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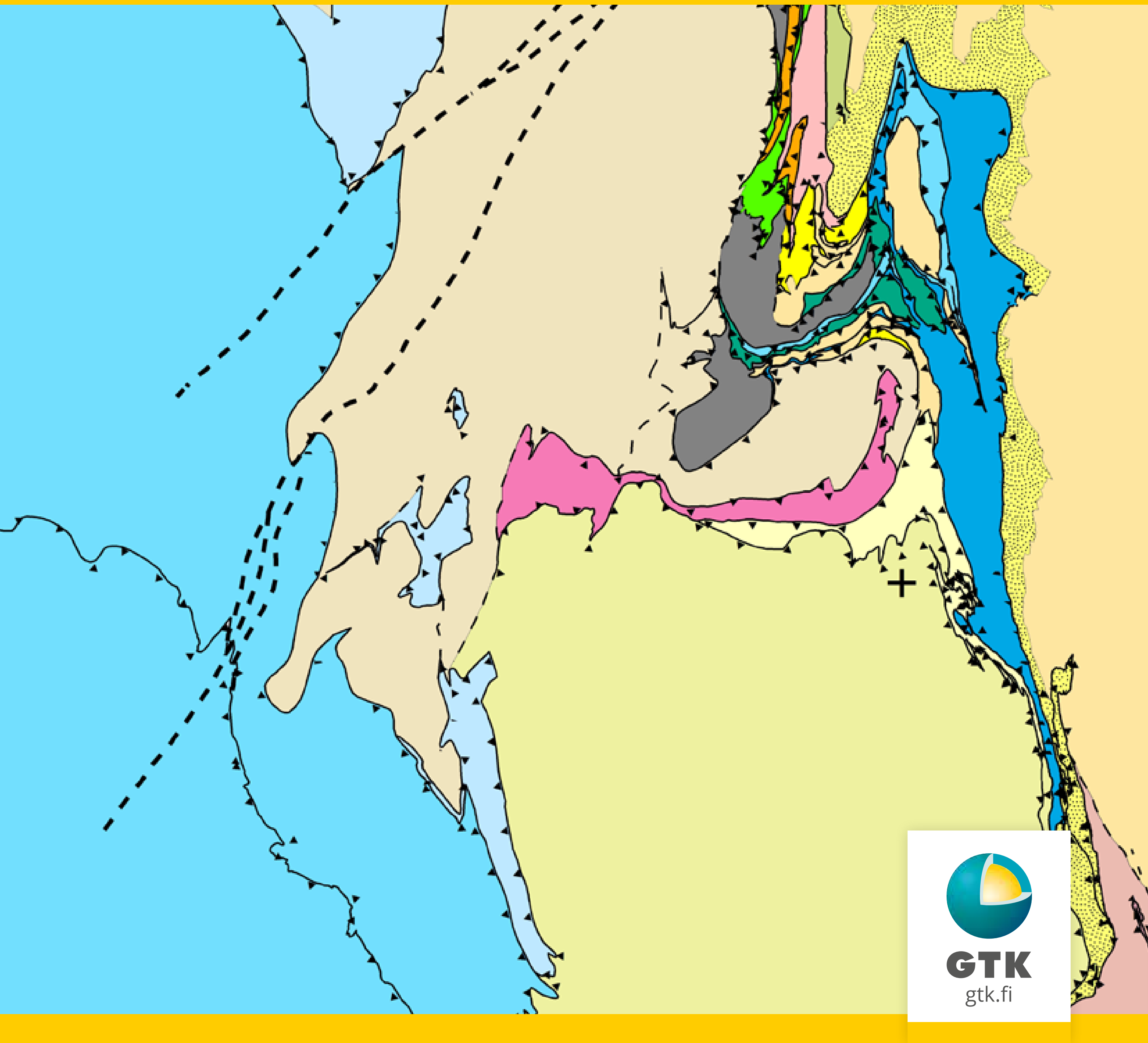
Bedrock of Finland at the scale 1:1 000 000 – Major stratigraphic units, metamorphism and tectonic evolution

Mikko Nironen

Special Paper 60



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Geological Survey of Finland, Special Paper 60

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Edited by
Mikko Nironen

Geological Survey of Finland
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Front cover: A tectonostratigraphic interpretation of bedrock in middle Finland.
Compiled by Jouni Luukas, GTK.

Unless otherwise indicated, the figures have been prepared by the authors of the articles.

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The bedrock of Finland was systematically mapped over 100 years by the Geological Survey of Finland (GTK). The mapping programme was finished in 2005, and bedrock mapping at GTK moved from printed maps to numerical databases. The bedrock map data are now collected into a bedrock map database and unit database (Finstrati), compatible with the international standards. The stratigraphic classification into lithostratigraphic and lithodemic units is now the fundamental basis for bedrock mapping, and encompasses for the first time entire Finland. In the first paper of this volume, '**Major stratigraphic units in the bedrock of Finland, and an approach to tectonostratigraphic division**', the major stratigraphic and lithodemic units in Finland are described with restriction into supergroups, supersuites, and complexes. Moreover, the tectonostratigraphic division of northern and eastern Finland is outlined.

In the second paper '**Guide to the Geological Map of Finland – Bedrock 1:1 000 000'**, the fundamental concept of tectonic province is described. The Guide is an explanation to the legend of the Geological Map of Finland – Bedrock 1:1 000 000. The legend is based on tectonic province division, and the tectonic provinces Karelia, Lapland–Kola, Norrbotten and Svecofennia, as well as their province boundaries, are described. Based on existing publications and evolution models therein, the tectonic evolution of the bedrock of Finland (and Fennoscandia), from the Neoarchaean to the Cenozoic, is modelled.

In the third paper '**Metamorphic map of Finland'**, the basis of the observed metamorphic features of the bedrock and the principles of the map are first explained. Map layers are presented for peak metamorphic grade, for metamorphic facies, and for peak and post-peak pressure and temperature conditions, based on PT pseudosections. Neoarchaean metamorphism in Archaean rocks of the Karelia Province mainly occurred in amphibolite and granulite facies with pressures varying from 6–7 kbar to 10 kbar. The Archaean metamorphism was overprinted by Proterozoic metamorphism, varying from local rehydration in shear zones to pervasive overprint up to tens of kilometres in width. The Palaeoproterozoic cover sequences of the Karelia Province show low- to medium-pressure metamorphism. Most of the Svecofennia Province was metamorphosed in upper amphibolite and granulite facies at low pressures of around 4–6 kbar. Small areas of low- to mid-amphibolite facies metamorphism commonly have tectonic boundaries with the surrounding higher-grade metamorphic areas, but for example in western Finland prograde metamorphism increases gradually towards the Vaasa complex.

Keywords: data bases, stratigraphic, units, tectonostratigraphic units, tectonic, units, tectonics, orogenic belts, accretion, plate collision, metamorphism, Svecofennian Orogeny, Archean, Paleoproterozoic, Proterozoic, Phanerozoic, Finland, Fennoscandian Shield.

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CONTENTS

Bedrock of Finland at the scale 1:1 000 000 – Major stratigraphic units, metamorphism and tectonic evolution
Edited by Mikko Nironen
Geological Survey of Finland, Special Paper 60, 7–8, 2017

EDITOR'S PREFACE

Systematic geological bedrock mapping based on different map sheet partitions was carried out by the Geological Survey of Finland (GTK) for more than 100 years. Mapping at the scale 1:400 000 started in the late 1800s; the first map was published in 1900 and the last one in 1980. The land coverage of this programme was 100%. Bedrock mapping at 1:100 000 scale started in the late 1940s from southern Finland. The maps were lithological, including rock types and associations, but in the late 1900s and early 2000s they also contained stratigraphic and structural information. After about 200 sheets of 1:100 000 scale bedrock maps with 57% land coverage, the mapping programme was finished in 2005. Besides this programme, several maps were published at the scale 1:1 000 000 (1:1M), the latest one in 1997.

The need to achieve a uniform presentation of the bedrock of Finland led to the initiation of a digital bedrock map database project called DigiKP in 2006. At the beginning of the DigiKP project, the database structure was based on traditional lithological mapping, because the majority of the source data (mainly bedrock maps at the scale 1:100 000) were lithological maps. In 2007, the original 1:200 000 scale was changed to a seamless map database without any specific scale. A non-spatial database of stratigraphic geological units was developed during the DigiKP project, with the co-operation of the Stratigraphic Commission of Finland. The stratigraphic units are now stored into the GTK database (Finstrati), and the major stratigraphic units are presented here (Luukas et al.).

A project for compilation of a new database and bedrock map in the scale 1:1M initiated also in 2006. Originally, the aim was to produce several 'themes' including lithology, structure, stratigraphy, age, metamorphism, metallogeny, major tectonic units, and geological areas. Almost all of these data exist at present; the 'themes' are now digital maps and map databases. Structural and metamorphic data exist as separate databases, and the explanation to the metamorphic map, covering for the first time whole Finland, is presented here (Hölttä & Heilimo).

A new, printed bedrock geological map was one aim of the 1:1M project, and was published in 2016 with the title Geological Map of Finland – Bedrock 1:1 000 000. Implementing of the stratigraphic units into the 1:1M database proved to be difficult because of differences in unit scales, and therefore the bedrock data was divided into rock associations that have no direct link to unit stratigraphy. The 119 rock associations, shown in the legend of the printed map, are linked to international stratigraphic chart that provides crude age limits to each association. The map also includes major tectonic units as tectonic provinces. A guide to the printed map, and the tectonic evolution model behind the legend, are presented here (Nironen).

Compilation of new databases and maps are the result of a joint GTK work. As responsible of the 1:1M Bedrock map I want to thank all the colleagues in the GTK regional offices for comments on earlier versions of the map. I am especially grateful to Jukka Kousa, Jouni Luukas and Jukka Eskelinen for co-operation in processing the map data, and Anneli Lindh for compiling the printed map. The technical editor of this volume was Kristina Karvonen. Roy Siddall checked the English language.

Espoo, 7 March 2017

Mikko Nironen
Editor of this Special Paper volume

Bedrock of Finland at the scale 1:1 000 000 – Major stratigraphic units, metamorphism and tectonic evolution
Edited by Mikko Nironen
Geological Survey of Finland, Special Paper 60, 9–40, 2017

MAJOR STRATIGRAPHIC UNITS IN THE BEDROCK OF FINLAND, AND AN APPROACH TO TECTONOSTRATIGRAPHIC DIVISION

by

Jouni Luukas[1], Jukka Kousa[1], Mikko Nironen[2] and Jouni Vuollo[3]

Luukas, J., Kousa, J., Nironen, M & Vuollo, J. 2017. Major stratigraphic units in the bedrock of Finland, and an approach to tectonostratigraphic division. *Geological Survey of Finland, Special Paper 60, 9–40, 9 figures, 1 table and 1 appendix.*

The bedrock of Finland was systematically mapped over 100 years by the Geological Survey of Finland (GTK). The printed maps were lithological maps at the scales 1:400 000 and 1:100 000. The mapping programme was finished in 2005, and bedrock mapping at GTK moved from printed maps to numerical databases. Nowadays, the bedrock map data are collected into a seamless bedrock map database and non-spatial unit database (Finstrati). These databases are based on international vocabularies and are compatible with the international standards, and the naming of geological units follows the accepted guidelines and international stratigraphic codes recognized by the Stratigraphic Commission of Finland. The stratigraphic classification into lithostratigraphic and lithodemic units is now the fundamental basis for bedrock mapping. The major stratigraphic and lithodemic units in Finland according to the Finstrati database are described with restriction into supergroups, supersuites and complexes within four defined tectonic provinces, i.e. Karelia, Svecofennia, Lapland-Kola and Norrbotten. Moreover, the tectonostratigraphic division of northern and eastern Finland is outlined by defining nappe systems and complexes.

Keywords: bedrock, data bases, stratigraphy, stratigraphic units, tectonostratiraphic units, Finland

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BACKGROUND

Systematic geological bedrock mapping was carried out by the Geological Survey of Finland (GTK) for more than 100 years. The bedrock maps at the scale 1:100 000, published in the 1900s by the Geological Survey of Finland (GTK), were lithological, including rock types and associations, but in the 1990s and early 2000s they also contained stratigraphic and structural information. The 1:100 000 scale bedrock mapping programme was finished in 2005 and replaced by mapping at 1:200 000 scale in limited areas.

In the first years of the new millennium, the need to achieve a uniform presentation of the bedrock of Finland led to the implementation of a digital bedrock map database project called DigiKP, the aim of which was to produce a uniform seamless vector bedrock map at the scale 1:200 000. The DigiKP project was active in 2006–2009. One of the reasons for this need was the growing interest in and importance of international cooperation. The year 2005 was the starting point for the global activity coordinated by IUGS (International Union of Geological Sciences)/CGI working group (Commission for the Management and Application of Geoscience Information) (Vuollo et al. 2011).

At the beginning of the DigiKP project, the database structure was based on traditional lithological mapping, because the majority of the source data (mainly 1:100 000 scale bedrock maps) were lithological maps. In 2007, the database structure was replaced with a new unit-based approach. The new data model is based on the NADM-C1 (North American Data Model Steering Committee 2004) definition and supplemented according to national needs. The original plan for centralized storage based on an ESRI Geodatabase data structure (Oracle/ArcSDE platform) has also been revised, and the databases are now divided into spatial (Oracle/ArcSDE) and non-spatial parts (Finstrati, the geological unit register with attribute data in relational databases) (Vuollo et al. 2011). At the same time, the original 1:200 000 scale was changed to a seamless map database without any specific scale. The 1:200 000 and 1:1 000 000 scale products are based on this primary map database.

A non-spatial database of stratigraphic geological units (Finstrati) was developed during the DigiKP project. In the construction stage of bedrock map database, the whole Finnish bedrock was divided into stratigraphic units that had already been in use in northern Finland. Almost 2400 lithostratigraphic or lithodemic units were generated and described during the project. The nomenclature was generated according to international rules (North American Commission on Stratigraphic Nomenclature, 2005) and with the co-operation of the Stratigraphic Commission of Finland (SCF). The role of the SCF is to provide guidance for stratigraphic procedure, terminology and revision of geological units in Finland (Strand et al. 2010). The first classifications of the bedrock into lithostratigraphic and lithodemic units were carried out in rather small areas in central Finland (Laajoki & Luukas 1988, Laajoki et al. 1989, Laajoki 1991). This method was adopted in bedrock mapping in northern Finland during the 1990s (Lehtonen et al. 1998).

The Finstrati unit classification follows either the lithostratigraphic or lithodemic classification. The preliminary tectonostratigraphy presented at the end of this paper is based on the tectonostratigraphic classification (Fig. 1). Period and epoch division follows the classification described in Table 1.

In the future, Finstrati will be maintained by GTK in collaboration with the Precambrian

Lithostratigraphic units	Lithodemic units		Tectonostratigraphic units
Supergroup	Supersuite	Complex	Nappe system
Group	Suite		Nappe complex
Formation	Lithodeme		Nappe
Member	Phase		Thrust sheet

Fig. 1. Stratigraphic classification used in the database for Precambrian geological units in Finland (Finstrati).

Table 1. Division of Neoarchaean and Palaeoproterozoic periods and epochs, applied from the Finstrati database.

Eon	Era	Period	Epoch	Age Ma from	Age Ma to
Proterozoic	Neoproterozoic	Ediacaran		635	542
		Cryogenian		850	635
		Tonian	Tonian 2	910	850
			Tonian 1	1000	910
	Mesoproterozoic	Stenian	Stenian 2	1130	1000
			Stenian 1	1200	1130
		Ectasian	Ectasian 4	1250	1200
			Ectasian 3	1280	1250
			Ectasian 2	1350	1280
			Ectasian 1	1400	1350
		Calymmian	Calymmian 5	1440	1400
			Calymmian 4	1470	1440
			Calymmian 3	1520	1470
			Calymmian 2	1590	1520
			Calymmian 1	1600	1590
	Paleoproterozoic	Statherian	Statherian 4	1660	1600
			Statherian 3	1740	1660
			Statherian 2	1770	1740
			Statherian 1	1800	1770
		Orosirian	Orosirian 7	1820	1800
			Orosirian 6	1840	1820
			Orosirian 5	1870	1840
			Orosirian 4	1880	1870
			Orosirian 3	1910	1880
			Orosirian 2	1960	1910
			Orosirian 1	2050	1960
		Rhyacian	Rhyacian 2	2060	2050
			Rhyacian 1	2300	2060
		Siderian	Siderian 2	2400	2300
			Siderian 1	2500	2400
Archean	Neoarchean		Neoarchean 2	2650	2500
			Neoarchean 1	2800	2650
	Mesoarchean			3200	2800

sub-commission of the SCF. The database now records information on all stratigraphic units of bedrock in Finland and their usage in the literature, making it a centralized reference point for all stratigraphic unit information on Finnish bedrock.

DIVISION INTO MAJOR LITHOSTRATIGRAPHIC AND LITHODEMIC UNITS

The following division is based on the identification of the major lithospheric blocks, i.e. tectonic provinces of Karelia, Lapland-Kola, Norrbotten and Svecofennia (Fig. 2; see Nironen, this volume). In this text, supergroups, supersuites and complexes are defined; descriptions of minor units can be found in data services linked to Finstrati. The main Finstrati division is shown in the appendix. The subdivision of Precambrian periods into epochs follows the international convention (Table 1: Orosirian 1, Orosirian 2, etc.). This chronostratigraphic classification is presented chronometrically by using absolute ages, i.e. each eon, era, period and epoch is defined by an arbitrary numerical age. The unit with age at a period or epoch boundary is considered to be part of the younger period/epoch.

