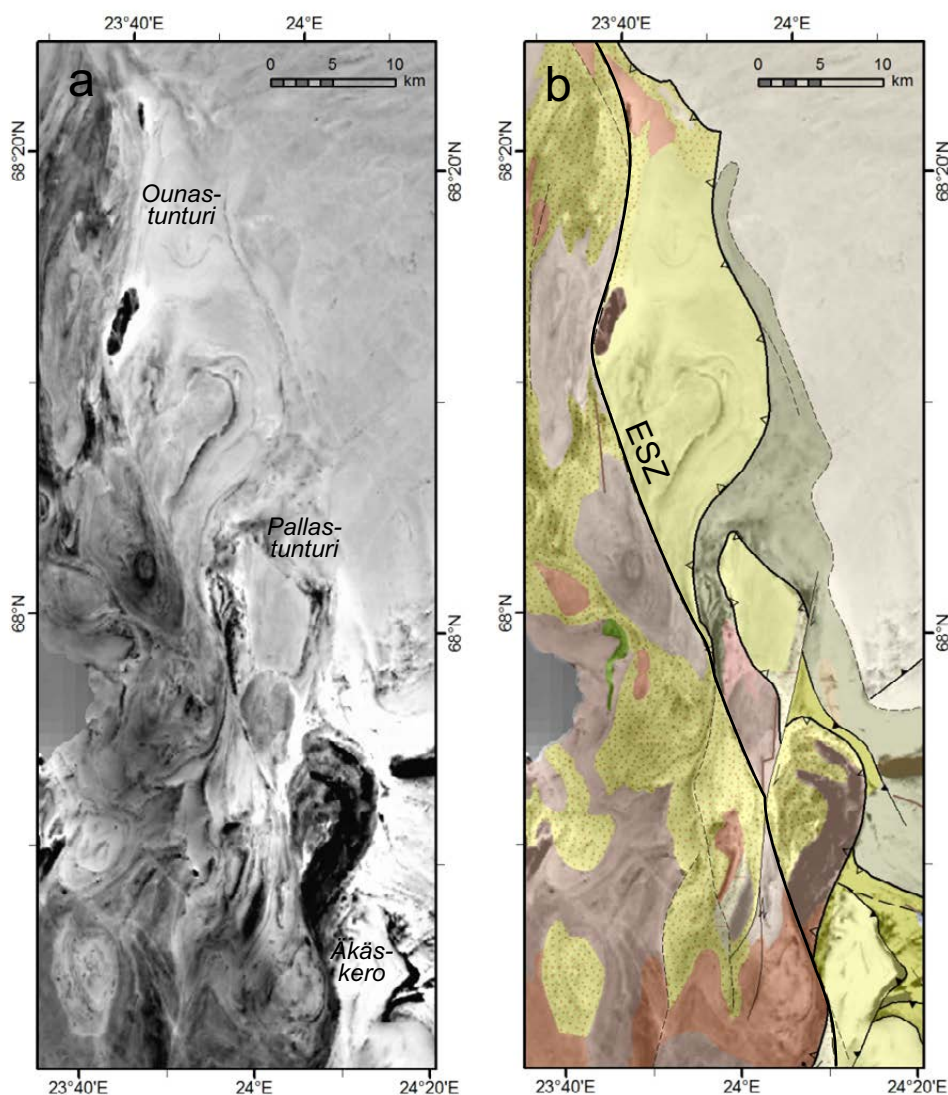
Fig. 19. a) Aeromagnetic map of the Ounastunturi–Äkäskero area. b) Interpretation of shear zones, ESZ = Enontekiö shear zone.

Interpreted order of ductile deformation in domain 5:

1) Compression => folding in older (pre-Kumpu group) supracrustal rocks, culmination of metamorphism;

2) Thrusting from S => folding of Kumpu group rocks (sinistral shear couple?);

3) Thrusting from SW => NE thrusting of Uusivirka suite, Haparanda suite and Kumpu group rocks;

4) Thrusting from W => emplacement of the Kumpu group rocks in the Ounastunturi–Äkäskero area, development of the Enontekiö shear zone (?).

5) NW–SE compression? => development of the Enontekiö shear zone.

4.4 Correlation of deformation and metamorphism

The metamorphic map (Fig. 20) is based on outcrop and thin section observations and is independent of structural interpretations. It describes the peak metamorphic stage of prograde metamorphism, but one has to bear in mind that the age of peak metamorphism may vary from one area to another, and that there may have been several metamorphic events; the map is the net result of the whole metamorphic history. The metamorphic map is also a crustal depth map: the structures visible in the greenschist facies developed higher in the crust than the ones in areas of high metamorphic conditions. Some struc-

tures (e.g. detachment zones) may have developed in a wide depth range, and they can therefore be correlated from one metamorphic area to another. Conversely, the deep-level continuations of faults are generally shear zones or fold structures.

Several remarkable features, visible in the metamorphic map (Fig. 20), have to be taken into account:

(1) The isograds are in places located along shear zones, but they generally crosscut both shear zones and lithological boundaries (this may account for the scarcity of suitable observation sites);

(2) Between domains 1 and 2 there is an abrupt change in metamorphic grade from greenschist facies to mid-amphibolite facies (kyanite-bearing rocks);

(3) In subdomain 3a, the metamorphic grade increases towards the east and there is an area of high amphibolite facies rocks among lower grade rocks; and

(4) Kumpu group rocks are found in both the greenschist and amphibolite facies areas.

In domain 1, the thrust zones that delineate the Kittilä suite rocks to the east are located in the area of greenschist facies. This can be explained by emplacement of the Kittilä allochthon before early Svecofennian (1.89–1.87 Ga) metamorphism and deformation. In the metamorphic map, the continuation of the Kittilä suite rocks to the north crosses the mid-amphibolite facies and amphibolite–granulite transition isograds, but since there are no observations from this area, the isograd locations are not to be taken strictly (P. Hölttä, oral communication 2014). Greenschist facies metamorphic assemblages indicate that the rocks were never deeper in the crust than 6–10 km. Considering the present 9.5 km maximum thickness of the Kittilä suite rocks, obtained in 3D modeling (Niiranen et al. 2014a), the maximum thickness of the stack, including the allochthon and the overlying nappe, was originally 15–18 km.

In line with earlier interpretations, the structures in domain 2 are here interpreted as the result of progressive thrusting, first from the N and subsequently from the NNE and NE. The abrupt change in metamorphic grade from greenschist facies to
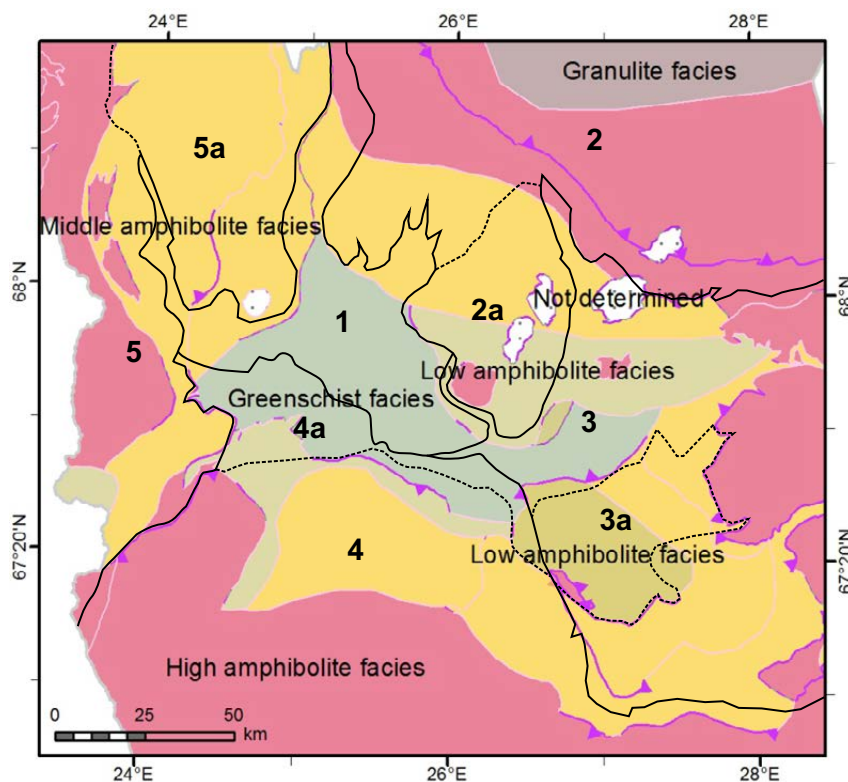

Fig. 20. Metamorphic map of the central Lapland area, and structural domains. For more detailed explanation of the metamorphic areas, see Hölttä and Heilimo (2017).

mid-amphibolite facies between domains 1 and 2 is here explained by a frontal thrust related to thrusting from the NNE; this indicates that thrusting was late-metamorphic or post-metamorphic. Hölttä et al. (2007) proposed that the 'inverted' metamorphic gradient from the granulites towards the SW was the result of thrust stacking during which higher grade gneisses were thrust over lower grade schists during late stage of metamorphism. They proposed that the Kittilä allochthon was emplaced during late D3 deformation. However, since the greenschist facies – mid-amphibolite facies isograd crosscuts the northeastern part of the Kittilä suite rocks, the allochthon was already emplaced before thrusting from the NNE.

Isograds between greenschist facies and low amphibolite facies, and between low amphibolite facies and mid-amphibolite facies areas crudely follow the Venejoki shear zone between domain 4 and subdomain 4a. Some of the mismatch may be explained by the lack of observations close to the Venejoki shear zone, but overall, this implies that thrusting along the Venejoki shear zone was post-metamorphic (or late-metamorphic), and that domain 4 represents a deeper crustal section than subdomain 4a.

As can be seen from the metamorphic map, some of the Kumpu group rocks are in the greenschist facies area (Levi, Kaarestunturi, Kumputunturi, Mantovaara) whereas others are in middle amphibolite facies area (Luosto–Pyhätunturi, Ylläs–Aakenustunturi, Äkäskero, Ounastunturi; Figs. 10 and 20). Since greenschist facies represents the culmination of prograde metamorphism, metamorphic culmination was attained *after* deposition of the Kumpu group rocks e.g. at Levi. But as Lehtonen et al. (1998) concluded that regional peak metamorphism had been attained *before* the deposition of the Kumpu group sediments, there is an obvious discrepancy; were there two greenschist facies metamorphic events, differing in age but spatially overlapping? Was there enough data to properly assess the metamorphic grade in each formation of the Kumpu group?

The boundary of low-amphibolite facies and middle amphibolite facies between Levi and Ylläs–

Aakenustunturi is at the boundary of different structural domains (subdomain 4a and domain 5), indicating that the thrust bounding Aakenustunturi is also a metamorphic boundary and that thrusting in domain 5 was relatively late. Similarly, the increase to mid-amphibolite metamorphism east of Äkäskero and Ounastunturi in domain 5 may be explained by thrusting after peak regional metamorphism: emplacement of higher grade rocks on top of lower grade rocks caused inverted metamorphism to the latter, or rocks below the frontal thrust sheet were dragged to a higher crustal level.

The interpretations presented above indicate that the oldest identified deformations in each domain may be of different ages. According to Hölttä et al. (2007), metamorphism culminated during D2 in each metamorphic area. This does not mean that D2 was contemporaneous in each area, but that the rocks were deformed most intensely during peak metamorphic conditions.

The concept of Evins and Laajoki (2002) of early thrusting from the north and the development of a foreland fold and thrust belt is adopted here for the evolution in domains 2 and 3. The direction of thrusting progressed from N to NNE to NE during long-term thrusting, which was probably cyclic. Hölttä et al. (2007) proposed that the eastward prograde increase in metamorphic grade in subdomain 3a may reflect an oblique section of the crust as a result of D3 thrusting, or heat input from granites. The former interpretation is in contrast to the nappe tectonics adopted here. As concluded earlier (Section 4.3.3), the (presumably Archean) migmatitic area in subarea 3a (Figs. 15a and 20) is interpreted as a tectonic window within the Kelujärvi nappe.

Overall, correlation across the domains is difficult, because: 1) the thrust structures in domain 1 are different from thrust structures in domains 2 and 3; 2) thrusting in domains 2 and 3 occurred from the N–NE, whereas thrusting in domain 4 occurred from the S; and 3) thrust and shear structures in domain 5 differ from structures in other domains (except the western part of domain 4).

4.5 Temporal correlation of structures

Extension of the Archean crust in northern Finland initiated at ca. 2.5 Ga and ceased before the 1.9 Ga convergent deformation (e.g. Ward et al. 1989). The

sediments of the Sodankylä and Savukoski groups were deposited during extension in a basin, and during deposition, mafic and ultramafic lavas

extruded between and upon the sediments. The basin was formed in an intracontinental setting that subsequently developed into a continental margin setting. Thickening of the volcanic-sedimentary pile may have induced an early burial-type metamorphism.

The gabbroic bodies and dolerite dikes (Haaskalehto suite) at Kelontekemä (Fig. 17c) have been dated at 2.2 Ga (Rastas et al. 2001). The bodies are elongate and parallel to steeply dipping to vertical foliation. The Nilipää granite, dated at 2.14–2.13 Ga (Rastas et al. 2001, Ahtonen et al. 2007), crosscuts the foliation but is slightly deformed, whereas the Kelontekemä granite clearly crosscuts the foliation and shows only weak concentric foliation (Fig. 17c). The two granites are probably of different ages, although they are now grouped together in Finstrati as Iso Nilipää granite.

Hanski and Huhma (2005) concluded that the Kittilä allochthon was emplaced at ~1.92 Ga, based on 1.92 Ga felsic dikes crosscutting the mafic volcanic rocks. A Re–Os age of 1916 ± 19 Ma was obtained from gold-bearing arsenopyrite in the Suurikuusikko deposit (Wyche et al. 2015), providing an age for the Kiistala shear zone. Since the Kiistala shear zone deforms the large-scale fold pattern in the Kittilä suite rocks, the fold pattern developed soon after emplacement of the allochthon, during continued E–W compression.