Most of the new units were defined for the bedrock of southern Finland, and because of the limited

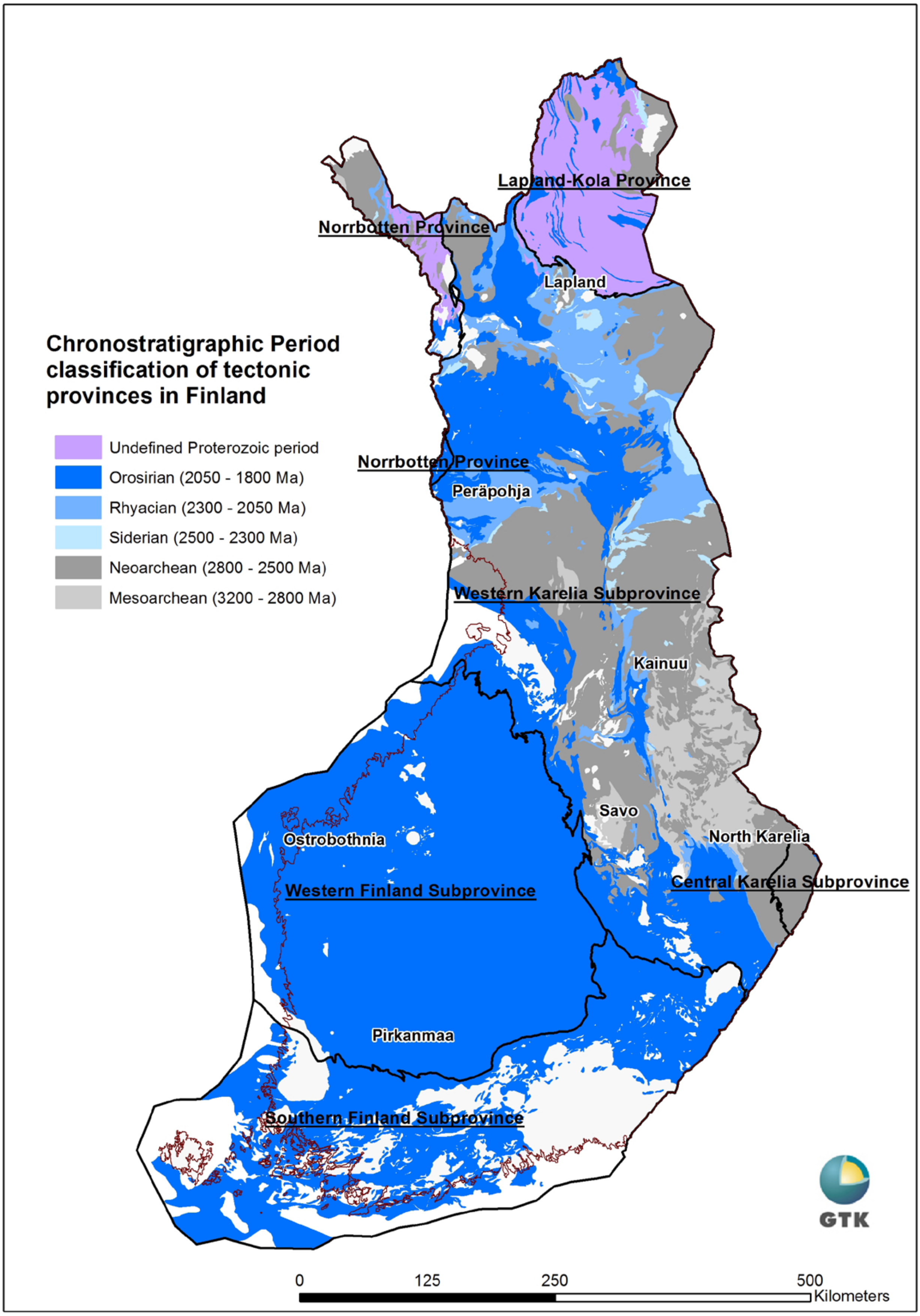

Fig. 2. Chronostratigraphic Period classification of bedrock and tectonic provinces in Finland according to Finstrati. The Karelia Province consists of the Central Karelia and the Western Karelia Subprovinces, and the Svecofennia Province is divided into the Western and Southern Finland Subprovinces. The white areas denote units that were emplaced or deposited after the assembly of the provinces (see Fig. 7).

time frame, the division in this area should be considered preliminary. We have added remarks on poorly constrained parts of the division.

The crude chronostratigraphic classification of the bedrock is presented in Figure 2. The map displays the ages of exposed rocks, and the province boundaries are shown. The Karelia Province contains large areas of Archaean bedrock partly overlain by Palaeoproterozoic rocks, whereas the Svecofennia Province is devoid of Archaean rocks.

Karelia Province

Slabunov et al. (2006) divided the Finnish part of the Karelian craton into several terranes, including the Central Karelian terrane, characterized by a short Neoarchaean crustal growth period. Hölttä et al. (2008) subdivided the 'Karelian Province' into the Western Karelian, Central Karelian and Vodlozero terranes. Hölttä et al. (2012) renamed the province as Karelia, with subdivision into the Western Karelia and Central Karelia Subprovinces. The major part of the Karelia Province in Finland belongs to the former, while the southeasternmost part is part of the Central Karelia Subprovince. The Karelia Province mainly consists of Archaean basement and Palaeoproterozoic supracrustal rocks of the Karelia supergroup.

Archaean units

Archaean lithostratigraphic units

A proper lithostratigraphic division of the supracrustal rocks in the Western Karelia Subprovince was performed in the Kuhmo greenstone belt (Fig. 3), where the Mesoarchaean groups Luoma, Suomussalmi, Ruokojärvi, Kuhmo and Tipasjärvi form the Kianta supergroup in the Finstrati classification (see Appendix). According to the present age data, the lowermost units are Mesoarchaean and the upper ones Neoarchaean. A variety of names have been given to the greenstone belts, such as the Kuhmo greenstone belt (Sorjonen-Ward & Luukkonen 2005), Tipasjärvi–Kuhmo–Suomussalmi Greenstone Complex (Papunen et al. 2009), and Suomussalmi and Kuhmo–Tipasjärvi belts (Huhma et al. 2012). Descriptions of the groups are found in these papers.

Three other Neoarchaean units, named as the Central Puolanka, Oijärvi and Kovero groups, are situated within the Western Karelia Subprovince. These groups lack the upper rank and are presented under the title 'Defined Neoarchean groups' in Finstrati. The Central Puolanka group was properly described by Laajoki (1991). The Kovero group consists of several formations that were described by Tuukki (1991), but the stratigraphic order of the formations is unknown. A short description of the Oijärvi group exists (Sorjonen-Ward & Luukkonen 2005), but knowledge of the stratigraphy is lacking.

In addition, the Central Karelia Subprovince includes the Hattu and Ilaja groups. A description of the two groups can be found, e.g., in Sorjonen-Ward (1993) and Sorjonen-Ward and Luukkonen (2005).

Archaean lithodemic units

The poorly defined supracrustal rocks rimming the eastern and northern border zone of the Central Lapland granitoid complex (Fig. 3) are defined in Finstrati as the Neoarchaean Central Lapland supersuite. This supracrustal belt was earlier known as the Vuojärvi group. It consists of the suites Vuojärvi, Pittiövaara, Karhulehto, Juppuravaara, Virttiövaara, Haisujupukka, Kaukonen, Posio and Heraselkä. The main lithologies are metasedimentary (sericite quartzites, biotite paragneisses and fuchsite quartzites), but some are metavolcanic (Karhulehto and Kaukonen). The suites are poorly defined and the age of the Vuojärvi suite straddles between Neoarchaean and Siderian 1 (see Lahtinen et al. 2015a). The supersuite could be correlative to the Neoarchaean Central Puolanka group. Overall, the supersuite needs revision and proper definition.

Some intrusive suites in eastern Finland have been classified under the title 'Diverse Neoarchean suites and lithodemes' because they do not have a common higher rank unit. Such units are the tonalitic-enderbitic Jonsa suite (2.7 Ga), granitic-granodioritic Konivaara suite (2.7–2.69 Ga), Siilinjärvi suite and Koitere suite. The last one was properly defined by Heilimo et al. (2010) as a specific sanukitoid suite. The poorly defined supracrustal Tuntsa suite in eastern Lapland, which does not belong to any local complex, is included in this diverse suites rank.

Archaean complexes

Hölttä et al. (2012) divided the Western Karelia Subprovince into eight complexes: the Mesoarchaean Siurua, Iisalmi and Lentua complexes, which include

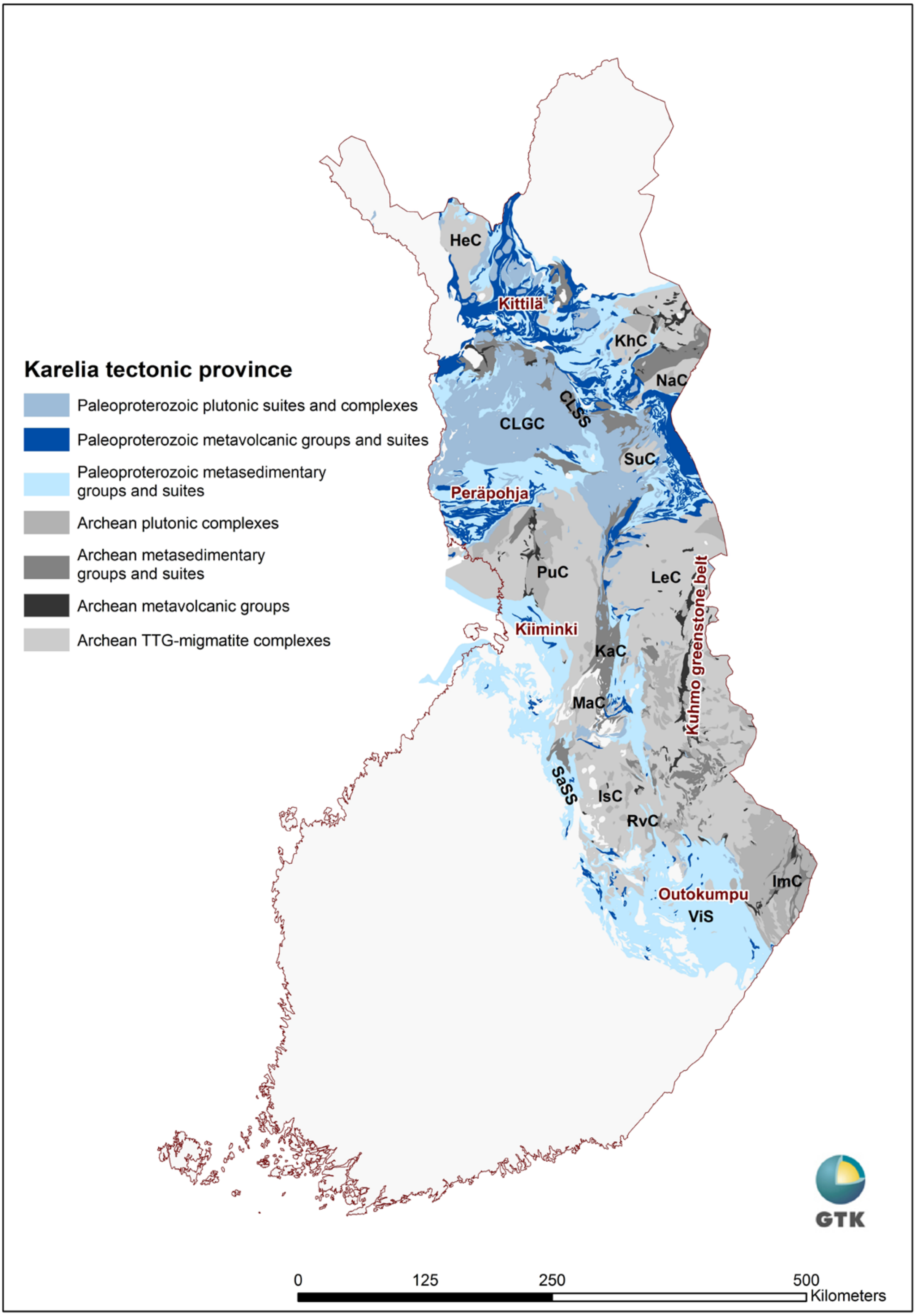

Fig. 3. Main units of the Karelia Province according to Finstrati. CLGC = Central Lapland granitoid complex, HeC = Hetta complex, KhC = Kemihaara complex, NaC = Naruska complex, SuC = Suomujärvi complex, PuC = Pudasjärvi complex, KaC = Kalpio complex, MaC = Manamansalo complex, LeC = Lentua complex, IsC = Iisalmi complex, RvC = Rautavaara complex, ImC = Ilomantsi complex, CLSS = Central Lapland supersuite, SaSS = Savo supersuite and ViS = Viinijärvi suite.

Mesoarchaean rocks, and the Neoarchaean Kuopio, Rautavaara, Manamansalo, Kalpio and Ranua complexes. The Central Karelia Subprovince, mainly occurring in northwestern Russia, extends to Finland as the Neoarchaean Ilomantsi complex. This division roughly follows the one presented by Sorjonen-Ward and Luukkonen (2005).

The Archaean complexes in the Western Karelia Subprovince are divided in Finstrati into two Mesoarchaean complexes (Siurua and Iisalmi complexes) and fifteen Neoarchaean complexes. The Lentua complex, recently described by Mikkola (2008) and Mikkola et al. (2013), covers the major part of eastern Finland. The Ranua complex was renamed in Finstrati as the Pudasjärvi complex, surrounding the Mesoarchaean Siurua complex. The Manamansalo, Kalpio and Kalhamajärvi complexes in Kainuu are characterized by intense Palaeoproterozoic reworking. Similarly, the Rautavaara complex and the southwestern most part of the Lentua complex are reworked by Palaeoproterozoic shear zones. The minor Kuopio, Joensuu and Tahvinmäki complexes represent antiformal domes of the Archaean basement covered by Palaeoproterozoic supracrustal rocks.

In northern Finland, the Kemihaara and Naruska granitoid complexes and the Suomujärvi and Hetta complexes are the most important Neoarchaean complexes. Basic descriptions of the complexes are found in Sorjonen-Ward and Luukkonen (2005). The minor Pomovaara and Porttikoski complexes are antiformal domes covered by Palaeoproterozoic supracrustal rocks. All Archaean complexes in northern Finland are poorly studied and lack proper definition.

In Finstrati, all Archaean complexes are divided into suites and lithodemes. In most cases, these units are poorly studied and the proportion of the Mesoarchaean and Neoarchaean rocks is difficult to define. The amount of Palaeoproterozoic intrusive rocks in the Archaean complexes is also in many cases poorly known. For this reason, in the hierarchical Finstrati classification, they are mostly classified as undefined units. Proper definition is only found from the Lentua complex, which consists of several defined suites and lithodemes.

The Neoarchaean Ilomantsi complex in the Central Karelia Subprovince consists of well defined (Sorjonen-Ward 1993) Silvevaara, Kuittila and Naarva intrusive suites, together with other, poorly defined suites.

Palaeoproterozoic units

Palaeoproterozoic lithostratigraphic units

The cover sequences deposited upon the Archaean basement have traditionally been named as Karelian formations, divided into Sumi (Sumian), Sariola (Sariolian), Jatuli (Jatulian) and Kaleva (Kalevian) groups or superhorizons (e.g. Simonen 1980, Hanski & Melezhik 2013). The terms 'tectofacies' and 'system' have been introduced for these old names by Laajoki (2005) and Hanski and Melezhik (2013), respectively. In general, the groups/tectofacies/systems mark a change in the depositional environment from intracontinental rifting to continental break-up. The old terms Sumi (oldest), Sariola, Jatuli and Kaleva (youngest) are considered as informal chronostratigraphic names that can be used as additional attributes. The division in Finstrati is based on decreasing epoch ages.

The rocks of the Lapland greenstone belt and underlying sedimentary rocks have traditionally been named as Lapponian schists (see Lehtonen et al. 1998 for references). Silvennoinen (1985) defined the Lapponia Supergroup, consisting of Neoarchaean Lower Lapponia and Archaean – Palaeoproterozoic Upper Lapponia groups. Based on new age data, Lehtonen et al. (1998) rejected the Lapponia division and renamed the Palaeoproterozoic (Siderian – Rhyacian) groups Salla, Onkamo, Sodankylä, Savukoski, Kittilä, Lainio and Kumpu.

In Finstrati the Salla, Onkamo (renamed as Kuusamo), Sodankylä and Savukoski groups are classified to be parts of the Karelia supergroup. The oldest metavolcanic and metasedimentary rocks in the Salla and Kuusamo groups in Lapland, the Kurkikylä, Honkajärvi and Korvuanjoki groups in Kainuu and the Kyykkä group in North Karelia, represent the Siderian Period, and are Sumian–Sariolian in historical context.

The Sodankylä and Kivalo groups in Lapland, the East-Puolanka group in Kainuu, the Herajärvi and Raatevaara groups in Northern Karelia and the Nilsiä group in Savo represent the Rhyacian 1 epoch, and are Jatulian in historical context. All these groups are dominated by quartzites, while mafic metavolcanic rocks are only present in Lapland. These rocks gradually change into more carbonaceous metasedimentary rocks, which are classified as the Hyypiä, Matara and Neulamäki groups in North Karelia and northern Savo and the Somerjärvi group in Kainuu. In Lapland, these rocks are included in the Kivalo and Sodankylä groups. The Savukoski group represents the Rhyacian 2 epoch.

During the Orosirian, turbiditic sediments were deposited in a deep marine environment. Rocks representing this period are typical in North Karelia, Kainuu and in the western border zone of the Karelia Province in Savo. In Finstrati, these rocks form the Väyrylä and Sotkamo groups in Kainuu, the Kiiminki, Salahmi and Levänen groups on the western edge of the Karelia Province and the Paakkola group in Peräpohja (Fig. 3). The uppermost groups in the Karelia supergroup are the Orosirian 2 Nuasjärvi and Vihajärvi groups in Kainuu, representing the historical upper Kaleva. The Nuasjärvi group is included in a separate tectonostratigraphic unit (Iijärvi nappe, Fig. 9) on the autochthonous Karelian basement. In this sense, it is correlative to the lithodemic Viinijärvi suite in North Karelia. Both units are closely related to the ophiolitic Outokumpu and Jormua suites. General descriptions of all the aforementioned groups are found in Laajoki (2005).