The tonalities and gabbros (norite–enderbite series) in the Lapland granulite complex intruded into the metasediments during ~1.92–1.905 Ga and were probably an important heat source for metamorphism (Tuisku & Huhma 2006, Tuisku et al. 2012). Metamorphism culminated at 1.91–1.90 Ga, decompression and cooling (uplift stage) occurred during 1.90–1.88 Ga, and cooling was almost finished by 1.87 Ga. The Pielpajärvi diorite, dated at 1905 ± 2 Ma (unpublished GTK data), crosscuts the gneissic foliation in the Lapland granulite belt (Fig. 21). Based on these values, first thrusting from the N–NNE may be bracketed at ~1.91 Ga, and the Kiistala shear zone acted as a transfer zone during thrusting. This thrusting was followed by a new thrusting event, recorded at Vuotso, where it overprints a rather late (D3) antiform (Nironen & Mänttäri 2003). Clockwise rotation of thrusting may be seen as the change in orientation of transfer zones: shear zones have NNE strike in the area of the Taatsi granodiorite and the Vuotso complex, but NE strike in the Lapland granulite complex (Fig. 21).

The Ruoppapalo granodiorite (Fig. 21), with an age of 1905 ± 5 Ma, has induced a metamorphic aureole to adjacent Kittilä suite rocks and is weakly deformed (Rastas et al. 2001, Ahtonen et al. 2007). Because the rocks of the Lapland granulite complex have been thrust upon the rocks of the Vuotso complex, the rocks in the Vuotso complex were deformed and metamorphosed before 1.91 Ga – but not necessarily much before. The age of the strongly foliated Taatsi granodiorite is unknown. The granodiorite probably intruded the Sodankylä and Savukoski group rocks and the Kittilä allochthon at 1.92–1.91 Ga, and was deformed during thrusting from the NNE, while the Ruoppapalo intrusion was largely preserved from this deformation.

In western Finnish Lapland, the rocks of the Uusivirka (super)suite, with 1.92–1.90 Ga ages (Lahtinen et al. 2015b), were deposited after emplacement of the Kittilä allochthon but before deposition of the Kumpu group sediments. The youngest ages measured from clasts of Kumpu conglomerates are ~1880 Ma (Lehtonen et al. 1998, Hanski & Huhma 2005). According to Lehtonen et al. (1998), prominent deformation (D2) and the regional metamorphic peak in central Lapland was obtained before the deposition of the Kumpu group rocks.

The upright folding at Vuojärvi may be constrained between 2.2 Ga (emplacement of the Haaskalehto suite gabbro) and ca. 1.88 Ga (deposition of the Kumpu group sediments) but since no counterpart for this folding was found, more exact timing of this folding remains open.

Based on the ages above, development of the fold and thrust belt, with thrusting from the north, occurred at 1.92–1.91 Ga, during D1–D2 of Evins and Laajoki (2002). According to Lehtonen et al. (1998), the maximum age of D2 deformation in central Lapland is 1.885 Ga; obviously, the D1–D2 deformations of Evins and Laajoki (2002) and Lehtonen et al. (1998) are different in age and style.

Bergman et al. (2006) considered thrusting in western Finnish Lapland to be part of deformation in the wide Pajala shear zone, following the N–S boundary of Sweden and Finland. They concluded that deformation in the Pajala shear zone covered a wide age range: an early deformation event at 1.89–1.87 Ga was followed by a period of granitoid-syenitoid magmatism, ductile deformation, and medium- to high-grade metamorphism at 1.86–1.85 Ga, and a period of deformation and high-grade metamorphism at 1.82–1.78 Ga. The
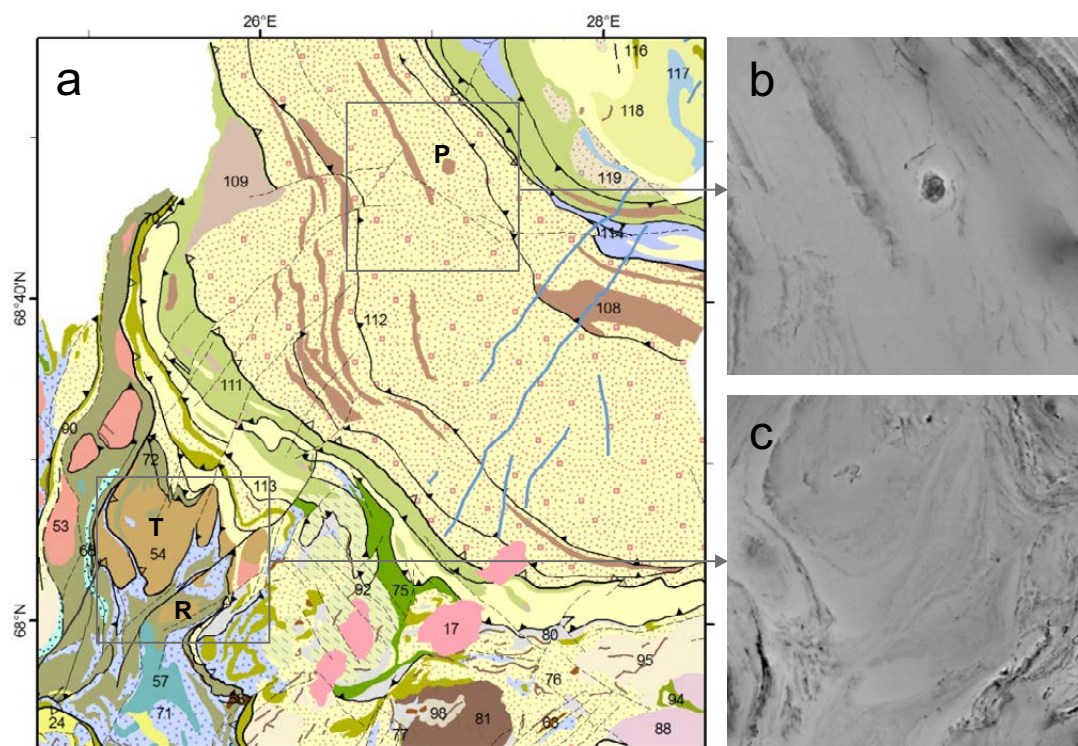
Fig. 21. a) Location of the Pielpajärvi diorite (P), Ruoppapalo granodiorite (R) and Taatsi granodiorite (T) in north-central Lapland. b) Pielpajärvi diorite in the aeromagnetic map. c) Ruoppapalo and Taatsi granodiorites in the aeromagnetic map.

detrital zircon study of Lahtinen et al. (2015b) corroborates that the 1.86–1.85 Ga period included a metamorphic event.

The age of thrusting towards the NE in western Finnish Lapland is ambiguous. Thrusting obviously occurred after metamorphic culmination, as well as after the deposition and lithification of the Kumpu group sediments. The Lakkavaara quartz monzonite (Fig. 18) yielded an age of 1862 ± 3 Ma (Hiltunen 1982). If the Lakkavaara intrusion is considered to be a syntectonic intrusion in the core of an antiform, as interpreted by Hiltunen and Tontti (1976), thrusting occurred at 1.86 Ga. This interpretation would be in line with the period of magmatism, ductile deformation, and metamorphism at 1.86–1.85 Ga (Bergman et al. 2006). Hiltunen (1982) interpreted that skarns and Fe–Cu–Au deposits near the contacts of the monzonitic intrusions were formed by contact metasomatism, induced by emplacement of the monzonites. However, as Niiranen et al. (2007) noted, the 1797 ± 5 Ma zircon age of the skarn is difficult to explain by the genetic model of Hiltunen (1982). They concluded that the deposits are of hydrothermal replacement-type, and suggested that alteration and mineralization occurred at ~1.80

Ga, contemporaneously with thrusting. Both interpretations have weaknesses: the 1.86 Ga intrusion may not be syntectonic, in which case it only gives the maximum age for thrusting; and Niiranen et al. (2007) gave rather weak arguments to support the contemporaneity of alteration and thrusting.