On the basis of age data (see Hanski & Huhma 2005), the Lainio and Kumpu groups have been united in Finstrati to form the Kumpu group, younger (Orosirian 4) and separate from the Karelia supergroup. The Kittilä group is reclassified in Finstrati as the Kittilä suite (see below).

Palaeoproterozoic lithodemic units

The 2.44 Ga mafic-ultramafic layered intrusions rimming the northern border zone of the Pudasjärvi and Lentua complexes form in Finstrati the Siderian 1 North Finland layered intrusion supersuite. This unit consists of the Peräpohja layered intrusion suite (earlier named as the Tornio-Näränkävaara belt), Koillismaa layered intrusion suite (Iljina & Hanski 2005), Eastern Lapland layered intrusion suite, and the separate Junttilanniemi suite in Kainuu. Several Siderian mafic dyke suites as well as two Siderian 1 granite suites, the Koillismaa syenite suite (Lauri & Mänttäri 2002) and the Tuliniemet suite (Mikkola et al. 2010) are included in this supersuite. The North Finland layered intrusion supersuite, defined during the establishment of Finstrati, represents a good example of grouping of properly defined and studied intrusions in Finland under a common higher rank class.

Diverse gneisses and meta-arkoses that encircle the Central Lapland granitoid complex in the south and west form the Palaeoproterozoic Rovaniemi supersuite in Finstrati. The supersuite consists of the Rovajärvi, Oikarila, Hosiojoki and Sieppijärvi suites. The division was partly defined during the establishment of Finstrati and partly as a result of the paper by Lahtinen et al. (2015a), and needs revision.

The western border zone of the Karelia Province is characterized by migmatitic paragneisses and minor mafic metavolcanic rocks of the Savo supersuite, which are thrust over the Archaean basement complexes in the east. It consists of the Näläntöjärvi suite (Luukas 1991), Lampaanjärvi suite and Suonenjoki suite, all of Orosirian 3 age. Age data on the Näläntöjärvi and Lampaanjärvi suites are found in Lahtinen et al. (2015b). The Savo supersuite is probably correlative to the southwestern part of the Kiiminki belt (Fig. 3), where similar supracrustal rocks exist (i.e. the Kiiminki group). This correlation is more or less tentative and needs revision.

Several intrusive and supracrustal suites that belong to the Karelia Province are classified in Finstrati under the title ‘Diverse Paleoproterozoic suites and lithodemes’. The Siderian and Rhyacian dyke suites of Kapustakangas, Karhusaari, Nyrhinoja, Koli sill, Kuukasjärvi, Rantavaara and Tohmajärvi represent different mafic dyke intrusion phases during Palaeoproterozoic extension. The Rhyacian Otanmäki and Kevitsa suites represent more voluminous intrusive stages. The Orosirian mafic dyke set in western Lapland was named as the Kolari suite during the establishment of Finstrati. The Orosirian 5 Heinävesi intrusive suite and Kaarakkala and Muuruvesi suites, situated along the western border zone of the Karelia province, form the Northern Savo intrusive supersuite (Fig. 7). The Kajaani granite suite, Puruvesi intrusive suite, Nattanen granite suite and Kitee granite suite represent the youngest intrusive stages at Statherian 1.

Palaeoproterozoic supracrustal suites in the Outokumpu area (Fig. 3), previously named as lower or upper Kalevian formations or nappes (Laajoki 2005), are considered in Finstrati metasedimentary suites of uncertain stratigraphic position, named as the Juojärvi, Retunen, Höytiäinen, Tohmajärvi and Viinijärvi suites. Rocks of the Outokumpu suite, characterized by Outokumpu type serpentinite bodies, occur as tectonic slices within the area of the Viinijärvi suite. The Jormua ophiolite suite in Kainuu is a correlative unit to the Outokumpu suite (Peltonen 2005).

In Central Lapland, the Kittilä group is reclassified as the Kittilä suite because of poor knowledge of its internal stratigraphy and because it contains allochthonous units (see Hanski & Huhma 2005).

Palaeoproterozoic complex

The Central Lapland granitoid complex (Fig. 3) consists of the plutonic suites Nilipää (Rhyacian), Suonivaara, Aalistunturi, Kinisjärvi, Köngässelkä and Pirtinvaara (Statherian 1), and the Lohiniva appinite suite (Statherian 1). Moreover, supracrustal rocks within the complex are named as the Räväsjärvi, Hamaramaa and Mellajoki suites. The division was created during establishment of the Finstrati database and needs revision.

Svecofennia Province

The Svecofennia Province includes the area defined as Svecofennian Domain by Gaál and Gorbatschev (1987), Korsman et al. (1997) and Lundqvist et al. (2000). Korsman et al. (1997) divided the Svecofennian Domain into three areas: Accretionary arc complex of southern Finland; Accretionary arc complex of western Finland; and Primitive arc complex of central Finland. The two first areas have been retained with the names Southern Finland Subprovince and Western Finland Subprovince, respectively (see Nironen, this volume). The Western Finland Subprovince is characterized by graphite- and sulphide-bearing schists in the supracrustal belts and metamorphism with trondhjemitic to granodioritic migmatite leucosomes, whereas migmatite leucosomes in the Southern Finland Subprovince are granitic (Korsman et al. 1999). Moreover, carbonate rocks are more common in the Southern Finland Subprovince than in the Western Finland Subprovince.

Western Finland Subprovince

Palaeoproterozoic lithostratigraphic units

The Western Finland Subprovince contains two defined supergroups, of which the older (>1.9 Ga) is named in Finstrati as the Northern Ostrobothnia supergroup and the younger (<1.9 Ga) as the Central Ostrobothnia supergroup. The Northern Ostrobothnia supergroup consists of the lower Pyhäsalmi group and upper Vihanti group (Mäki et al. 2015, Laine et al. 2015). These groups and correlative lithodemic units, the Venepalo plutonic suite and Kokkoneva intrusive suite, represent a magmatic event at 1.93–1.91 Ga (Orosirian 2). The Northern Ostrobothnia supergroup and its lithodemic counterparts equate the aforementioned Primitive arc complex.

The Central Ostrobothnia supergroup consists of the Ylivieska group in Ostrobothnia and the Tampere group in Pirkanmaa, which encircle the Central Finland granitoid complex (CFGC; Fig. 4). Both groups are of Orosirian 3 age. Descriptions of the rocks belonging into these groups are found in Kousa and Lundqvist (2000) and Kähkönen (2005). Overall, the age of the Central Ostrobothnia supergroup and its lithodemic counterparts is mainly Orosirian 3, but extends to Orosirian 4.

Palaeoproterozoic lithodemic units

The lithodemic units in western and central Finland are divided in Finstrati under the titles 'Western Finland supersuite' and 'Diverse Paleoproterozoic suites and lithodemes'. The Western Finland supersuite represents all supracrustal rock units in the subprovince, while the latter is mainly composed of diverse intrusive rock types in the same area. The main area of the subprovince consists of the CFGC, which is described in the next chapter.

The migmatitic biotite paragneisses of the Pirkanmaa migmatite suite on the southern and eastern side of the CFGC, and the Pirttikylä suite in the Ostrobothnia area (Fig. 4) represent the same sedimentary unit. The sedimentogenic Pyhäjärvi, Nivala, Lappfors and Teuva suites in Ostrobothnia are somewhat controversial and their stratigraphic position needs revision (Kousa et al. 1997, Lehtonen et al. 2005, Williams et al. 2008, Lahtinen et al. 2015b). Age data on the Pyhäjärvi suite rocks is found in Lahtinen et al. (2015b), suggesting a correlation to the Ylivieska group.

In central Ostrobothnia the Lapua suite (Evijärvi field in Kähkönen 2005), characterized by mafic MORB type metavolcanic rocks and associated metachert layers, is situated within the Pirttikylä suite as narrow belts. Similar minor mafic units are also found in the Pirkanmaa migmatite suite. The Jurva, Hirsilä and Makkola suites, mainly consisting of intermediate metavolcanic rocks, are situated in the western, southern and eastern border zone of the CFGC, and are possibly correlative to the Tampere group. The division of the Western Finland supersuite was compiled during the establishment of Finstrati and needs revision.

In central Ostrobothnia, diverse porphyritic (intrusive or subvolcanic) rocks that are grouped in Finstrati as the Venetpalo, Kokkokangas and Ostrobothnia mafic porphyrite suite represent lithodemic counterparts to the supracrustal rocks of Pyhäsalmi, Vihanti and Ylivieska groups. Similarly, there are several volcanic or subvolcanic suites within the CFGC that are correlative to the Ylivieska group: the volcanic Perho, Karttula, Mustajärvi,

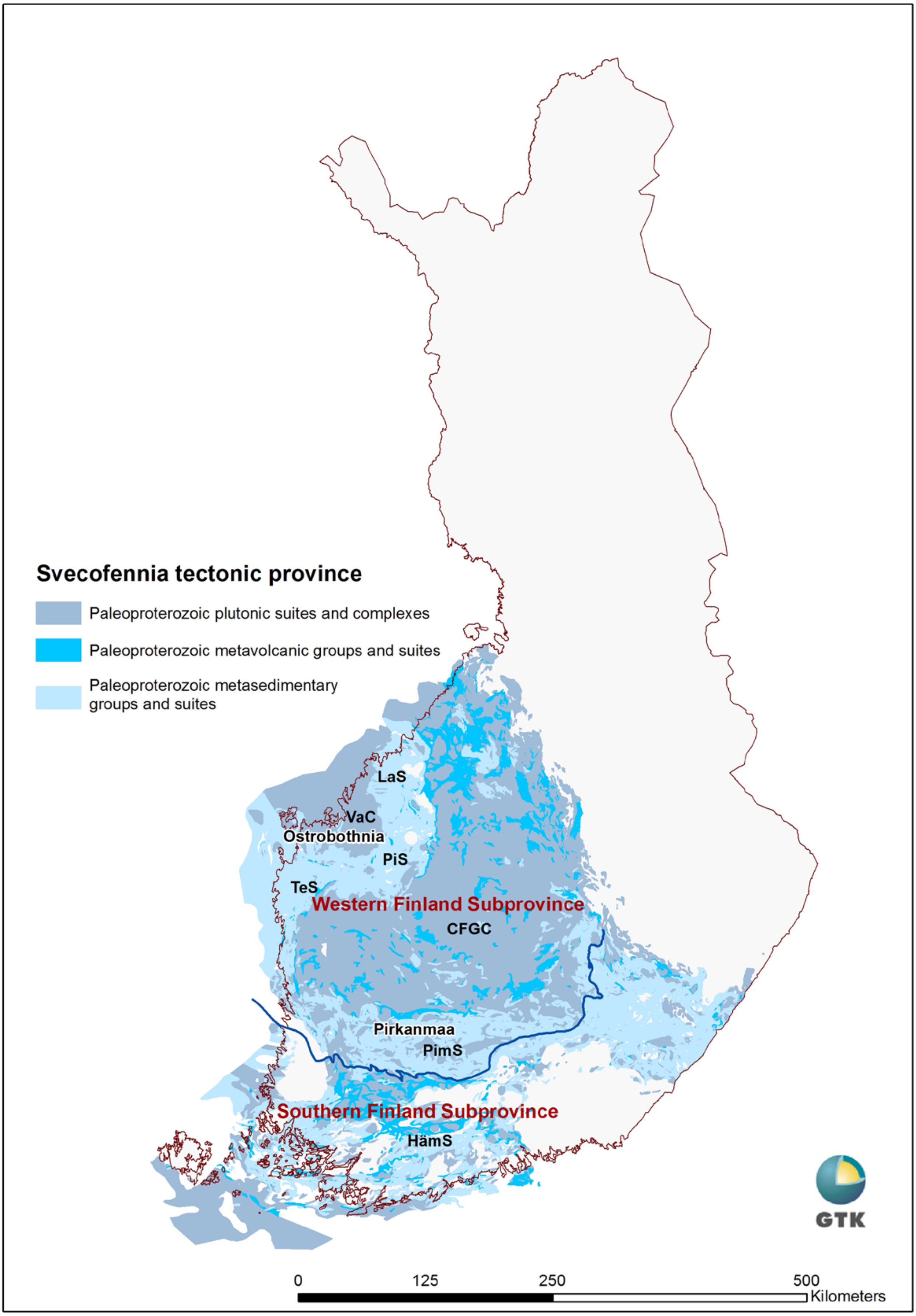

Fig. 4. The main Palaeoproterozoic lithodemic units of the Svecofennia Province according to Finstrati. CFGC = Central Finland Granitoid Complex, HämS = Häme migmatite suite, PimS = Pirkanmaa migmatite suite, LaS = Lapfors suite, VaC = Vaasa complex, TeS = Teuva suite and PiS = Pirttikylä suite.

Haukkamaa and Pihtipudas suites and the subvolcanic Kovelahti, Karhunkylä, Kalmari and Saunakylä suites of Orosirian 3 age (Nironen 2003 and references therein).

Other intrusive suites represent a distinct intrusive stage in the subprovince. The Kotalahti and Vammala suites contain Ni-bearing ultramafic intrusive rocks, the Ylivieska plutonic suite consists of Orosirian 3 mafic layered intrusions in Ostrobothnia, and the Korkatti suite is an Orosirian 4 bimodal intrusion phase in the same area (Kousa & Luukas 2007). The Rautalampi and Saarijärvi plutonic suites are Orosirian 4 intrusions mainly situated within the CFGC and partly crosscutting rocks of the Savo supersuite. The Pirkanmaa intrusive suite represents Orosirian 3 granitoid intrusions crosscutting rocks of the Pirkanmaa migmatite suite. The youngest intrusive suite is the Seinäjoki granite suite, which contains late (Orosirian 7) pegmatite intrusions in Western Finland. These pegmatite granites are temporally close to the Kajaani granite suite (Statherian 1).

Palaeoproterozoic intrusive complexes

The Central Finland granitoid complex occupies the main part of the Western Finland Subprovince. The plutonic rocks are mainly undefined intrusive rocks of alleged Orosirian 3 age. The scattered areas of supracrustal and subvolcanic rocks within the complex are described above. The Saarijärvi suite represents a younger (Orosirian 4) intrusive stage (Nironen et al. 2000, Rämö et al. 2001).

The migmatitic Vaasa complex on the western coast includes Orosirian 4 granites (Suikkanen et al. 2015, Kotilainen et al. 2016).

Southern Finland Subprovince

Palaeoproterozoic lithostratigraphic units

Lithostratigraphic units in the Southern Finland Subprovince have only been determined in small areas: the Orosirian 3–4 Kisko group (Väisänen & Mänttäri 2002, Nironen et al. 2016) and the Orosirian 5–6 Pyhäntaka formation (Nironen 2011, Nironen & Mänttäri 2012). These occurrences have a scattered distribution in the Southern Finland Subprovince without any correlation to each other, and they do not therefore form a supergroup in Finstrati. Moreover, the well-preserved rocks on the southern coast have been considered to form the Pellinge formation, although the stratigraphy is unclear (see Laitala 1973).

Palaeoproterozoic lithodemic units

The lithodemic units in southern Finland are divided in Finstrati under the titles 'Southern Finland supersuite' and 'Diverse Paleoproterozoic suites and lithodemes'. Similarly to the Western Finland supersuite, the Southern Finland supersuite represents all supracrustal rock units in the Southern Finland Subprovince.

A considerable part of the paragneisses in the Southern Finland supersuite comprise the Häme migmatite suite, a poorly defined unit extending in an E–W direction across southern Finland (Fig. 4). The volcanic suites in the subprovince are in the east called the Viholanniemi, Virtasalmi, Savonlinna and Pahakkala suites. These units were defined during the establishment of Finstrati and the division was mainly made on a geographical and geochemical basis. The Renkajärvi, Forssa, Nuutajärvi and Loimaa suites in the western part of the supersuite were recently defined by Sipilä and Kujala (2014).

The intrusive suites in the Southern Finland Subprovince are included in Finstrati under the title 'Diverse Paleoproterozoic suites and lithodemes'. A large proportion of the intrusive rocks in the subprovince belong to the Southern Finland plutonic suite. The studied intrusions in the Southern Finland plutonic suite (shown in Fig. 4) are classified as lithodemes (e.g. Pöytyä tonalite, Orijärvi pluton), and the rest are undefined; the rocks are Orosirian 3 to Orosirian 4 in age. Mafic layered intrusions (e.g. Hyvinkää gabbro, Parikkala gabbro) are grouped under the title 'Southern Finland layered intrusion suite'. These intrusions are mainly of Orosirian 4 age. Granites of Orosirian 6 age occur in a migmatitic belt in southern Finland, called the late Svecofennian granite-migmatite zone (Ehlers et al. 1993); these are named as the Southern Finland granite suite in Finstrati and are shown in Figure 7. The unit is poorly defined and only a few lithodemes exist in Finstrati (e.g. Perniö, Oripää, Nuuksio and Veikkola granites).

The Åva plutonic suite consists of relatively late (Statherian 1) granites occurring as separate plutons in southern Finland. Well-known examples include the Åva, Lemland, Luonteri, Mosshaga and Seglinge granites and associated rocks (Korsman et al. 1984, Patchett & Kouvo 1986, Suominen 1991, Kurhila et al. 2011).

The supracrustal Tiirismaa suite represents a unique lithological unit that has been separated from the Häme migmatite suite on the basis of detrital zircon data and the interpretation that these rocks were deposited upon intrusive and metamorphic rocks after 1870 Ma (Bergman et al. 2008, Lahtinen & Nironen 2010). This suite is correlative to the Pyhäntaka formation.

Lapland–Kola Province

The Lapland–Kola Province is mainly exposed in the Kola Peninsula, Russia, and the northeastern part is in northern Finland (Daly et al. 2001). In the bedrock map of Finland (Korsman et al. 1997), the area consisted of the Inari Complex and the Lapland Granulite Belt. In Finstrati, the Archaean Inarijärvi complex and the Palaeoproterozoic Silisjoki suite correspond to the Inari Complex, and the Lapland granulite complex and Kaamanen complex correspond to the Lapland Granulite Belt.