As concluded earlier (Section 4.4), the isograds in the metamorphic map (Fig. 20), roughly following the Venejoki shear zone, may be interpreted so that the metamorphic zonation reflects thrusting from the south that followed peak metamorphism. The Venejoki shear zone crosscuts the 1882 ± 1 Ma Kallo granitoid (Fig. 18; Väänänen & Lehtonen 2001), which sets the maximum age for thrusting.

The Molkoköngäs granite in the CLGC, with an age of 1855 ± 13 Ma Ga (Ahtonen et al. 2007), contains a strong, subhorizontal NE–SW stretching lineation. The NE-striking foliation and shear folding, found in domains 1 and 4a, may be correlated with open folding in the CLGC by a similar orientation, but it has to be noted that this criterion is not sufficient as such. The structures within the CLGC are difficult to interpret and may be the net result of several compressional (and extensional) stages at different times. Lahtinen et al. (2015a) tentatively

correlated the NNE trending D4 structures and N−S trending D5 structures in the Martimo belt with deformation in the CLGC, with 1.83–1.82 Ga and 1.79−1.77 Ga ages, respectively. The small Tainio gabbro, with an age of 1796 ± 4 Ma (Väänänen 2004), and other appinitic intrusions in the center of the CLGC, give the minimum age for main deformation in the CLGC.

Evidence of voluminous and extensive magmatism and metamorphism in the age range 1.85–1.76 Ga is found in the CLGC, in the Suomujärvi complex, and in western Lapland (Huhma 1986, Corfu & Evins 2002, Räsänen & Huhma 2001, Väänänen & Lehtonen 2001, Ahtonen et al. 2007, Niiranen et al. 2007). A migmatitic gneiss in the Hetta complex yielded an age of 1774 ± 6 Ma for high-grade metamorphism (Ahtonen et al. 2007). Corfu and Evins (2002) interpreted a period of ductile deformation and metamorphism in the Suomujärvi complex at 1.78−1.77 Ga or later by monazite and titanite dating. Ahtonen et al. (2007) dated zircons from several deformed granites adjacent to the Suomujärvi complex (Jumisko and Petäjäselkä granitoids) and obtained ages of 1.78–1.76 Ga.

5 TECTONIC MODEL

The tectonic model follows the ones presented by Lahtinen et al. (2005, 2009) and Nironen (2017), but is more detailed with respect to northern Lapland. It is based on the concept of elevated areas and shear zones in the rigid Archean basement, movement of rigid crustal blocks upon the Archean basement, and partitioning of strain in the 'soft' supracrustal rocks between these rigid units.

The Paleoproterozoic cover sequences (Karelia supergroup) were deposited upon the Archean Karelia continent mainly during the 2.5–1.9 Ga extensional stage. The Archean basement was a rather flat shield area, with some elevated areas such as the present Hetta complex and Pomokaira complex areas. Archean shear zones were reactivated during rifting, and they also had a control of deformation during the subsequent contractional stage.

Rifting at 2.44 Ga led to emplacement of the mafic layered intrusions of the Tornio−Näränkävaara belt, the Koitelainen and Akanvaara mafic layered intrusions as well as the felsic volcanic rocks of the Salla group, and deposition of the Sariola group sediments in a half-graben (Fig. 22a). During continued extension, the half-graben developed into a shallow, water-filled epicontinental basin, and the quartz-rich sediments of the Sodankylä group were deposited at the bottom of the basin (Fig. 22b; cf. Laajoki 2005, Fig. 7.18). Extension led to attenuation of the Archean crust and finally break-up of the continent at 2.06−2.05 Ga (Fig. 22c). An aulacogen (failed rift) developed in the central Lapland area, and ultramafic-mafic layered intrusions and komatiitic volcanic rocks were emplaced along a reactivated Archean shear zone. Rigid blocks were detached from the Archean continent along Archean shear zones, and these blocks remained at the craton margin when a passive margin had developed. The Suomujärvi complex and the block near the town Tornio (see Section 2.1) represent smaller blocks whereas the Pudasjärvi block was a continental ribbon. The modeled Pudasjärvi block consists of the present Pudasjärvi complex and basement of the Peräpohja belt and Central Lapland granitoid complex. The 1.98 Ga Korkiavaara arkosic sediments / tuffs were emplaced in a passive margin setting within the Pudasjärvi block (Fig. 22d).

The contractional stage of the model is shown in Figure 24. Visualization of the four-dimensional model (with time as the fourth dimension) in 2D is inevitably a gross simplification. As an example of the complexity, in the age range 1.9-1.8 Ga, the rocks in the study area represent a depth range from the surface of the Earth (Kumpu group sediments during deposition) to ca. 20 km (granulites of the Lapland granulite complex at 1.91 Ga). The model is presented in Figure 24 as horizontal planes: the rock distribution during the two first periods (Figs. 24 a-b) are from the surface of the Earth, showing mutual order of the allochthonous units. In the remaining figures, active deformation zones during corresponding periods are shown as they are located in the present erosional level.

Two collision events, between the Norrbotten, Lapland−Kola, and Karelia lithospheric blocks, occurred at 1.93−1.91 Ga (Lahtinen et al. 2005, Daly et al. 2006, Tuisku & Huhma 2006, Lahtinen et al. 2015b, Nironen 2017). The first contractional event in central Lapland was the development of a foreland fold and thrust belt as the result of the Norrbotten−Karelia collision. Parautochthonous
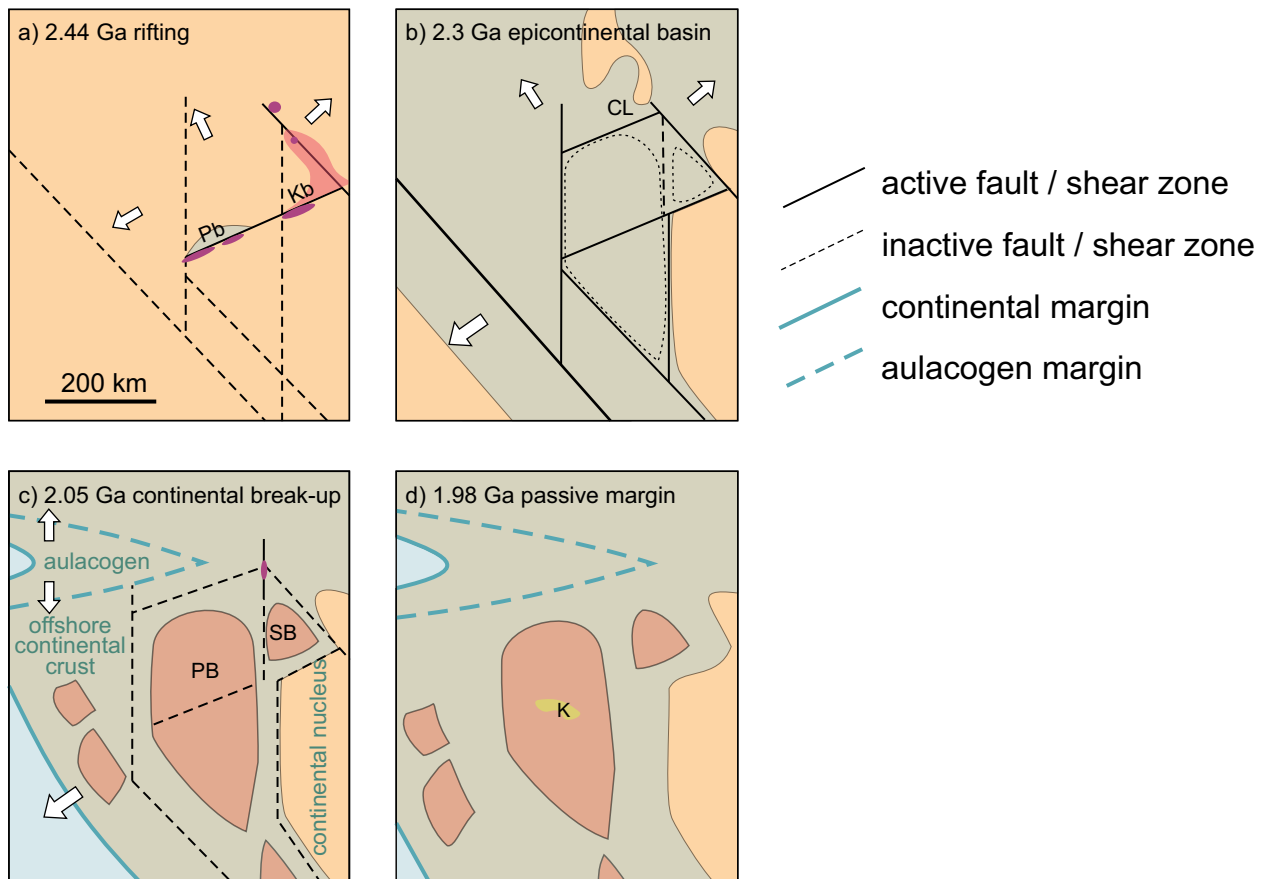
Fig. 22. Stages in the extensional evolution of the Archean crust of northern Finland. Cover sediments are shown by a grayish overlay. Directions of crustal extension are indicated by white arrows. a) Initial rifting with emplacement of mafic layered intrusions (purple) and felsic volcanic rocks (pink), and deposition of earliest sequences in the Peräpohja belt (Pb) and Kuusamo belt (Kb). b) Development of an epicontinental basin, extending to the central Lapland area (CL). Future Pudasjärvi and Suomujärvi blocks are shown by dotted lines. c) Detachment of crustal blocks. The Pudasjärvi block (PB) is a continental ribbon, the Suomujärvi block (SB) is a smaller continental fragment. d) Emplacement of the Korkiavaara arkosic sediments / felsic tuff (K) in a passive margin stage.

craton margin sediments were imbricated with allochthonous (oceanic) volcanic rocks and thrust at 1.93–1.92 Ga towards the east to their present position (Kittilä suite; Figs. 23a, 24a). The southern margin of the sequences was the aulacogen that had developed during continental break-up (Fig. 22c), and further north the sequences were thrust over the Hetta complex. The elevated areas in the cratonic basement, the Hetta complex and the Pomokaira complex (HC and PC; Fig. 24b), were 'rigid units' against the thrust sequences. The sediments of the Uusivirka suite and the Martimo belt were part of the thrust and fold belt, but they were emplaced somewhat later, at 1.92–1.91 Ga; the sediments were emplaced upon the Pudasjärvi block, which was also moving eastwards (Fig. 24b).

Collision between the Lapland–Kola and Karelia lithospheric blocks at ~1.92 Ga led to the development of another foreland fold and thrust belt, with thrusting towards south: low-angle folding and nappe structures extended far south and deformed the Kittilä allochthon (Figs. 23 a–b, 24 a–b). In the core of the Lapland–Kola orogen (Lapland granulite complex), a mountain range started to develop, and metamorphism culminated at 1.91–1.90 Ga. During 1.91–1.88 Ga, the thrust direction gradually changed towards the southeast (Fig. 24c).

Accretional events in the south (Lahtinen et al. 2005, Nironen 2017) caused movement of the Pudasjärvi block, first towards the ENE, against the less attenuated Archean continental nucleus at 1.91 Ga (Fig. 24b), and subsequently towards the north at 1.89–1.88 Ga (Fig. 24c). The crust was detached from the mantle part during movement of the Pudasjärvi block. The Suomujärvi block came into contact with the Pudasjärvi block and rotated.
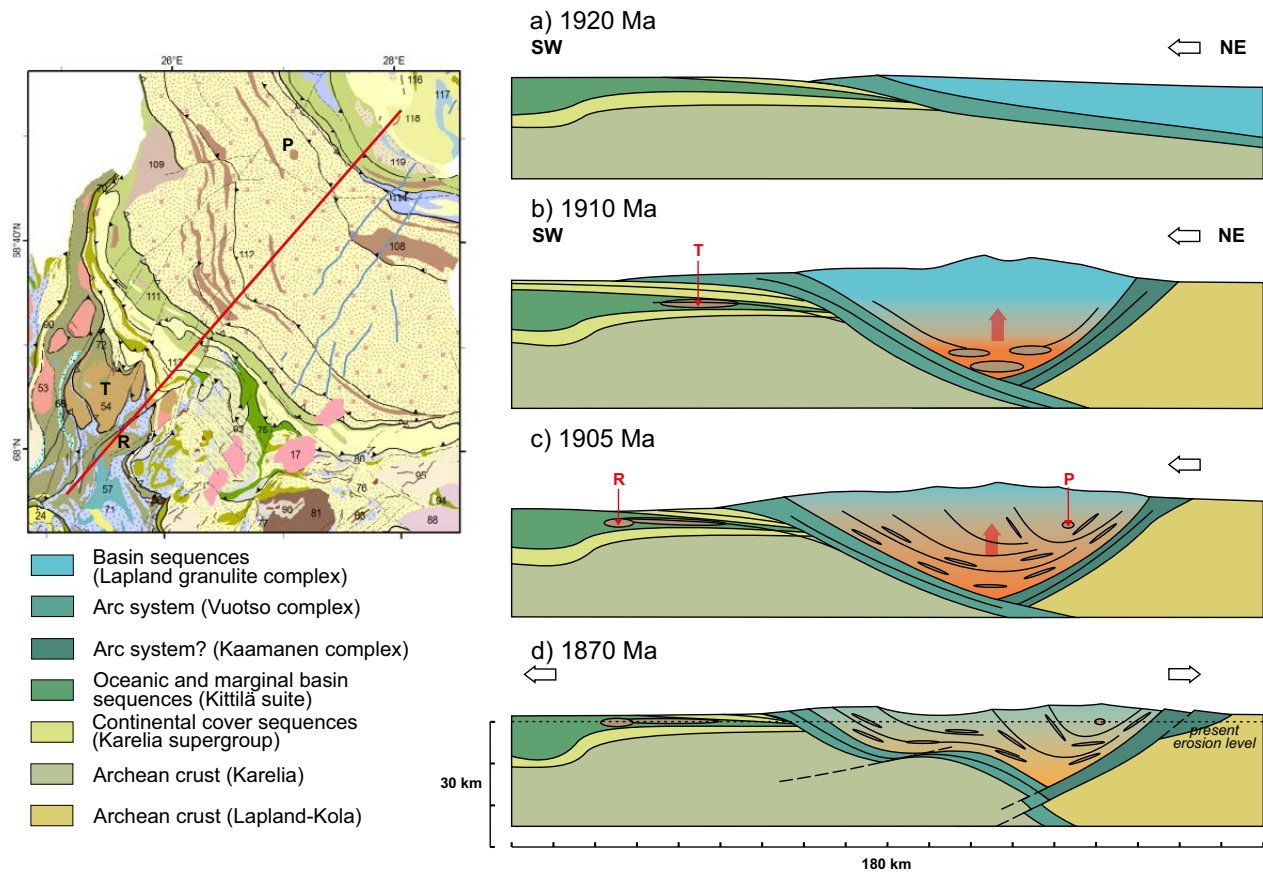
Fig. 23. Model of tectonic evolution in north–central Lapland. Brown ovoids represent enderbitic intrusions. The red overprint denotes heat and the red arrow shows direction of heat transfer. The cross-section at 1870 Ma is based on the FIRE 4A reflection seismic profile (Patison et al. 2006, Fig. 14). The red line in inset indicates the location of the cross-section. White arrows show the direction of tectonic transport. T = Taatsi granodiorite, R = Ruoppapalo granodiorite, P = Pielpajärvi diorite. Emplacement of the intrusions is explained in more detail in Section 4.5.