Neoarchaean units

Neoarchaean complex

The (presumably) Neoarchaean Inarijärvi complex consists of several suites. The northeastern part of the complex is named as Cappeskaidi suite, a cross-border unit extending to Norway. The Archaean, poorly defined Vätsäri, Varttasaari, Petsivaara and Ahvenselkä suites are antiformal domes among the Palaeoproterozoic Silisjoki suite rocks. The Pulmanki and Surnupää suites represent poorly known supracrustal sequences in the complex. The separate Kevo suite within the Palaeoproterozoic Kaamanen complex represents a tectonic window in a thrust belt. The Statherian 1 Vainospää granite of the Nattanen granite suite (see Fig. 7) crosscuts rocks of the Inarijärvi complex.

Palaeoproterozoic units

Palaeoproterozoic lithostratigraphic and lithodemic units

The Opukasjärvi group in the southwestern edge of the Neoarchaean basement is the only lithostratigraphic unit in the Lapland-Kola Province. The group was originally defined by Kesola (1995), but in the Finstrati classification the original uppermost Opukasjärvi formation is reclassified as the Silisjoki suite partly covering the Archaean Inarijärvi complex. The Silisjoki suite is a poorly defined unit. The Orosirian 2 intrusions such as Luossavarri and Njuohkarggu are classified in Finstrati to form the Luossavarri suite.

Palaeoproterozoic complexes

In the Finstrati classification, the Palaeoproterozoic Kaamanen complex and Lapland granulite complex correspond to the former Lapland granulite belt: the Kaamanen complex represents the northeastern part and the Orosirian 2 Lapland granulite complex the south-central part. The Vuotso complex, fringing the Lapland granulite complex, was previously thought to be Neoarchaean, but is now considered Palaeoproterozoic (Daly et al. 2001). All the units are poorly defined.

Norrbotten Province

The Norrbotten Province was defined as a separate lithospheric block rather recently (Lahtinen et al. 2005). It is separated by the Karelia Province by a shear complex (Pajala shear zone; Bergman et al. 2006). Recent seismic anisotropy studies (Vecsey et al. 2014) have confirmed the existence of different mantle lithosphere domains on either side of the shear complex. The Archaean and Palaeoproterozoic rocks of the Norrbotten Province in the Finnish western Lapland are poorly known.

Archaean units

Archaean complex

The Archaean rocks in the northwesternmost part of Finland belong to the Rommaeno complex, recently described by Karinen et al. (2015). The complex extends to northern Sweden and mainly consists of undefined Neoarchaean granodioritic gneisses with subordinate Neoarchaean supracrustal metavolcanic rocks of the Ropi suite. The minor Laassaniemi gneiss on the Swedish border represents the Mesoarchaean lithodeme in the Rommaeno complex. The Muonio complex is the second Neoarchaean complex in the Norrbotten Province. This poorly defined complex is restricted to the domal antiforms in the Muonio area. Further studies are needed to properly define this unit.

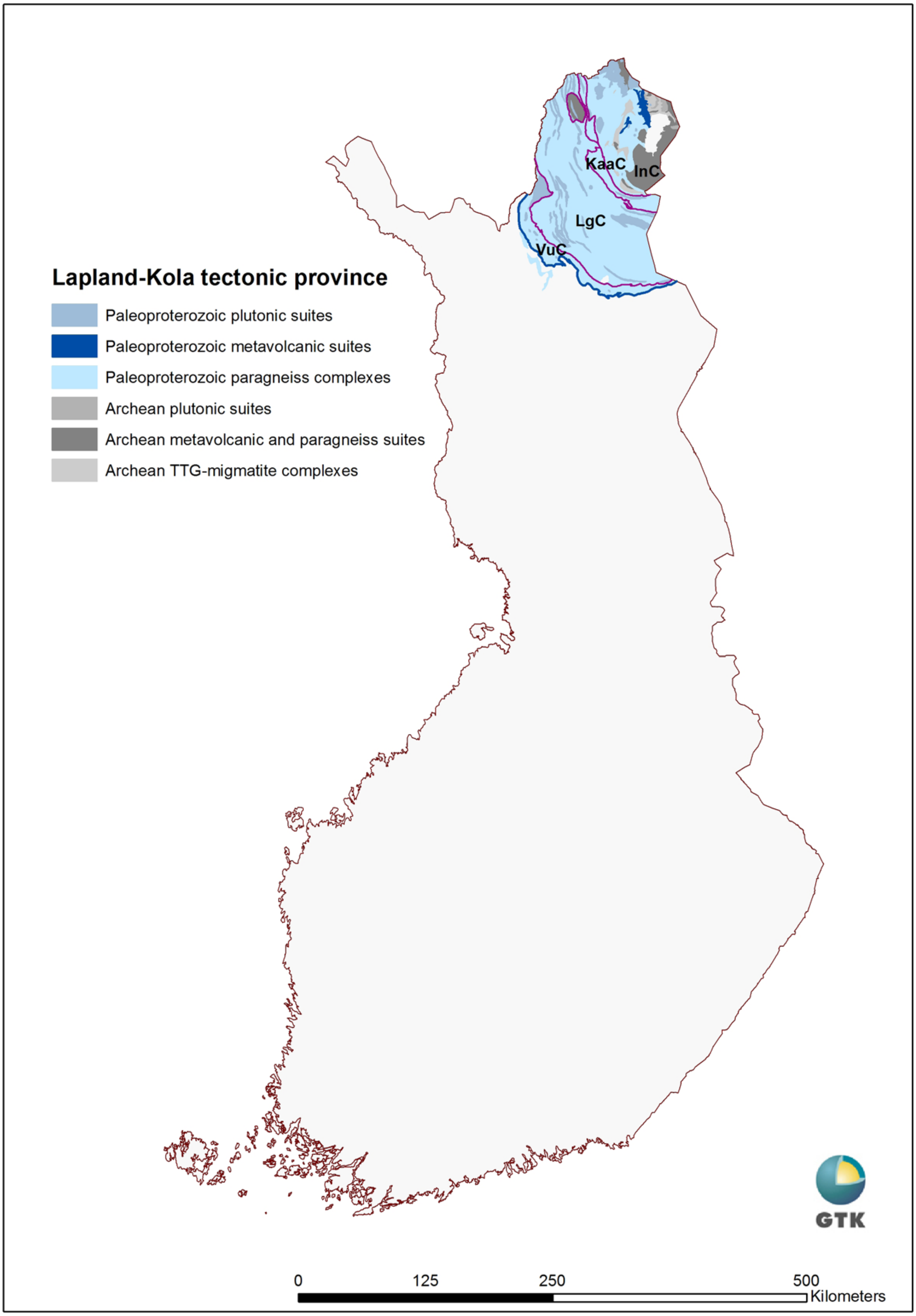

Fig. 5. The main lithodemic units of the Lapland–Kola Province according to Finstrati. InC = Inarijärvi complex, LgC = Lapland granulite complex, VuC = Vuotso complex and KaaC = Kaamanen complex.

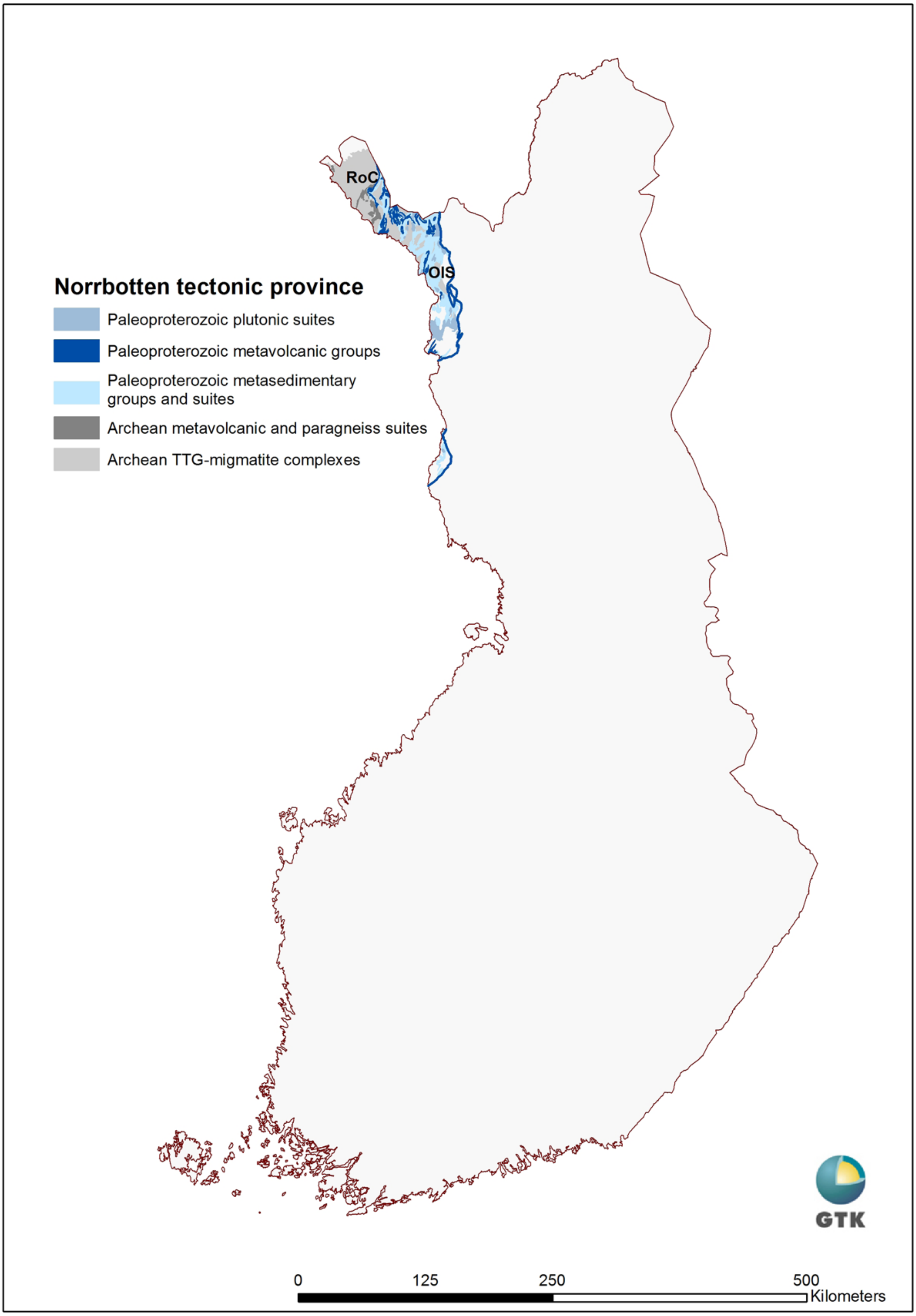

Fig. 6. The main lithodemic units of the Norrbotten Province according to Finstrati. OlS = Olostunturi suite and RoC = Rommaeno complex.

Palaeoproterozoic units

Palaeoproterozoic lithostratigraphic and lithodemic units

The Palaeoproterozoic rocks in the Norrbotten Province mainly belong in the Lätäseno group and the Olostunturi suite. Rocks of the Lätäseno group are situated in the eastern border zone of the Archaean Rommaeno complex. Three different formations are suggested to form this group (Karinen et al. 2015). Arkositic gneisses, amphibolites and diverse paragneisses between the Lätäseno group and Karelia Province are classified as lithodemes of the Olostunturi suite. The possible correlation of the Lätäseno group and Olostunturi suite to similar rocks in the Karelia Province needs detailed work in the future.

Intrusive rocks of the Norrbotten Province (in Finland and Sweden) are classified into the Haaparanta suite and Western Lapland intrusive suite, with ages varying from Orosirian 3 to Statherian 1 (see Bergman et al. 2006); evidently, these suites should be studied more thoroughly and reclassified.

Meso- and Neoproterozoic units

Meso- and Neoproterozoic lithostratigraphic units

Mesoproterozoic lithostratigraphic units, the Muhos formation in northern Ostrobothnia and the Satakunta formation on the western coast of Finland, are presented in Finstrati under the title ‘Diverse Mesoproterozoic formations’. Continuations of the formations are located beneath the Gulf of Bothnia between Finland and Sweden, and correlative units are found in Sweden. No common supergroup has yet been proposed to combine these units. The Ediacaran Hailuoto formation and Lauhanvuori formation represent similar Neoproterozoic lithostratigraphic units without any higher rank. A description of these formations has been published by Kohonen and Rämö (2005).

Mesoproterozoic lithodemic units

Mesoproterozoic lithodemic units in the Finstrati classification comprise the Southern Finland rapakivi supersuite, comprising both Palaeoproterozoic and Mesoproterozoic units. It contains the Statherian 4 Kymi rapakivi suite in southeastern Finland and the Calymmian 2 Åland rapakivi suite in southwestern Finland. The minor Siipyy rapakivi suite (Böle and Siipyy granites), Taalikkala suite, Kuisaari suite (also called Häme dyke swarm) and Föglö dyke suite are classified under the Southern Finland rapakivi supersuite. A detailed description of these rocks has been published by Rämö and Haapala (2005).

The Stenian 2 Laanila and Salla dykes, Stenian 2 Kuhmo kimberlite suite and Ectasian 3 Satakunta olivine diabase suite represent Mesoproterozoic lithodemic units without any higher rank. Similar Neoproterozoic units include the Edicaran Kaavi kimberlite suite and the Cryogenian Kuusamo kimberlite suite.

Palaeozoic units

Palaeozoic units are mainly restricted to the northwestern part of Lapland, where the Caledonian thrust belt contains the Nalganas, Nablar and Vaddas nappes (Lehtovaara 1995). These lithodemic units are underlain by a Cambrian (possibly partly Ediacaran) rock association that has been divided into the autochthonous Dividal group and the parautochthonous Jerta nappe. A description of these rocks exists by Kohonen and Rämö (2005).

The Devonian Sokli and Iivaara alkaline intrusions represent the youngest intrusive stage in Finnish bedrock.

Mesozoic units

The rocks of the Lappajärvi impact suite represent the youngest (Cretaceous) units in Finstrati.

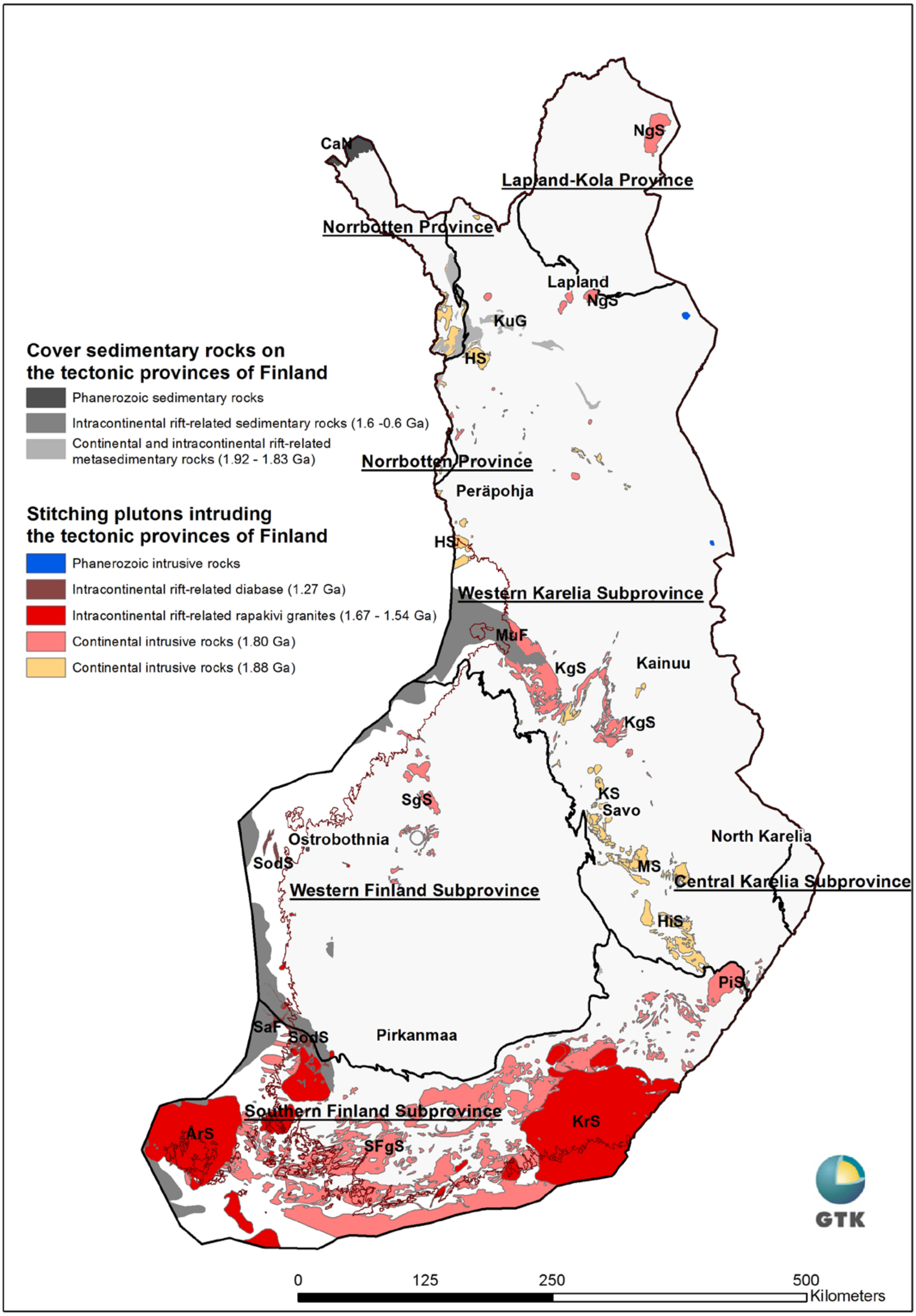

Fig. 7. Cover sedimentary rocks and stitching plutons intruding the tectonic provinces. SFgS = Southern Finland granitoid suite, ÅrS = Åland rapakivi suite, KrS = Kymi rapakivi suite, PiS = Puruvesi intrusive suite, HiS = Heinävesi intrusive suite, MS = Muuruvesi suite, KS = Kaarakkala suite, SgS = Seinäjoki granite suite, SodS = Satakunta olivine diabase suite, KgS = Kajaani granite suite, HS = Haaparanta suite, NgS = Nattanen granite suite, CaN = Caledonian nappes, KuG = Kumpu group, MuF = Muhos formation, SaF = Satakunta formation.