The craton cover sequences of the Kuusamo belt and central Lapland were intensely deformed, whereas the cover sequences in the Peräpohja belt, within the rigid Pudasjärvi block, remained less deformed. The sequences between the Pudasjärvi block and the elevated Pomokaira complex area also remained relatively undeformed (this area is now characterized by greenschist facies assemblages). Metamorphism culminated in the deep crust during 1.88 Ga. During continued northward push, the crust was thickened in the frontal part of the Pudasjärvi block. Uplifting occurred in the tectonically thickened crust, the rocks which had been metamorphosed and folded in deeper crust were exhumed, and the Kumpu group sediments were accumulated upon the metamorphosed rocks in front of shear zones at 1.88–1.87 Ga. By 1.87 Ga the main stage of deformation in northern Finland was over, and the mountain range in the core of the Lapland–Kola orogen started to collapse (Fig. 23d)..

Areas in westernmost Finnish Lapland, including the Äkäsjokisuu–Aakenustunturi area, were subject to NE-vergent thrusting at 1.86–1.85 Ga (Fig. 24d), as the result of dextral thrusting along a transpressional, N–S trending shear zone (the Pajala shear zone).

Transpression was followed by E–W compression. The upright folding with N–S axial planes, interpreted as D4 deformation in the Peräpohja and Kuusamo belts and found in several localities in central Lapland, is here given an age of ~1.85 Ga. Shear zones in appropriate orientations were reactivated during compression (Fig. 24e).

NW–SE compression, tentatively dated at 1.84–1.83 Ga (Fig. 24f), caused folding in the Suomujärvi complex, thrusting in the Savukoski area, folding in the Central Lapland granitoid complex, and development or reactivation of the Enontekiö shear zone. The connection of E–W compression and following NW–SE compression to plate tectonic configura-

tions is unknown. Late Svecofennian continental collision further south at 1.82–1.80 Ga (Lahtinen et al. 2009) caused deformation of the Kumpu group rocks, and reactivation of existing deformation zones in Lapland, e.g. the Venejoki and Sirkka shear zones (Fig. 24g).

Orogenic collapse in the entire Svecofennian occurred during the period 1.80–1.77 Ga. The tectonically thickened parts of the crust, the Central Lapland granitoid complex and the Suomujärvi complex, became the locus of high grade metamorphism. A detachment zone developed in these areas as the result of horizontal NE–SW extension (Fig. 24h). These areas were uplifted, the peak of uplift was attained at 1.80 Ga, and emplacement the appinitic intrusions is related in time and space to the uplift. The subhorizontal detachment zone is exposed in the present erosional level. Extension progressed into crustal flattening, the NW–SE trending shear zone between the two complexes was reactivated, and the 1.78–1.77 Ga monazite

ages of granitoids in the Suomujärvi complex, and 1.78–1.76 Ga zircon ages of granites (Jumisko and Petäjäselkä), date this reactivation. Normal faulting in the Peräpohja belt (Sihtuuna, Fig. 3) was part of the orogenic collapse. Normal faulting probably also occurred elsewhere in central Lapland.

The youngest structures in central Finnish Lapland are faults in NW–SE direction (Fig. 24i). Some faults deform Nattanen-type granites, with ages of 1.79–1.77 Ga (Heilimo et al. 2009). The character of these faults is unclear: some show (apparent) horizontal displacement, while others appear to be normal faults. Therefore, they may represent different events, i.e. NE–SW extension and transfer faulting that developed during NW–SE extension. Older shear zones in a suitable direction were also reactivated. The age of these deformations is unknown.

The structural evolution, interpreted in previous Sections and modelled in Figure 24, is grouped in Table 1.
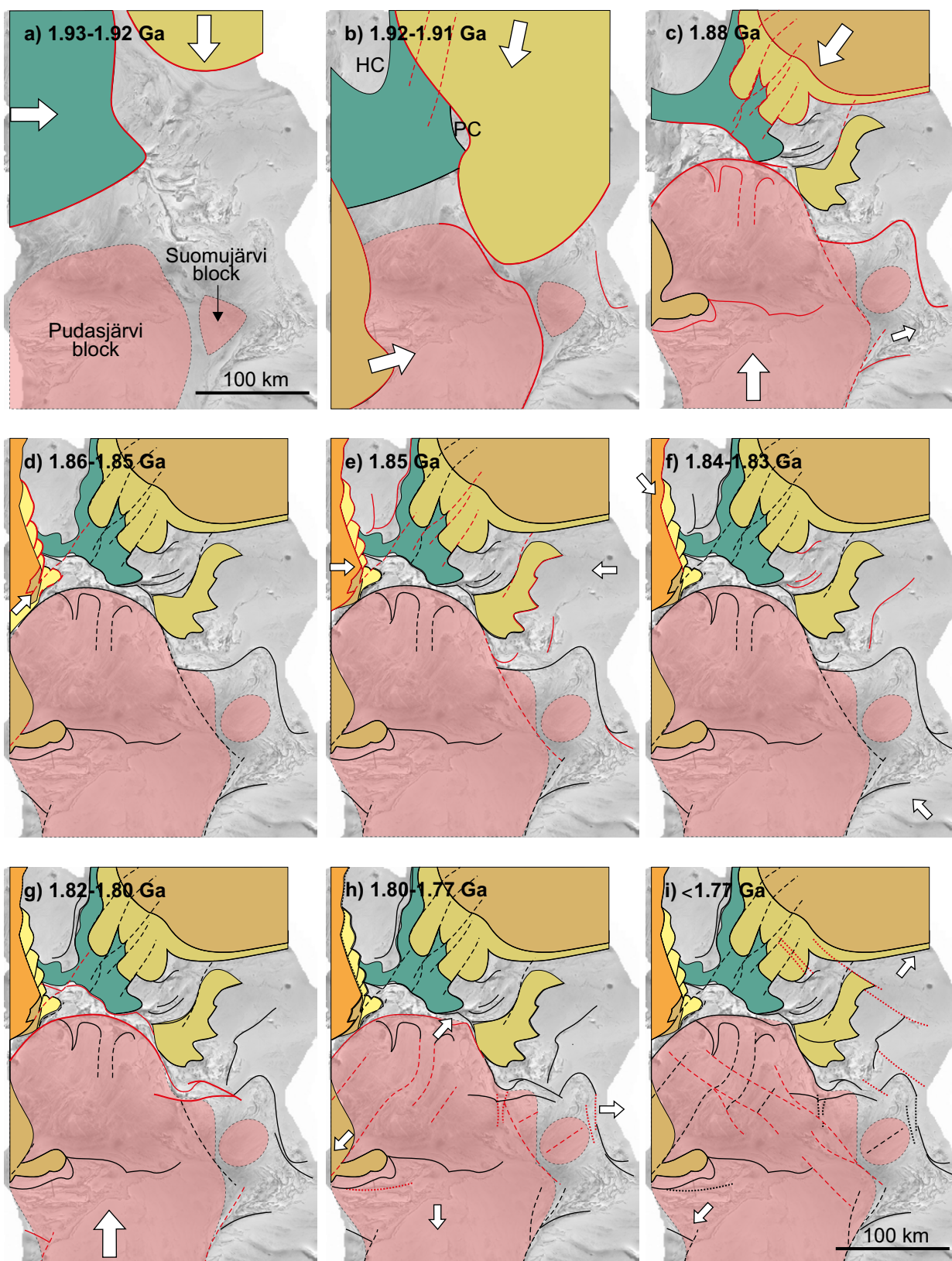
Fig. 24. Model of tectonic evolution in northern Finland (excluding northernmost Finland). Only the allochthonous units are shown. Archean units are shown in red, Paleoproterozoc in blue-green, light brown, yellow and yellow-brown. The large white arrows indicate the direction of tectonic transport, and small arrows the direction of compression/extension. Solid red and black lines are active and passive thrust zones, respectively. Broken red and black lines are active and passive shear zones, respectively. Dotted red and black lines are active and passive normal faults, respectively. HC = Hetta complex, PC = Pomokaira complex. See text for details.

Table 1. Structural evolution in the Peräpohja and Kuusamo belts and in the five domains of central Lapland (CL).

Age (Ga)	Peräpohja	Kuusamo	CL, 1	CL, 2	CL, 3	CL, 4	CL, 5
1.93–1.92	thusting from W		thrusting from W				
1.92–1.91		thrusting from W-SW	thrusting from N	thrusting from N	thrusting from N		
1.90–1.89			E-W compression?	thrusting from NNE	thrusting from NNE		
1.88–1.87	thrusting from S: N-S to NNE-SSE compression	thrusting from S: dextral transpression, N-S compression	thrusting from NE, thrusting from S	thrusting from NE		thrusting from S	thrusting from S
1.86–1.85							thrusting from SW
1.85	E-W compression	E-W compression		E-W compression	E-W compression	E-W compression	thrusting from W
1.84–1.83		NW-SE compression	NW-SE compression		NW-SE compression	NW-SE compression	NW-SE compression?
1.82–1.80					thrusting from S	thrusting from S	thrusting from S
1.80–1.77	N-S extension					NE-SW extension, E-W extension	

6 DISCUSSION

In the last figure of the evolution model (Fig. 24i), most of the major deformation zones in northern Finland, visible in the map 'Geological Map of Finland – Bedrock. 1:1 000 000', are presented. Some of the zones – or areas – require further discussion.

The Pudasjärvi block is here considered to include the rocks of the Vuojärvi and Virttiövaara suites at Vuojärvi and Kelontekemä, respectively. The age of these rocks is still unresolved: zircons from rocks presently included in the Vuojärvi suite are of Neoarchean age, indicating an Archean provenance (Räsänen & Huhma 2001, Lahtinen et al. 2015b). In Finstrati the rocks are considered Neoarchean. At Kelontekemä, the 2.2. Ga Haaskalehto suite gabbroic bodies and dolerite dikes are parallel to steeply dipping to vertical foliation in rocks of the Virttiövaara suite (Fig. 17). This may be explained so that the bodies are (bedding-parallel) sills that were deformed together with the supracrustal rocks. In this case upright folding may be con-

strained between 2.2. Ga and 2.1 Ga because the 2.1 Ga Nilipää granite (probably) crosscuts the foliation. Dating of the Kelontekemä granite (Fig. 17c) would give the definite minimum age for the foliation in the Virttiövaara suite rocks. If deposition is considered Paleoproterozoic, it is difficult to explain the subvertical fabric in the framework of 2.5–1.9 Ga extension. Another possibility is that the Haaskalehto suite rocks were emplaced into already folded supracrustal rocks; in this case, upright folding occurred before 2.2 Ga. At Vuojärvi, the timing of the two earliest folding events remains unresolved. The later upright folding at Vuojärvi, with NNW–SSE compression, cannot be linked with northward movement of the Pudasjärvi block, but could be associated with accretion of the Pudasjärvi block against the Archean continental nucleus at 1.91 Ga.

Hanski and Huhma (2005) pointed out that granulite clasts have not been documented in the Kumpu group rocks, and presented two reasons to explain this: either the sediments were transported

from other directions, and/or the granulites were not yet exposed during sedimentation. In the tectonic model, the sediments of the Kumpu group were deposited at several localities at the margin of the modeled Pudasjärvi block, and the sediments derived mainly from the uplifted frontal part of the Pudasjärvi block, with no contribution from the granulites. Considering that the Kumpu group sediments were deposited on top of metamorphosed rocks, exhumation of the metamorphosed rocks occurred shortly after the northward movement of the Pudasjärvi block had ceased.

In the model, in western Finnish Lapland peak metamorphism at 1.88 Ga was followed by exhumation of the metamorphosed rocks, deposition of the Kumpu group sediments upon the metamorphosed and folded rocks, lithification of the sediments, and folding of the lithified sediments (sedimentary rocks) before NE-vergent thrusting at 1.86−1.85 Ga. This interpretation gives an explanation for the Lainio group as different from Kumpu group (Lehtonen et al. 1998): the sediments were deposited contemporaneously, but only the Lainio group rocks were subject to thrusting at 1.86−1.85 Ga. The fold pattern, with steep foliation in the Kumpu group rocks (at Aakenustunturi), remains unexplained by a plain thrusting event.

According to the interperetation of deformation events in western Finnish Lapland, E−W compression occurred after NE-vergent thrusting. The proposed 1.85 Ga time for E−W compression is similar in age and orientation to the compression that resulted in F4 folding in southwestern Finland (Nironen 1999). Assuming that such a correlation is reasonable, such a large-scale E−W compression has no link to any modeled plate tectonic event.

The late Svecofennian evolution in the Central Lapland granitoid complex was a major thermal event but the fragmental knowledge of ages of deformation and magmatism makes modeling of this evolution difficult. Reflection seismic studies (Patison et al. 2006) suggest that although crustal stacking occurred in the area of the CFGC, the crust in the CLGC area is still thicker than in adjacent areas; hence uplift and exhumation of the modeled detachment zone is possible. An attempt to explain uplift of the CLGC and the Suomujärvi complex during the late metamorphic event is the modelled aulacogen: the Pudasjärvi block moved upon the thinned crust, the crust was tectonically thickened, and the area became the locus of voluminous granite and minor mafic magmatism tens of millions of years after tectonic thickening. A somewhat similar evolution was presented by Lahtinen et al. (2005) for the Late Svecofennian granite zone in southern Finland.