PRELIMINARY TECTONOSTRATIGRAPHIC DIVISION OF NORTHERN AND EASTERN FINLAND

Principles of tectonostratigraphic classification

In addition to the lithostratigraphic and lithodemic Finstrati classification described above, the international classification scheme gives an opportunity to divide the Finnish bedrock into tectonostratigraphic units. Local tectonostratigraphic divisions have been made in Kainuu (Laajoki 1991, Kontinen 1992), in the Kaavi–Outokumpu area (Park & Doody 1990, Laajoki 2005) and in the Finnish Caledonides (Lehtovaara 1995). Strand et al. (2010) described the principles of tectonostratigraphic classification (Table 1), which is used in the preliminary tectonostratigraphic division of northern and eastern Finland (Fig. 8).

According Strand et al. (2010), nappe is the fundamental unit in tectonostratigraphic classification, and higher rank units are nappe system and nappe complex. A nappe system represents a thrust fault system in which the movements and displacements of individual nappes have taken place during the same deformation event. In a nappe complex, the movements and displacements of nappes have taken place during different deformation phases or orogenies, the movements and displacements are unknown, or they have uncertain relative ages. At a lower hierarchy level, nappes can consist of thrust sheets.

Preliminary tectonostratigraphic division of northern and eastern Finland

The preliminary tectonostratigraphic higher rank division into nappe systems and complexes in Finland is shown in Figures 8 and 9. In this proposal, each tectonic province is divided into fault-bounded blocks, nappe systems or nappe complexes. The Karelia Province consists of five Archaean blocks that include overlying autochthonous or parautochthonous units. For example the Eastern Finland block consist of the Lentua and Ilomantsi complexes and overlying quartzites. The Northern Ostrobothnia nappe system represents a tectonic unit that was thrust on the Pudasjärvi block during an early stage of the Svecofennian orogeny. The Northern Karelia, Northern Savo and Kainuu nappe complexes have a more complex evolution, and they are therefore classified as nappe complexes. The relative ages of these nappe complexes is under consideration.

As an example, the preliminary tectonostratigraphic division of the western part of the Karelia Province is shown in Figure 9. The Archaean Lentua, Pudasjärvi and Iisalmi complexes are blocks separated by Proterozoic shear zones. The Archaean Manamansalo, Kalpio and Kalhamajärvi complexes are situated between these blocks as highly sheared units. The northern Ostrobothnia nappe system consists of the Utajärvi parautochthon (Utajärvi group in Finstrati) and the Kiuruvesi nappe (Kiiminki group and Näläntöjärvi suite in Finstrati). These units were formed in a single thrusting event.

The Kainuu nappe complex consists of tectonic units that were originally formed in different geotectonic settings. For example, the Jormua nappe represents sea floor basalts, gabbros and peridotites, the Iijärvi nappe deep marine turbidites, and the Korholanmäki nappe shallow sea sediments. In the middle of the complex there are also slices of Archaean basement, Jatuli quartzite and lower Kaleva sediments as separate unnamed thrust sheets. Tectonic stacking of these units took place during different deformation phases (e.g. Kärki et al. 1993). The names of the suggested nappes have been adopted and modified from Laajoki (1991) and Kontinen (1992).

The Central Lapland nappe complex consists of older (Orosirian 1) nappes that were thrust eastwards (Kittilä suite) and some tectonic units (Orosirian 2, Sodankylä and Savukoski groups) that attained in their present location during Palaeoproterozoic tectonic movements.

The northernmost part of the Lapland–Kola Province in Finland consists of the Archaean autochthonous core (Inari complex) and Palaeoproterozoic parautochthonous cover rocks (Silisjoki suite). These two units form the Inari block. The allochthonous units of the Lapland–Kola Province consist of the Northern Lapland nappe system, as well as separate tectonic slices in central Lapland (Sodankylä nappe).

The Norrbotten Province consists of the Archaean Rommaeno block in the west, and the autochthonous and parautochthonous rocks of the Lätäseno group and the Olostunturi suite in the east, jointly named as the Karesuvanto parautochthon. The easternmost sequences of the Olostunturi suite have been thrust upon rocks of the Central Lapland nappe system.

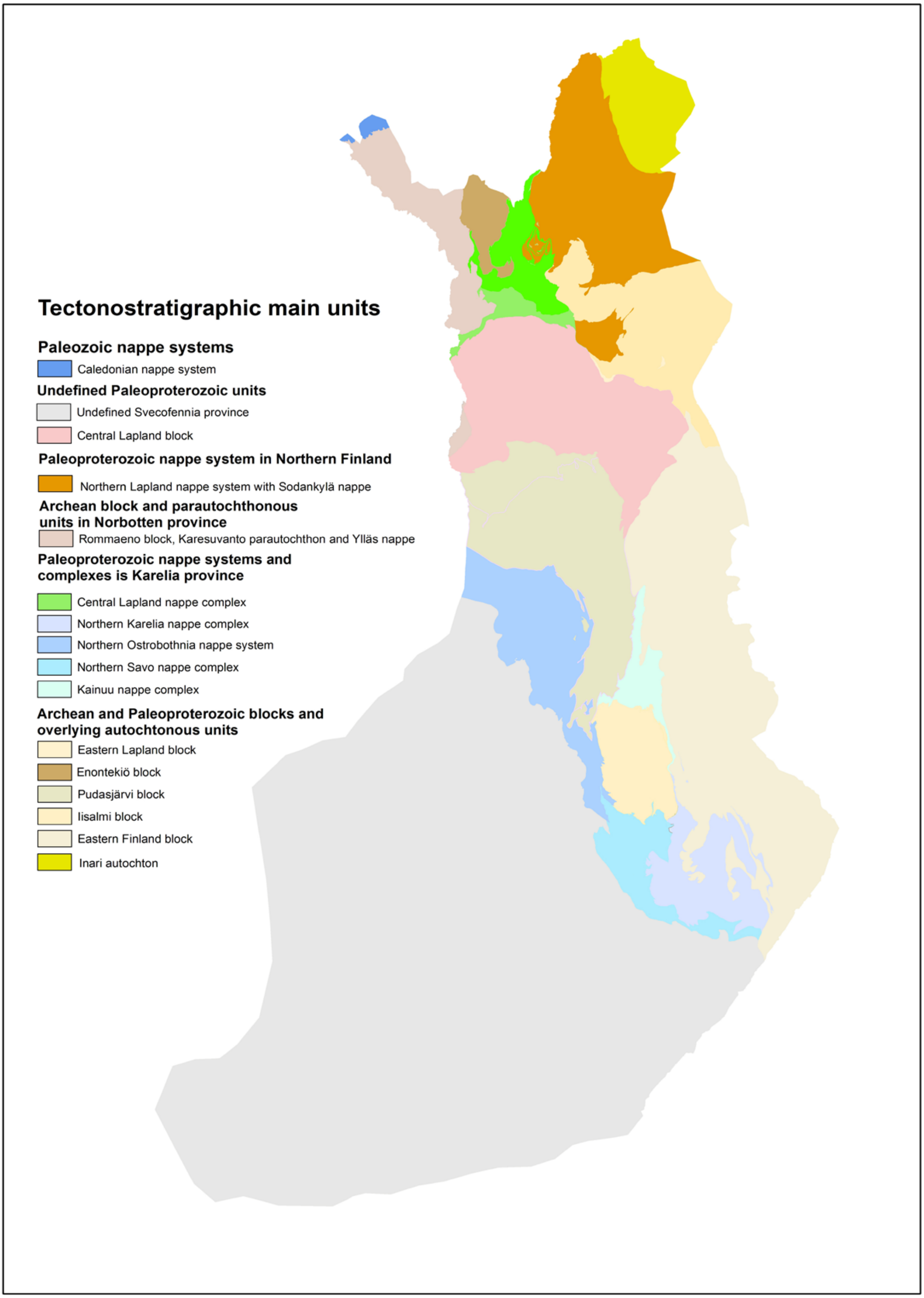

Fig. 8. Tectonostratigraphic units of northern and eastern Finland according to Finstrati.

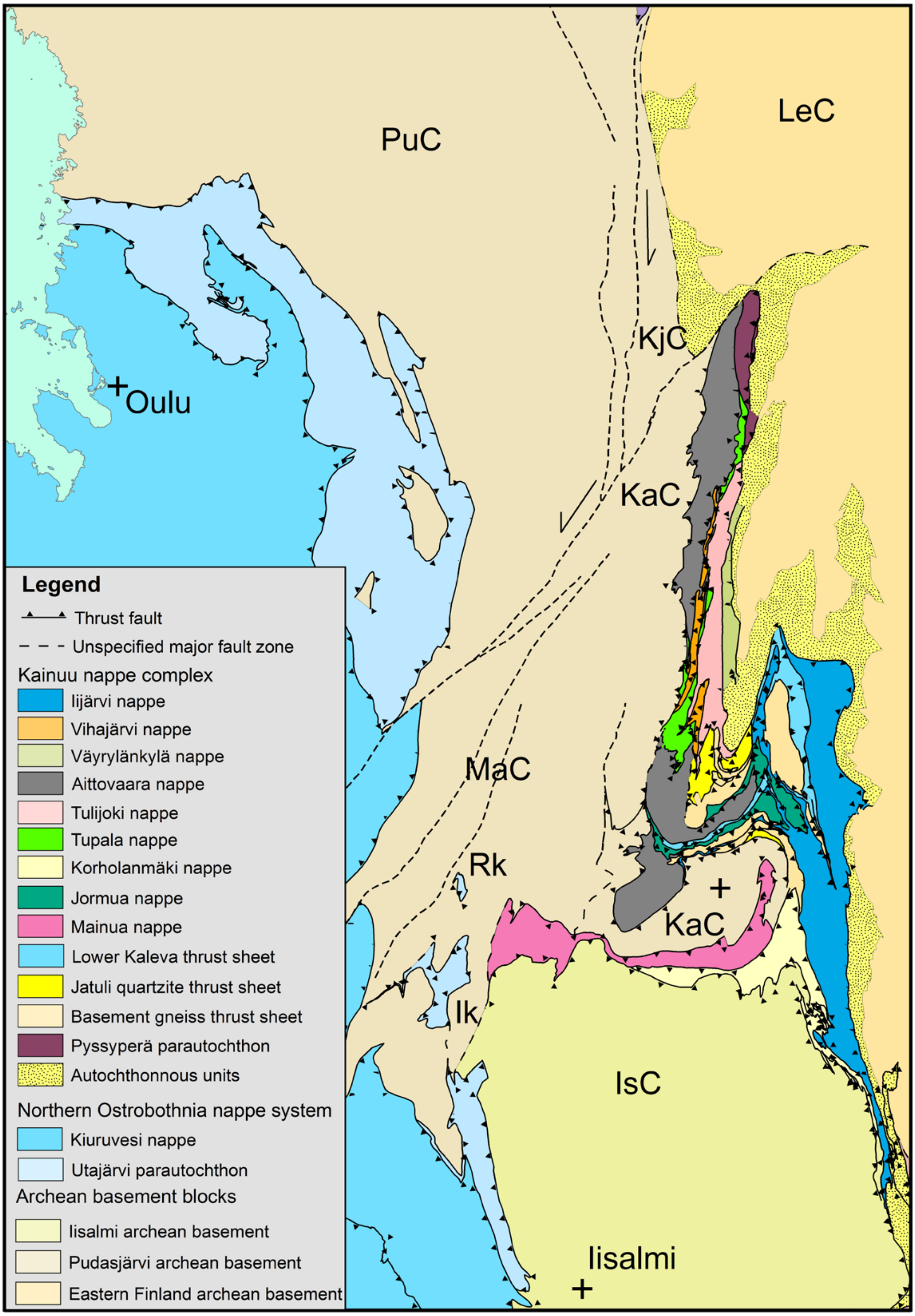

Fig. 9. Tectonostratigraphic units of Kainuu and Northern Ostrobothnia according to Finstrati. Rk = Rimpikangas klippe, Ik = Itämäki klippe. Lithodemic units in the Archaean basement blocks are LeC = Lentua complex, IsC = Iisalmi complex, PuC = Pudasjärvi complex, MaC = Manamansalo complex, KaC = Kalpio complex, KjC = Kalhamajärvi complex.

SUMMARY

The spatial Finstrati database contains almost 2400 lithostratigraphic or lithodemic units, linked to the spatial bedrock map database (DigiKp). These databases were produced and are maintained by GTK. The nomenclature was generated according to international rules (North American Commission on Stratigraphic Nomenclature, 2005) and with the co-operation of the Stratigraphic Commission of Finland (SCF). This paper briefly describes the major stratigraphic units of the Finnish bedrock according Finstrati. Finstrati will be updated in the future with new stratigraphic units presented in scientific publications and new map projects. At present, all the units are informal, but in the future, properly defined units will be approved as formal units by the SCF.

In this paper, a preliminary tectonostratigraphic division is also proposed for northern and eastern Finland. In this proposal, previously named tectonostratigraphic units are arranged according to the rules presented by the SCF. A tectonostratigraphic division for southern Finland will be presented in the near future.

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Appendix 1.

EON	ERA	SUPERGROUP CODE SUPERSUITE CODE COMPLEX CODE	GROUP CODE SUITE CODE	UNIT NAME	PERIOD	EPOCH	PROVINCE
1				**Archean**			
	11			**Paleoarchean**			
		1110		**Diverse Paleoarchean suites and lithodemes**			Karelia
			111001	Diverse paleoarchean lithodemes			Karelia
		1199		**Undefined Paleoarchean unit**			Karelia
	12			**Mesoarchean**			Karelia
		1201		**Kianta supergroup**			Karelia
			120101	Luoma group			Karelia
			120102	Suomussalmi group			Karelia
			120103	Ruokojärvi group			Karelia
			120104	Kuhmo group			Karelia
			120105	Tipasjärvi group			Karelia
		1202		**Diverse Mesoarchean formations**			Karelia
		1210		**Diverse Mesoarchean suites and lithodemes**			Karelia
		1251		**Iisalmi complex**			Karelia
			125199	Diverse lithodemes in Iisalmi complex			Karelia
		1252		**Siurua complex**			Karelia
			125299	Diverse lithodemes			Karelia
		1299		**Undefined Mesoarchean unit**			Karelia
	13			**Neoarchean**			Karelia
		1301		**Diverse Neoarchean groups**			Karelia
			130101	Central Puolanka group		Neoarchaean 2	Karelia
			130102	Hattu group		Neoarchaean 1	Karelia
			130103	Ilaja group		Neoarchaean 1	Karelia
			130104	Kovero group		Neoarchaean 1	Karelia
			130105	Oijärvi group		Neoarchaean 1	Karelia
		1302		**Diverse Neoarchean formations**			Karelia
		1309		**Central Lapland suprersuite**		Neoarchaean 2	Karelia
			130901	Vuojärvi suite		Neoarchaean 2	Karelia
			130902	Pittiövaara suite		Neoarchaean 2	Karelia
			130903	Karhulehto suite		Neoarchaean 2	Karelia
			130904	Juppuravaara suite		Neoarchaean 2	Karelia
			130905	Virttiövaara suite		Neoarchaean 2	Karelia
			130906	Haisujupukka suite		Neoarchaean 2	Karelia
			130907	Kaukonen suite		Neoarchaean 2	Karelia
			130908	Posio suite		Neoarchaean 2	Karelia
			130909	Heraselkä suite		Neoarchaean 2	Karelia
		1310		**Diverse Neoarchean suites and lithodemes**		not determined	Karelia
			131001	Jonsa suite		Neoarchean 1	Karelia
			131002	Konivaara suite		Neoarchean 1	Karelia
			131004	Tuntsa suite		Neoarchean 1	Karelia
			131006	Siilinjärvi suite		Neoarchean 2	Karelia
			131007	Koitere suite		Neoarchaean 1	Karelia

Appendix 1. Cont.

EON	ERA	SUPERGROUP CODE SUPERSUITE CODE COMPLEX CODE	GROUP CODE SUITE CODE	UNIT NAME	PERIOD	EPOCH	PROVINCE
		1350		**Rommaeno complex**		Neoarchaean 1	Norrbotten
			135001	Ropi suite		Neoarchaean 1	Norrbotten
			135099	Diverse lithodemes in Rommaeno complex		Neoarchaean 1	Norrbotten
		1351		**Muonio complex**		not determined	Norrbotten
			135199	Diverse lithodemes in Muonio complex		not determined	Norrbotten
		1352		**Pomokaira complex**		Neoarchean 2	Karelia
			135299	Diverse lithodemes in Pomokaira complex		Neoarchean 2	Karelia
		1353		**Inarijärvi complex**		Neoarchean 2	Lapland-Kola
			135301	Pulmankijärvi suite		Neoarchean 2	Lapland-Kola
			135302	Cappeskaidi suite		Neoarchean 2	Lapland-Kola
			135303	Surnupää suite		Neoarchean 2	Lapland-Kola
			135304	Vätsäri suite		Neoarchean 2	Lapland-Kola
			135305	Varttasaari suite		Neoarchean 2	Lapland-Kola
			135306	Petsivaara suite		Neoarchean 2	Lapland-Kola
			135307	Ahvenselkä suite		Neoarchean 2	Lapland-Kola
			135308	Kevo suite		Neoarchean 2	Lapland-Kola
			135399	Diverse lithodemes in Inarijärvi complex		not determined	Lapland-Kola
		1354		**Kemihaara granitoid complex**		not determined	Karelia
			135401	Tulppio suite		not determined	Karelia
			135499	Diverse lithodemes in Kemihaara granitoid complex		not determined	Karelia
		1355		**Naruska granitoid complex**		not determined	Karelia
			135599	Diverse lithodemes in Naruska complex		not determined	Karelia
		1357		**Suomujärvi complex**		not determined	Karelia
			135799	Diverse lithodemes in Suomujärvi complex		not determined	Karelia
		1358		**Pudasjärvi complex**		not determined	Karelia
			135801	Olhava Suite		not determined	Karelia
			135802	Tannila suite		not determined	Karelia
			135805	Hautakangas suite		not determined	Karelia
			135807	Tainivaara suite		not determined	Karelia
			135808	Arppee suite		not determined	Karelia
			135809	Portimo suite		not determined	Karelia
			135899	Diverse lithodemes in Pudasjärvi complex		not determined	Karelia
		1362		**Manamansalo complex**		not determined	Karelia
			136201	Piiparinmäki suite		not determined	Karelia
			136202	Pirttimäki suite		not determined	Karelia
			136203	Rapisevankangas gneiss suite		not determined	Karelia
			136204	Rahajärvi suite		not determined	Karelia
			136299	Diverse lithodemes in Manamansalo complex		not determined	Karelia
		1365		**Kalpio complex**		not determined	Karelia
			136599	Diverse lithodemes in Kalpio complex		not determined	Karelia
		1366		**Kalhamajärvi complex**		not determined	Karelia

Appendix 1. Cont.