The association of mineral deposits with structures was barely touched in this study. The structural control of two important mineral deposit types in central Lapland, Ni-Cu-PGE and gold, are discussed here. The Kevitsa and Sakatti Ni-Cu-PGE deposits are located at the margins of the greenschist facies area, charcterized by thrusts (Fig. 25). The funnel-shaped Kevitsa mafic layered intrusion, with a 2058 ± 4 Ma age, is relatively undeformed except for NE-trending faults (Hanski & Huhma 2005 and references therein, Santaguida et al. 2015). The host rock of the Sakatti deposit is probably an ultramafic intrusive body within volcanic rocks of the Savukoski group; the host rocks are relatively weakly deformed but the deposit has been split into several bodies during thrusting from the north (Brownscombe et al. 2015, AngloAmerican 2017). The Lomalampi PGE-Ni-Cu deposit is hosted by a komatiitic cumulate body within volcanic rocks of the Savukoski group (Konnunaho et al. 2015); there is no information of structures around the deposit except that a NE-trending shear zone, inferred as a thrust with vergence to the SE, exists 2 km NW of the deposit. Since the ultramafic magmas derive from the mantle (e.g. Hanski & Huhma 2005), the most important structural controls for the Ni-Cu-PGE deposits are the conduits along which the magmas rose through the crust. The three deposits may have been emplaced at 2.06 Ga along an approximately N-S trending, Archean crustal-scale shear zone, as modelled in Figure 22c; the Kevitsa and Lomalampi deposits were offset during thrusting at 1.92−1.91 Ga and/or 1.84−1.83 Ga (Figs. 24 b, f), whereas the Sakatti deposit remained almost intact.

Most of the gold occurrences in central Lapland area of the orogenic gold type, are structurally controlled, and are confined to the area of greenschist facies metamorphism (Fig. 25; Eilu 2015). Many of the gold deposits are located at or close to the Sirkka shear zone, with a complex and prolonged deformation history. As shown by the works of Patison (2007) and Saalmann and Niiranen (2010), the shear zones controlling the deposits have been reactivated during several deformation events. Thus, the age of gold mineralization spans from 1.92−1.91 Ga (Suurikuusikko) to late Svecofennian (1.84 − 1.77 Ga). In the model, the Kiistala shear zone, hosting the Suurikuusikko deposit, formed as a transfer
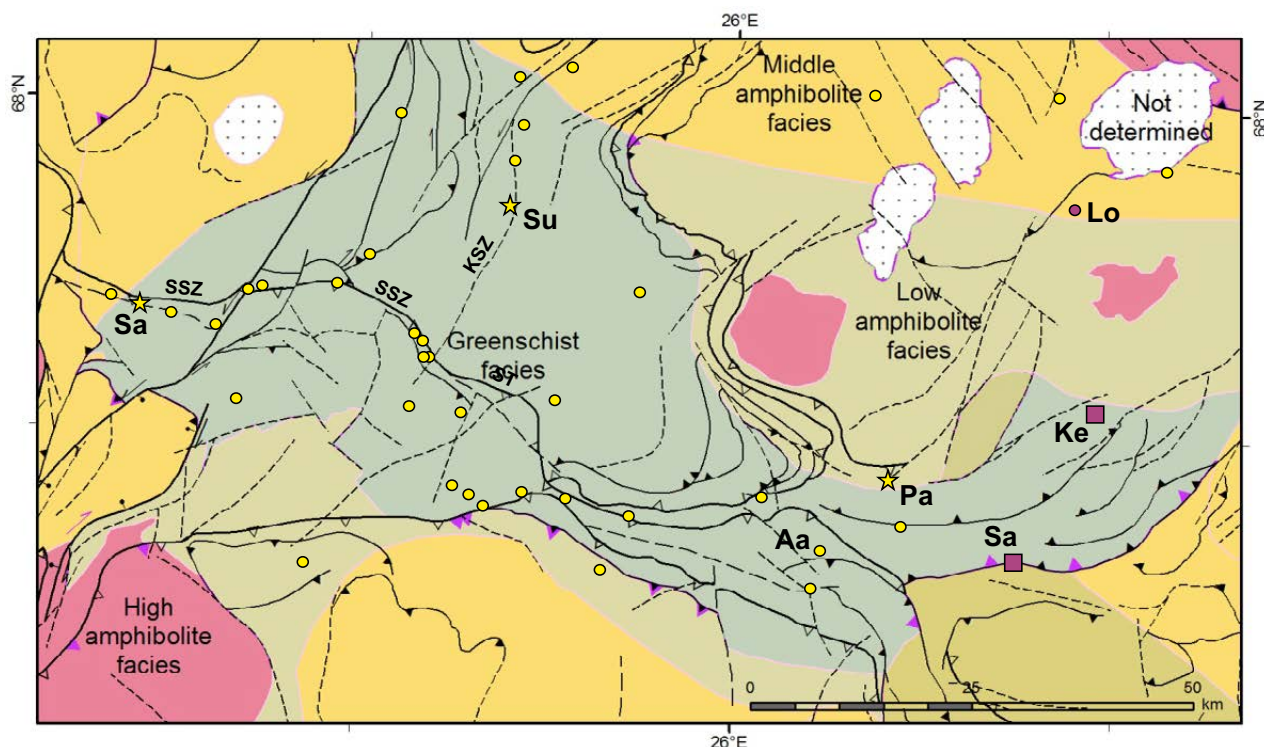
Fig. 25. Gold and Ni–Cu–PGE deposits in central Lapland, shown on the metamorphic map. Mines and larger deposits are marked by yellow stars (gold) and purple squares (Ni–Cu–PGE), occurrences by circles. Su = Suurikuusikko (active mine), Sa = Saattopora (closed mine), Pahtavaara (closed mine), Aa = Aamurusko (under exploration), Ke = Kevitsa (active mine), Sa = Sakatti (under exploration), Lo = Lomalampi (under exploration). SSZ = Sirkka shear zone, KSZ = Kiistala shear zone. Deposits are from GTK mineral deposit database, structural lines are from bedrock database (1:1 000 000).

zone during thrusting from the N–NNE (Fig. 24b). The Sirkka shear zone formed at 1.88 Ga, during thrusting from the S (Fig. 24c), but gold mineralization occurred during late Svecofennian reactivation of the older shear zones (Fig. 24g).

A new type of gold occurrence (the Aamurusko gold discovery; Fig. 25), with high-grade gold in quartz veins, was recently found in the Kumpu group conglomerates of the Kaarestunturi formation (Basha 2017). The occurrence was modeled by the deposition of the Kumpu sediments in a pull-apart basin, and gold mineralization during inversion of the basin. In the present model, the sediments were deposited in front of an uplifted early Svecofennian thrust zone (Fig. 24c) at 1.88–1.87 Ga, and the rocks were deformed and gold mineralization occurred during the late Svecofennian thrusting event at 1.82–1.80 Ga (Fig. 24g). With the Aamurusko gold discovery as an example, the structural interpretations given here will hopefully bring new ideas to mineral exploration in northern Finland.

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Structural evolution in the Peräpohja and Kuusamo belts and the Central Lapland area was interpreted, based on existing literature, aerogeophysical maps, and the GTK bedrock database. Central Lapland, the largest and economically most interesting of the areas, was divided into five domains. Based on independent interpretations of each belt and domain, a model is presented for the tectonic evolution in northern Finland. The development of gold and Ni-Cu-PGE deposits, presently active in northern Finland, is discussed in the framework of the model.