EON	ERA	SUPERGROUP CODE SUPERSUITE CODE COMPLEX CODE	GROUP CODE SUITE CODE	UNIT NAME	PERIOD	EPOCH	PROVINCE
			136699	Diverse lithodemes in Kalhamajärvi complex		not determined	Karelia
		1368		**Rautavaara complex**		not determined	Karelia
			136801	Susi-Kervinen supracrustal suite		not determined	Karelia
			136802	Vuottojärvet suite		not determined	Karelia
			136899	Diverse lithodemes in Rautavaara complex		not determined	Karelia
		1369		**Lentua complex**		not determined	Karelia
			136901	Nurmes suite		Neoarchean 2	Karelia
			136902	Nunnanlahti suite		Neoarchean 1	Karelia
			136903	Ipatti suite		Neoarchean 1	Karelia
			136904	Haasianvaara suite		not determined	Karelia
			136905	Jonkeri suite		Neoarchean 1	Karelia
			136906	Kuohattijärvi suite		Neoarchean1	Karelia
			136907	Sokojärvi suite		Neoarchean1	Karelia
			136908	Änäkäinen suite		Neoarchean1	Karelia
			136909	Saari-Kiekki suite		Neoarchean1	Karelia
			136999	Diverse lithodemes in Lentua complex		not determined	Karelia
		1370		**Tahvinmäki complex**		not determined	Karelia
			137099	Diverse lithodemes in Tahvinmäki complex		not determined	Karelia
		1372		**Ilomantsi complex**		not determined	Karelia
			137201	Silvevaara suite		Neoarchean 1	Karelia
			137202	Kuittila suite		Neoarchean 1	Karelia
			137203	Naarva suite		not determined	Karelia
			137205	Kutsu suite		Neoarchean 2	Karelia
			137206	Harkkojärvi suite		not determined	Karelia
			137299	Diverse lithodemes in Ilomantsi complex		not determined	Karelia
		1373		**Kuopio complex**		not determined	Karelia
			137399	Diverse lithodemes in Kuopio complex		not determined	Karelia
		1374		**Porttikoski complex**		not determined	Karelia
			137499	Diverse lithodemes in Porttikoski complex		not determined	Karelia
		1375		**Joensuu complex**		not determined	Karelia
			137599	Diverse lithodemes in Joensuu complex		not determined	Karelia
		1376		**Hetta complex**		not determined	Karelia
			137699	Diverse lithodemes in Hetta complex		not determined	Karelia
		1399		**undefined Neoarchean unit**		not determined	
2				**Proterozoic**			
	21			**Paleoproterozoic**			
		2101		**Karelia supergroup**			Karelia
			210101	Salla group	Siderian	Siderian 1	Karelia
			210102	Kuusamo group	Siderian	Siderian 2	Karelia
			210103	Kurkikylä group	Siderian	Siderian 1	Karelia
			210104	Honkajärvi group	Siderian	Siderian 1	Karelia
			210105	Kyykkä group	Siderian	Siderian 1	Karelia

Appendix 1. Cont.

EON	ERA	SUPERGROUP CODE SUPERSUITE CODE COMPLEX CODE	GROUP CODE SUITE CODE	UNIT NAME	PERIOD	EPOCH	PROVINCE
			210106	Korvuanjoki group	Siderian	Siderian 1	Karelia
			210119	Diverse Sumi-Sariola formations	Siderian	Siderian 1	Karelia
			210120	Herajärvi group	Rhyacian	Rhyacian 1	Karelia
			210121	East-Puolanka group	Rhyacian	Rhyacian 1	Karelia
			210123	Sodankylä group	Rhyacian	Rhyacian 1	Karelia
			210124	Kivalo group	Siderian-Rhyacian		Karelia
			210125	Raatevaara group	Rhyacian	Rhyacian 1	Karelia
			210127	Nilsiä group	Rhyacian	Rhyacian 1	Karelia
			210149	Diverse Jatulian formations	Rhyacian	Rhyacian 1	Karelia
			210150	Utajärvi group	Rhyacian	Rhyacian 1	Karelia
			210151	Neulamäki group	Rhyacian	Rhyacian 1	Karelia
			210152	Somerjärvi group	Rhyacian	Rhyacian 1	Karelia
			210154	Hyypiä group	Rhyacian	Rhyacian 1	Karelia
			210155	Matara group	Rhyacian	Rhyacian 1	Karelia
			210156	Savukoski group	Rhyacian	Rhyacian 1	Karelia
			210169	Diverse Marine Jatuli formations	Rhyacian	Rhyacian 1	Karelia
			210170	Sotkamo group	Orosirian	Orosirian 1	Karelia
			210171	Väyrylä group	Orosirian	Orosirian 1	Karelia
			210172	Salahmi group	Orosirian	Orosirian 1	Karelia
			210173	Kiiminki group	Orosirian	Orosirian 1	Karelia
			210174	Levänen group	Orosirian	Orosirian 1	Karelia
			210178	Paakkola group	Orosirian	Orosirian 1	Karelia
			210190	Nuasjärvi group	Orosirian	Orosirian 2	Karelia
			210191	Vihajärvi group	Orosirian	Orosirian 2	Karelia
			210199	Diverse Upper Kaleva formations	Orosirian	Orosirian 2	Karelia
		2102		**Diverse Paleoproterozoic groups**			
			210201	Opukasjärvi group	Rhyacian	Rhyacian 1	Lapland-Kola
			210203	Kumpu group	Orosirian	Orosirian 3	Karelia
			210205	Lätäseno group	Rhyacian	Rhyacian 1	Norrbotten
			210208	Kisko group	Orosirian	Orosirian 3	Svecofennia
		2103		**Diverse Paleoproterozoic formations**			
			210301	Diverse Paleoproterozoic formations	not determined		
		2104		**Northern Ostobothnia supergroup**	Orosirian	Orosirian 2	Svecofennia
			210401	Pyhäsalmi group	Orosirian	Orosirian 2	Svecofennia
			210402	Vihanti group	Orosirian	Orosirian 2	Svecofennia
		2105		**Central Ostobothnia supergroup**	Orosirian	Orosirian 3	Svecofennia
			210501	Tampere group	Orosirian	Orosirian 3	Svecofennia
			210502	Ylivieska group	Orosirian	Orosirian 3	Svecofennia
		2110		**North Finland layered intrusion supersuite**	Siderian	Siderian 1	Karelia
			211001	Peräpohja layered intrusion suite	Siderian	Siderian 1	Karelia
			211002	Koillismaa layered intrusion suite	Siderian	Siderian 1	Karelia
			211003	Eastern Lapland layered intrusion suite	Siderian	Siderian 1	Karelia

Appendix 1. Cont.

EON	ERA	SUPERGROUP CODE SUPERSUITE CODE COMPLEX CODE	GROUP CODE SUITE CODE	UNIT NAME	PERIOD	EPOCH	PROVINCE
			211004	Junttilanniemi suite	Siderian	Siderian 1	Karelia
			211005	Pääjärvi dyke suite	Siderian	Siderian 1	Karelia
			211006	Viianki dyke suite	Siderian	Siderian 1	Karelia
			211007	Taivalkoski dyke suite	Siderian	Siderian 1	Karelia
			211008	Kärppäsuo dyke suite	Siderian	Siderian 1	Karelia
			211009	Peuratunturi dyke suite	Siderian	Siderian 1	Karelia
			211010	Koillismaa syenite suite	Siderian	Siderian 1	Karelia
			211011	Tuliniemet suite	Siderian	Siderian 1	Karelia
			211012	Kelottijärvi suite	Siderian	Siderian 1	Karelia
		2111		**Western Finland supersuite**			Svecofennia
			211101	Teuva suite	Orosirian		Svecofennia
			211102	Jurva suite	Orosirian		Svecofennia
			211103	Hirsilä suite	Orosirian		Svecofennia
			211104	Pirkanmaa migmatite suite	Orosirian		Svecofennia
			211105	Pyhäjärvi suite	Orosirian		Svecofennia
			211106	Nivala suite	Orosirian		Svecofennia
			211107	Pirttikylä suite	Orosirian		Svecofennia
			211108	Lapua suite	Orosirian		Svecofennia
			211110	Lappfors suite	Orosirian		Svecofennia
			211111	Makkola suite	Orosirian	Orosirian 3	Svecofennia
		2112		**Southern Finland supersuite**			Svecofennia
			211201	Häme migmatite suite	Orosirian		Svecofennia
			211202	Viholanniemi volcanic suite	Orosirian	Orosirian 2	Svecofennia
			211203	Pahakkala volcanic suite	Orosirian		Svecofennia
			211204	Renkajärvi suite	Orosirian		Svecofennia
			211205	Forssa volcanic suite	Orosirian		Svecofennia
			211206	Korpo suite	Orosirian		Svecofennia
			211207	Matkonmäki suite	Orosirian		Svecofennia
			211208	Virtasalmi suite	Orosirian		Svecofennia
			211209	Savonlinna suite	Orosirian		Svecofennia
			211210	Nuutajärvi suite	Orosirian		Svecofennia
			211211	Loimaa suite	Orosirian		Svecofennia
		2113		**Diverse Paleoproterozoic suites and lithodemes**			
			211301	Kapustakangas suite	Siderian	Siderian 1	Karelia
			211302	Karhusaari suite	Rhyacian	Rhyacian 1	Karelia
			211303	Nyrhinoja dyke suite	Siderian	Siderian 2	Karelia
			211304	Koli sill suite	Siderian	Siderian 2	Karelia
			211305	Kuukasjärvi suite	Rhyacian	Rhyacian 1	Karelia
			211306	Otanmäki suite	Rhyacian	Rhyacian 1	Karelia
			211307	Karhujupukka suite	Rhyacian	Rhyacian 1	Karelia
			211308	Rantavaara suite	Rhyacian	Rhyacian 1	Karelia
			211309	Keivitsa layered intrusion suite	Rhyacian	Rhyasian2	Karelia

Appendix 1. Cont.

EON	ERA	SUPERGROUP CODE SUPERSUITE CODE COMPLEX CODE	GROUP CODE SUITE CODE	UNIT NAME	PERIOD	EPOCH	PROVINCE
			211310	Tohmajärvi dyke suite	Rhyacian	Rhyacian 1	Karelia
			211311	Kolari dyke suite	Orosirian	Orosirian 1	Karelia
			211312	Paukkajanvaara dyke suite	Orosirian	Orosirian 1	Karelia
			211314	Haaparanta suite	Orosirian	Orosirian 3	Karelia
			211315	Heinävesi intrusive suite	Orosirian	Orosirian 5	Karelia
			211316	Kaarakkala suite	Orosirian	Orosirian 5	Karelia
			211317	Muuruvesi suite	Orosirian	Orosirian 5	Karelia
			211318	Kajaani granite suite	Statherian	Statherian 1	Karelia
			211319	Puruvesi intrusive suite	Statherian	Statherian 1	Karelia
			211320	Nattanen granite suite	Statherian	Statherian 1	Karelia
			211321	Juojärvi suite	Rhyacian	Rhyacian 1	Karelia
			211322	Viinijärvi suite	Orosirian	Orosirian 2	Karelia
			211323	Jormua ophiolite	Orosirian	Orosirian 2	Karelia
			211324	Outokumpu suite	Orosirian	Orosirian 2	Karelia
			211325	Retunen suite	Orosirian	Orosirian 1	Karelia
			211327	Western Lapland intrusive suite	Orosirian	Orosirian 7	Karelia
			211329	Tohmajärvi suite	Orosirian	Orosirian 1	Karelia
			211330	Höytiäinen suite	Orosirian	Orosirian 1	Karelia
			211331	Olostunturi suite	Rhyacian		Norrbotten
			211332	Kittilä suite	Rhyacian		Karelia
			211334	Martimo suite	Orosirian	Orosirian 1	Karelia
			211335	Uusivirka suite	Orosirian	Orosirian 2	Norrbotten
			211336	Vähäkurkkio suite	Statherian		Norrbotten
			211337	Raiseatnu suite	Orosirian		Norrbotten
			211338	Kitee granite suite	Statherian	Statherian 1	Karelia
			211348	Silisjoki suite	Orosirian	Orosirian 1	Lapland-Kola
			211349	Luossavarri suite	Orosirian	Orosirian 2	Lapland-Kola
			211350	Venetpalo plutonic suite	Orosirian	Orosirian 2	Svecofennia
			211351	Kokkoneva intrusive suite	Orosirian	Orosirian 2	Svecofennia
			211355	Kotalahti suite	Orosirian	Orosirian 3	Svecofennia
			211356	Vammala suite	Orosirian	Orosirian 3	Svecofennia
			211357	Ylivieska plutonic suite	Orosirian	Orosirian 3	Svecofennia
			211358	Korkatti suite	Orosirian	Orosirian 4	Svecofennia
			211360	Rautalampi plutonic suite	Orosirian	Orosirian 4	Svecofennia
			211361	Saarijärvi plutonic suite	Orosirian	Orosirian 4	Svecofennia
			211362	Pirkanmaa intrusive suite	Orosirian	Orosirian 3	Svecofennia
			211363	Ostrobothnia mafic pophyrite suite	Orosirian	Orosirian 3	Svecofennia
			211364	Seinäjoki granite suite	Orosirian	Orosirian 7	Svecofennia
			211367	Southern Ostrobothnia intrusive suite	Orosirian		Svecofennia
			211380	Southern Finland plutonic suite	Orosirian	Orosirian 4	Svecofennia
			211381	Southern Finland layered intrusion suite	Orosirian	Orosirian 4	Svecofennia
			211382	Tiirismaa suite	Orosirian	Orosirian 5	Svecofennia
			211383	Southern Finland granite suite	Orosirian	Orosirian 6	Svecofennia

Appendix 1. Cont.

EON	ERA	SUPERGROUP CODE SUPERSUITE CODE COMPLEX CODE	GROUP CODE SUITE CODE	UNIT NAME	PERIOD	EPOCH	PROVINCE
			211385	Åva plutonic suite	Statherian	Statherian 1	Svecofennia
			211399	Diverse Paleoproterozoic lithodemes			
		2114		**Rovaniemi supersuite**			Karelia
			211401	Oikarila suite	Orosirian	Orosirian 1	Karelia
			211402	Sieppijärvi suite	Orosirian	Orosirian 1	Karelia
			211403	Rovajärvi suite	Orosirian	Orosirian 1	Karelia
			211404	Hosiojoki suite	Orosirian	Orosirian 1	Karelia
		2115		**Savo supersuite**			Karelia
			211501	Näläntöjärvi suite	Orosirian	Orosirian 1	Karelia
			211502	Lampaanjärvi suite	Orosirian	Orosirian 1	Karelia
			211503	Suonenjoki suite	Orosirian	Orosirian 1	Karelia
		2150		**Lapland granulite complex**			Lapland-Kola
			215001	Saariselkä suite	Orosirian		Lapland-Kola
			215002	Kuttura suite	Orosirian		Lapland-Kola
		2151		**Vuotso complex**	not determined		Lapland-Kola
			215101	Kussuolinkivaara suite	not determined		Lapland-Kola
			215199	Diverse lithodemes in Vuotso complex	not determined		Lapland-Kola
		2152		**Kaamanen complex**	not determined		Lapland-Kola
			215299	Diverse lithodemes in Kaamanen complex	not determined		Lapland-Kola
		2155		**Central Lapland granitoid complex**			Karelia
			215501	Suonivaara suite	Orosirian		Karelia
			215502	Nilipää suite	Rhyacian	Rhyacian 1	Karelia
			215504	Räväsjärvi suite	Rhyacian?		Karelia
			215505	Pirtinvaara suite	Statherian	Statherian 1	Karelia
			215506	Hamaramaa suite	Rhyacian?		Karelia
			215507	Lohiniva appinite suite	Statherian	Statherian 1	Karelia
			215508	Mellajoki suite	Rhyacian?		Karelia
			215509	Aalistunturi granite suite	not determined		Karelia
			215510	Kinisjärvi suite	not determined		Karelia
			215511	Köngässelkä suite	Statherian	Statherian 1	Karelia
			215599	Diverse lithodemes	not determined		Karelia
		2156		**Vaasa complex**	Orosirian	Orosirian 5	Svecofennia
			215699	Diverse lithodemes	Orosirian	Orosirian 5	Svecofennia
		2158		**Central Finland granitoid complex**	Orosirian	Orosirian 3	Svecofennia
			215801	Kovelahti suite	Orosirian	Orosirian 3	Svecofennia
			215802	Mustajärvi suite	Orosirian	Orosirian 3	Svecofennia
			215803	Haukkamaa suite	Orosirian	Orosirian 3	Svecofennia
			215804	Karhunkylä suite	Orosirian	Orosirian 3	Svecofennia
			215805	Kalmari suite	Orosirian	Orosirian 3	Svecofennia
			215806	Saunakylä suite	Orosirian	Orosirian 3	Svecofennia
			215807	Lestijärvi suite	Orosirian	Orosirian 3	Svecofennia
			215808	Pihtipudas suite	Orosirian	Orosirian 3	Svecofennia
			215809	Karttula suite	Orosirian	Orosirian 3	Svecofennia

Appendix 1. Cont.

EON	ERA	SUPERGROUP CODE SUPERSUITE CODE COMPLEX CODE	GROUP CODE SUITE CODE	UNIT NAME	PERIOD	EPOCH	PROVINCE
			215810	Perho suite	Orosirian	Orosirian 3	Svecofennia
			215811	Vilppula suite	Orosirian	Orosirian 3	Svecofennia
			215899	Diverse lithodemes in Central Finland granitoid complex	Orosirian	Orosirian 3	Svecofennia
		2199		**undefined Paleoproterozoic unit**			
	22			**Mesoproterozoic**			
		2201		**Diverse Mesoproterozoic formations**			
			220101	Diverse mesoproterozoic formations	not determined		
		2210		**Southern Finland rapakivi supersuite**			
			221001	Kymi rapakivi suite	Statherian	Statherian 4	
			221002	Åland rapakivi suite	Calymmian	Calymmian 2	
			221003	Siipyy rapakivi suite	Calymmian	Calymmian 2	
			221004	Taalikkala suite	Statherian	Statherian 4	
			221005	Kuisaari suite	Statherian	Statherian 4	
			221007	Föglö dyke suite	Calymmian	Calymmian 2	
		2211		**Diverse Mesoproterozoic suites and lithodemes**			
			221101	Diverse mesoproterozoic lithodemes	Stenian	Stenian 2	
			221102	Kuhmo kimberlite suite	Stenian	Stenian 1	
			221103	Satakunta olivine diabase suite	Ectasian	Ectasian 3	
		2299		**undefined Mesoproterozoic unit**			
	23			**Neoproterozoic**			
		2301		**Diverse Neoproterozoic formations**			
			230101	Diverse neoproterozoic formations	not determined		
		2310		**Diverse Neoproterozoic suites and lithodemes**			
			231001	Kaavi kimberlite suite	Ediacaran		
			231002	Kuusamo kimberlite suite	Cryogenian		
			231003	Sääksjärvi impact suite	Ediacaran		
		2399		**undefined Neoproterozoic unit**			
3				**Phanerozoic**			
	31			**Paleozoic**			
		3101		**Diverse Paleozoic groups**			
			310101	Dividal group	Cambrian		
			310102	Jerta nappe	Cambrian		
		3110		**Diverse Paleozoic suites and lithodemes**			
			311001	Nalganas nappe	not determined		
			311002	Nabar nappe	not determined		
			311003	Vaddas nappe	Silurian		
			311099	Diverse Paleozoic lithodemes	not determined		
		3199		**undefined Paleozoic unit**			
	32			**Mesozoic**			
		3201		**Diverse Mesozoic suites and lithodemes**			
			320101	Lappajärvi impact suite	Cretaceous		
		3299		**undefined Mesozoic unit**			

GUIDE TO THE GEOLOGICAL MAP OF FINLAND – BEDROCK 1:1 000 000

by

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This Guide is an explanation to the legend of the Geological Map of Finland – Bedrock 1:1 000 000. The background and approach to renewing the map are presented, and the reader is briefly introduced to the terminology of present and past geological units, and to the overall evolution of the Finnish bedrock. The fundamental concepts of tectonic province and province boundary are described, and each tectonic province, as well as the province boundaries, are briefly described. The legend of the map is based on tectonic province division. The core of the Guide is an evolution model from the Neoarchaean to the Cenozoic, linked to the map by legend titles.

Keywords: bedrock, tectonic, units, tectonics, accretion, plate collision, Svecofennian Orogeny, Archean, Proterozoic, Phanerozoic, Finland, Fennoscandian Shield

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BACKGROUND AND APPROACH

Published maps of the bedrock of Finland at the scale 1:1 000 000, starting from early 1900s onwards, have included rock types and associations of various ages. The last bedrock map of this traditional type was published by Simonen (1980). The next one, the Bedrock map of Finland by Korsman et al. (1997), introduced a new approach: the legend reflected the tectonic model adopted by the compilers, and hence the map was a geological rather than a bedrock map. The name of the present map, the Geological Map of Finland – Bedrock (Nironen et al. 1016), was chosen because, like the map of Korsman et al. (1997), it includes a tectonic interpretation.

Twenty years have passed since the publication of the previous map, and several advances have taken place at GTK (Geological Survey of Finland): aerogeophysical mapping covered the whole of Finland by 2007; the 1:100 000 bedrock mapping programme was replaced by thematic mapping projects; and geological map data are now collected into the corporate GTK database. The first version of the harmonized map database was published in 2009. Another step forward included the implementation of stratigraphic classification based on geological units (Finstrati; see Luukas et al., this volume).

Since the time of the previous map compilation in 1997, a vast amount of new isotope data (U–Pb zircon and Sm–Nd data on magmatic rocks, and zircon data on detrital grains in sedimentary rocks) have been published. These data have enabled new ideas on the tectonic evolution from the build-up of an Archaean continent to its break-up and the development of a new Palaeoproterozoic continent during the Svecofennian orogeny, and many of these ideas have ended up in the tectonic model presented here.

The Geological Map of Finland – Bedrock is the printed version (and modification) of a bedrock database (DigiKP1M) at the scale 1:1 000 000. The ca. 200 rock types in the GTK database have been reduced to 119 rock associations for the present map. Similarly to the map of Korman et al. (1997), the rock associations are arranged according to a depositional (sedimentary and volcanic rocks) or intrusive (igneous rocks) setting in specific tectonic environments. A difference from the previous map compilation is that the legend is based on tectonic environments (geodynamic settings) rather than tectonic events; this is not a drastic change, because tectonic events and environments are closely linked. For most rock associations, the tectonic environment is specified, whereas some lack a detailed description, reflecting differences in understanding and available information.

The Archaean and Palaeoproterozoic rocks are variably metamorphosed; this is indicated in the map legend by the prefix 'meta' in the names of supracrustal rocks. However, in the case of igneous and subvolcanic rocks, the protolith name has been used. The Mesoproterozoic rocks are metamorphosed to a low grade (see also Hölttä and Heilimo, this volume).

Much effort has been put into structural interpretation, which is mainly based on aerogeophysical maps and to some extent on direct outcrop observations. The control of deformation zones on bedrock distribution has been emphasized. The interpretations, including the sense of displacement in deformation zones, tend to show the first, ductile deformation, not subsequent displacements that commonly take place in the same zones in brittle-ductile or brittle environments. The net displacements in oblique-slip faults may include e.g. early thrusting and subsequent horizontal displacement.

References are generally made to review articles in the book *Precambrian Geology of Finland – Key to the Evolution of the Fennoscandian Shield* (Lehtinen et al. 2005) instead of original papers published prior to 2005. References to selected later articles have been added to update to the present understanding of the bedrock in Finland and beyond.

GEOLOGICAL OUTLINE

Fennoscandia, used as a geographical term, consists of the countries Norway, Sweden, Finland and the northwestern part of Russia (Fig. 1a). Geologically, this area comprises the Archaean and Proterozoic rocks of the Fennoscandian Shield (also called the Baltic Shield; Gorbatschev & Bogdanova 1993), Neoproterozoic and Phanerozoic sedimentary rocks of the East European Platform, and allochthonous Palaeozoic rocks of the Caledonides (Fig. 1b). The bedrock of Finland mainly consists of crystalline rocks of the Fennoscandian Shield; there are only remnants of platform rocks in onshore Finland.

Fennoscandia is also the name of a crustal segment: the protocontinents Sarmatia and Volgo-Uralia assembled at ca. 2.0 Ga, and at 1.82–1.80 Ga the combined Volgo-Sarmatia collided with the protocontinent Fennoscandia to form the new continent Baltica, corresponding to the present East European Craton (Fig 1b; Gorbatschev & Bogdanova 1993, Bogdanova et al. 2008, Bogdanova et al. 2015).

The Archaean bedrock of Finland is dominated by TTG (tonalite-trondhjemite-granodiorite) group rocks with an age span of 3.5–2.73 Ga (Fig. 1c; Hölttä et al. 2012a and references therein). Other plutonic rocks include sanukitoids, quartz diorites and granites, with ages from 2.74 Ga to 2.66 Ga. Moreover, there are paragneisses and greenstone belts with variable lithologies: the Kuhmo

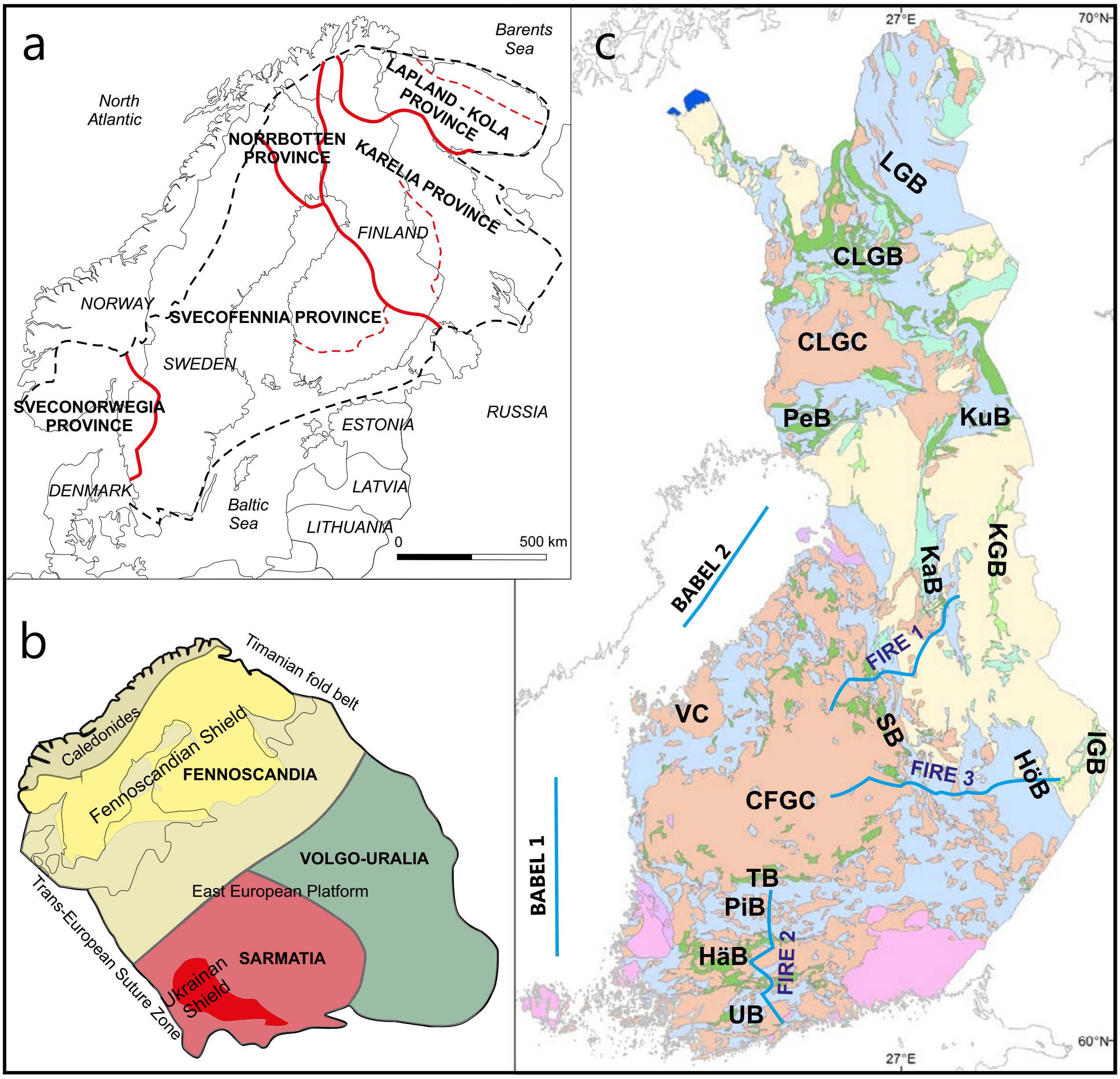


Fig. 1. a) Tectonic provinces in the Fennoscandian Shield (modified from Lahtinen et al. 2005, Daly et al. 2006, Bingen et al. 2008). Province boundaries are shown by solid red line, subprovince boundaries by broken red line. b) The East European Craton (Baltica) with crustal segments Fennoscandia, Sarmatia and Volgo-Uralia (modified from Gorbatschev and Bogdanova 1993). c) Generalized bedrock map of Finland. The locations of BABEL 1 and 2 deep seismic reflection profiles, and sections of FIRE 1, FIRE 2 and FIRE 3 profiles are shown by blue lines. LGB = Lapland granulite belt, CLGB = Central Lapland greenstone belt, CLGC = Central Lapland granitoid complex, PeB = Peräpohja belt, KuB = Kuusamo belt, KGB = Kuhmo greenstone belt, KaB = Kainuu belt, SB = Savo belt, IGB = Ilomantsi greestone belt, HöB = Höytiäinen belt, VC = Vaasa complex, CFGC = Central Finland granitoid complex, TB = Tampere belt, PiB = Pirkanmaa belt, HäB = Häme belt, UB = Uusimaa belt.

greenstone belt (Fig. 1c) consists of ca. 2.84–2.80 Ga komatiitic, basaltic rocks overlying felsic metavolcanic rocks, whereas the Ilomantsi greenstone belt is dominated by metasedimentary rocks, with 2.76–2.72 Ga felsic metavolcanic rocks and less abundant komatiitic rocks.

The Palaeoproterozoic metavolcanic–metasedimentary successions partially covering the Archaean basement in eastern Finland (and northwestern Russia) have traditionally been grouped together as Karelian formations. The deposition of these rocks onto the Karelia craton spans over 500 Ma, from 2.44 Ga to less than 1.92 Ga (Laajoki 2005, Lahtinen et al. 2010). The Karelian formations have been divided into the Sumi, Sariola, Jatuli and Kaleva tectofacies (Laajoki 2005) or chronostratigraphic systems (Hanski & Melezhik 2013). In the tectofacies concept, the tectofacies are separated by major unconformities, and they mark changes in the tectonic environment from intracontinental rifting to continental break-up: Sumi, Sariola and Jatuli represent continental–epicontinental deposits, and Kaleva represents a shift from a rift-marginal basin to a marine basin. The Sumi and Sariola rocks have a scattered occurrence in eastern and northern Finland, whereas the Jatuli rocks form the main part of the Proterozoic cover on the Archaean bedrock.

Layered mafic intrusions with ages around 2.44 Ga occur at the southern margin of the Peräpohja and Kuusamo belts, and in central Lapland (Hanski & Huhma 2005; Fig. 1c). These rocks, as well as 2.44 Ga felsic metavolcanic Sumi rocks, mark the onset of rifting of the Archaean crust in Finland. Mafic magmatism at 2.3 Ga, 2.2 Ga, 2.1 Ga and 2.05 Ga, in the form of intrusions, sills and dyke swarms, is further evidence of episodic extension of the crust (Hanski & Huhma 2005, Vuollo & Huhma 2005).

The depositional ages of the immature clastic metasedimentary and ultramafic–mafic metavolcanic Sariola rocks and the metavolcanic–metasedimentary Jatuli rocks range from 2.43 Ga to 2.3 Ga and from 2.3 Ga to 2.06 Ga, respectively (Laajoki 2005, Hanski & Melezhik 2013). The composition of the Jatuli rocks varies spatially: the remnant basin fills in the Höytiäinen belt (Fig. 1c) are quartzites, whereas arkosites and sedimentary carbonate rocks dominate further north; sedimentary carbonate rocks are missing in central Lapland.

The Kaleva rocks include turbiditic metagreywackes and minor metaconglomerates in the Höytiäinen, Savo, Kainuu and Peräpohja belts, and predominantly homogeneous deep marine metapsammites, occurring west of the Höytiäinen belt and in the Kainuu belt (Fig.1c). Remnants of 1.95 Ga ophiolite complexes occur as tectonic slivers in the metapsammites (Peltonen 2005, Peltonen et al. 2008). The Kaleva deposits have been variously divided (Lower/Upper, Eastern/Western), and they probably represent both early rift basin (ca. 2.1 Ga) and collision-related (ca. 1.9 Ga) foredeep to foreland deposits that together were thrust into complex allochthonous packages between 1.95 Ga and 1.92 Ga, during an initial stage of the Svecofennian orogeny (see below; Kohonen 1995, Lahtinen et al. 2010, Ranta et al. 2015).

The oldest rocks in the Finnish bedrock, not related to rifting of the Archaean crust, are the ca. 2.0 Ga oceanic mafic–ultramafic metavolcanic rocks and serpentinites in the Central Lapland greenstone belt (Fig. 1c; Hanski & Huhma 2005). They occur as slivers in an allochthonous–parautochthonous package of younger Palaeoproterozoic supracrustal rocks that was emplaced during an initial stage of the Svecofennian orogeny (Lahtinen et al. 2005).

In northernmost Finland, intrusive rocks with ages of 1.95–1.93 Ga (Meriläinen 1976), and the surrounding supracrustal rocks as well as the Lapland granulite belt (Fig. 1c), are parts of the Lapland–Kola orogen. The Lapland–Kola orogen developed at 1.95–1.91 Ga, initially as accretion and finally as continental collision (Daly et al. 2006). Noritic-enderbitic rocks intruded metasediments of the Lapland granulite belt at 1.92–1.91 Ga, the peak of granulite grade regional metamorphism was attained during 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 (Tuisku & Huhma 2006).

A complex set of orogenic events, jointly named as the Svecofennian orogeny, occurred during 1.92–1.77 Ga (Korsman et al. 1999, Lahtinen et al. 2005) and caused the growth of new juvenile crust in central and southern Finland. The oldest Svecofennian rocks in this area are the 1.92 Ga primitive island arc rocks in the Savo belt (Fig. 1c; Kähkönen 2005). Nd isotopic evidence (Lahtinen & Huhma 1997, Rämö et al. 2001) suggest a ≥ 2.0 Ga nucleus for the Central Finland granitoid complex (Fig. 1c) and southernmost Finland. Island arc-type volcanic rocks and mafic–ultramafic intrusions, similar to rocks found in deeply eroded parts of modern oceanic and continental arcs, were emplaced into older, mainly turbiditic sequences (now biotite paragneisses and metagreywackes) at 1.90–1.87 Ga (Kähkönen 2005, Peltonen 2005), and together these assemblages form a curving (Z-type) belt that extends from the

Tampere belt to the northwest, encircles the Vaasa complex and continues to north-central Sweden (Skellefte district). Granitoids and minor gabbros (1.89–1.87 Ga) intruded the supracrustal rocks and formed the Central Finland granitoid complex (Nironen 2005). Together, these rocks comprise the Western Finland arc complex.

In southern Finland, the Häme belt is dominated by 1.89–88 Ga arc-type intermediate and arc rift-type mafic metavolcanic rocks (Fig. 1c; Kähkönen 2005). Synvolcanic mafic intrusions occur among the metavolcanic rocks (Peltonen 2005). In the Uusimaa belt, 1.90–88 Ga felsic to ultramafic metavolcanic rocks with arc-type to MORB-type geochemical characteristics, occurring among metagreywackes, quartz-feldspar gneisses and sedimentary carbonate rocks, are crosscut by 1.88–1.87 Ga granitoids (Kähkönen 2005). This part has been referred to as the Southern Finland arc complex.

Three regional metamorphic events overprinted the rocks in southern and central Finland during the Svecofennian orogeny. An early (ca. 1.91 Ga) metamorphic event preceded emplacement of pyroxene-bearing granitoids in the Savo belt (Fig. 1c; Lahtinen et al. 2015a). The main Svecofennian high-T/low-P type (1.88–1.87 Ga) event generally reached upper amphibolite grade, and can be detected throughout the Finnish Svecofennian (Korsman et al. 1999, Hölttä & Heilimo, this volume). The late Svecofennian high-T metamorphism (1.84–1.80 Ga) reached granulite grade in large areas in southernmost Finland and was associated with transpressional deformation and emplacement of 1.84–1.81 Ga granites. Two metamorphic events in western Lapland at 1.92–1.90 Ga and 1.86–1.85 Ga have recently been suggested (Lahtinen et al. 2015b). These may be associated with the Svecofennian orogeny, whereas a later (1.79–1.77 Ga) metamorphic event, recorded in large areas in central and western Finnish Lapland (Corfu & Evins 2002, Ahtonen et al. 2007, Niiranen et al. 2007), possibly has a different tectonic connotation.

After 1.76 Ga, orogenic activity ceased in the area of Finland and the continental crust was gradually stabilized. During 1.65–1.54 Ga, a crustal rifting episode caused emplacement of the rapakivi granites of southern Finland, as well as associated anorthosites and mafic dykes (Rämö & Haapala 2005). Rapakivi magmatism was the last major increment to the Precambrian bedrock of Finland.

TECTONIC PROVINCES

A major aim of the present Guide is to describe the evolution and relationships of the four fundamental, continent-scale lithospheric blocks, named as tectonic provinces (see inset map). The legend of the map is aimed to explain the stage of evolution *at 1.86 Ga, when four lithospheric blocks had been united to form a new Palaeoproterozoic continent, consisting of the tectonic provinces Karelia, Lapland–Kola, Norrbotten and Svecofennia*. The rocks coeval or older than the assembly are grouped under the title 'Tectonic provinces'. After the 1.86 Ga assembly, the tectonic provinces had a common tectonic history. The supracrustal or plutonic rocks that were deposited or intruded after the assembly, and some rocks that were emplaced in foreland environment before 1.86 Ga, are shown beyond the explanation of the tectonic provinces. In the following sections, the tectonic provinces and their boundaries are briefly described, with emphasis on the tectonic units within the provinces.

Tectonic province definition

In the past years, 'megaunits' in Fennoscandia have been referred to using several qualifying terms such as craton, orogen, belt, province and domain (e.g. Gáal & Gorbatschev 1987). Logical division of bedrock into major crustal blocks is conceptually difficult, and internationally established definitions such as geologic province (see Neuendorf et al. 2005) are rather vague. In this Guide, the geological province scheme of Geoscience Australia (http://www.ga.gov.au/applications/provexplorer/australian-geological-provinces) is taken as a basis. The tectonic provinces are groups of other types of provinces (sedimentary, igneous, structural, metamorphic or metallogenic) that are linked by a common tectonic history. Provinces may be small or large, and they are four-dimensional: in addition to an area and thickness, they represent a definable period of geological time. The definable period of geological time for the tectonic provinces under consideration starts from Palaeoproterozoic (1.86 Ga) amalgamation. In addition to the Geoscience Australia definition, tectonic provinces are here defined as lithospheric blocks that were separated from each other by oceanic lithosphere before the Palaeoproterozoic assembly. The conceptual difference between a tectonic province and an orogen is that a tectonic province is a component in accretion or collision, whereas orogen is a region that has been subjected to deformation during an orogenic cycle that results from accretion or collision; an orogen normally comprises parts of at least two provinces. As an example, in Finland, only the easternmost part of the Karelia Province is relatively unaffected by the Svecofennian orogeny, and consequently, the Svecofennian orogen covers much of the Karelia Province. The entire Fennoscandian Shield is divided according to the tectonic province scheme (Fig. 1a).

The **Karelia Province**, extending east to northwestern Russia and west to northern Sweden, is the largest province within the Fennoscandian Shield and consists of Archaean crust partly overlain by the Palaeoproterozoic cover sequence (the Karelian formations). The Finnish part of the Karelia Province has been divided into two subprovinces: the Western Karelia Subprovince, which consists of Mesoarchaean and Neoarchaean complexes and includes most of the Archaean bedrock of Finland, and the Central Karelia Subprovince, which barely extends to the easternmost part of Finland and is characterized by a short Neoarchaean crustal growth period (Fig. 1a; Hölttä et al. 2012b).

In the Finnish part of the Karelia Province, autochthonous Palaeoproterozoic cover rocks mainly occur in northern Finland. In addition to these, there are several allochthonous units mainly consisting of craton margin sequences: the Northern Karelia and Kainuu nappe complexes in eastern Finland, the Northern Ostrobothnia nappe system in central Finland and the Central Lapland nappe complex in Lapland (Fig. 2a; see also Luukas et al., this volume). The sequences in the Northern Savo nappe complex are of mixed origin.

The main part of the exposed **Lapland–Kola Province** is in the Kola Peninsula of Russia (Fig. 3). Daly et al. (2001) described the Lapland–Kola Province (orogen) as a collage of partially reworked late Archaean terranes and intervening belts of Palaeoproterozoic juvenile crust, welded together in the Palaeoproterozoic. Daly et al. (2001) considered the Archaean Belomorian belt part of the orogen. Although the Belomorian belt experienced metamorphic reworking during the Palaeoproterozoic that did not affect the 'Karelian protocraton' to the southwest (Bibikova et al. 2001), and early Palaeoproterozoic mafic-felsic volcanism occurred in the boundary area (Bogina et al. 2015), there is no evidence for separation of the Belomorian belt from the 'Karelian protocraton', with an oceanic basin between, during the Palaeoproterozoic. Therefore, according to the tectonic province definition given above, the Belomorian belt is included in the Karelia Province. Similarly, the area in the northern part, referred to as Murmansk craton, is here considered as a subprovince within the Lapland–Kola Province, because it remained assembled with other Archaean blocks throughout the Palaeoproterozoic Era (Daly et al. 2006). The predominant part of the Lapland–Kola orogen in Finland is the Palaeoproterozoic Northern Lapland nappe system (Fig. 2a). The Sodankylä nappe, located within the Karelia Province, is part of the Northern Lapland nappe system (see also Luukas et al., this volume).

The **Norrbotten Province** was recently introduced as a crustal block (Lahtinen et al. 2005). It is separated from the Karelia Province by a major shear zone (Lahtinen et al. 2015a), and consists of Archaean crust partly overlain by a Palaeoproterozoic sequences. The Ylläs nappe (Fig. 2a) in the eastern part of the Norrbotten Province consists of two clastic sedimentary rock sequences, with depositional ages of 1.92–1.90 Ga (Lahtinen et al. 2015a) and ≤1.88 Ga (Hanski & Huhma 2005).

An assemblage of Palaeozoic rocks within the Norrbotten Province, at the northwestern tip of Finland, are part of the fold and thrust belt that was displaced eastwards upon the Precambrian rocks of the Norrbotten Province during the 430–390 Ma Scandian event of the Caledonian orogeny (Roberts 2003). Since this subhorizontal lithologic package (Palaeozoic rocks on top of Precambrian rocks) does not have a common tectonic history, it is not considered to be a separate tectonic province.

The **Svecofennia Province** consists almost solely of Palaeoproterozoic rock assemblages. The Palaeoproterozoic juvenile crust of Finland is considered to have formed by accretion of the Western Finland and Southern Finland arc complexes to the Archaean continent during the Svecofennian orogeny (Nironen 1997, Lahtinen et al. 2005). These arc complexes are respectively denoted as the Western Finland Subprovince and Southern Finland Subprovince. The terms Central Svecofennian and Southern Svecofennian (arc complex) have also been used, but since these terms cover areas that extend beyond Finland and are not properly defined, the present subprovince division of Svecofennia is restricted to the area of Finland.

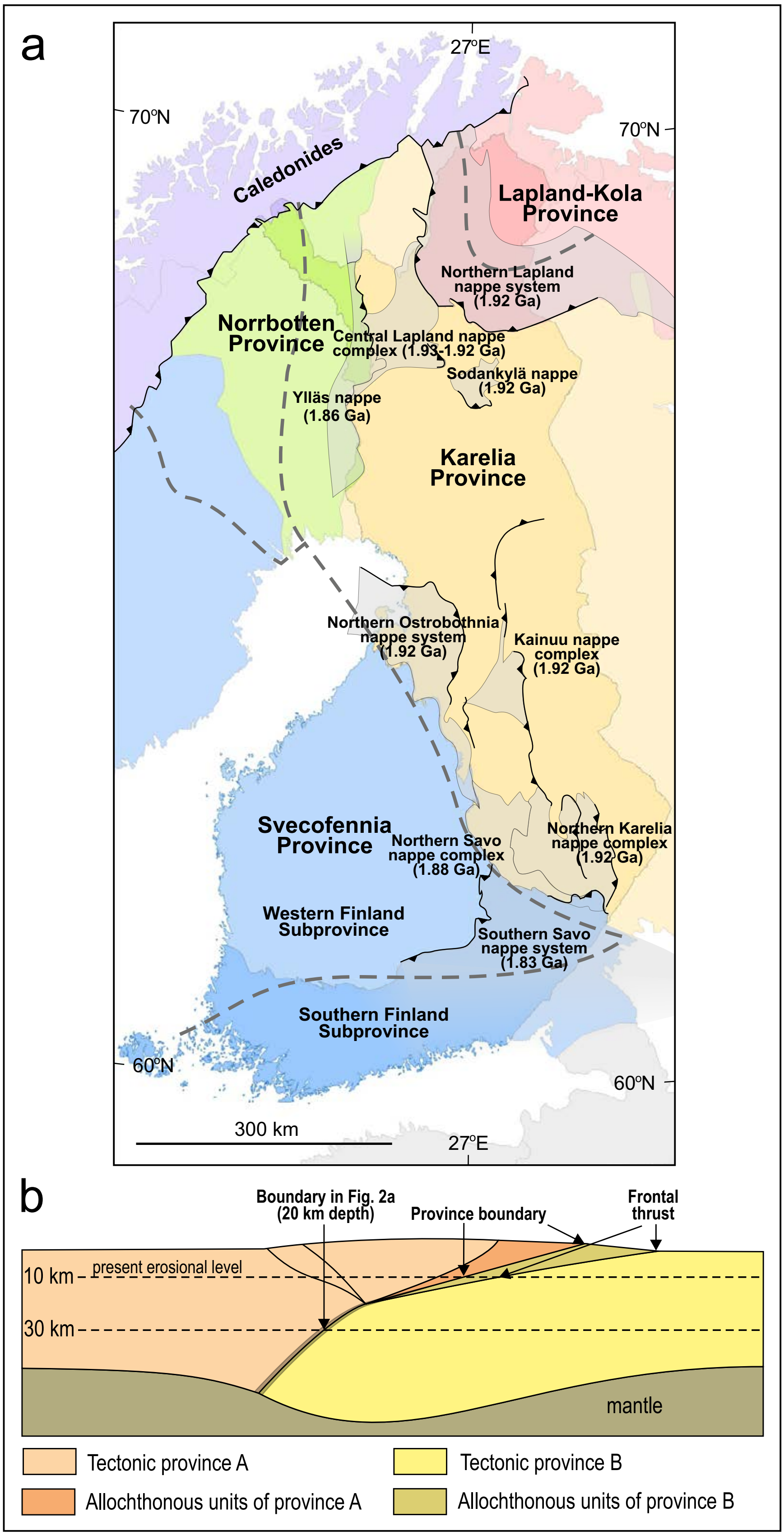


Fig. 2. a) Allochthonous units and tectonic boundaries in and around Finland. Allochthonous units are shown by grey shading. The ages given for allochthonous units denote the age of first thrusting; the units may have been involved in several thrusting events. Frontal thrusts and their dip directions are shown by thin black lines. Province boundaries are shown as they are from the surface down to the base of allochthonous units (= a few km depth). Sutures, interpreted at ca. 20 km depth, are shown by thick broken lines. b) Schematic presentation of the tectonic boundaries.

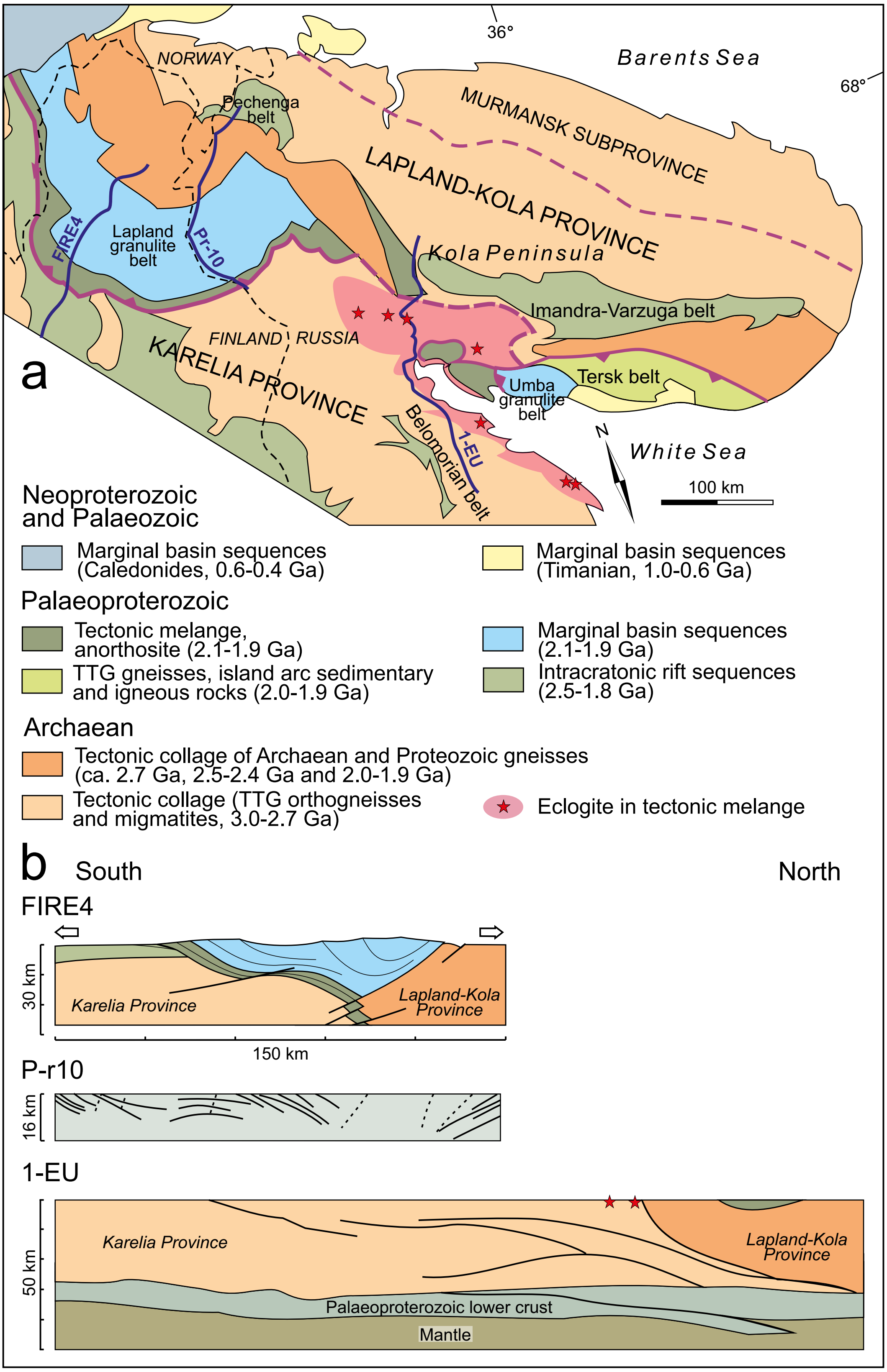


Fig. 3. a) Tectonic units in the Lapland–Kola Province (modified from Daly et al. 2006 and Mints et al. 2014). The tectonic province boundary (with inferred dip) is shown by a thick purple line (broken when poorly constrained). b) Interpretations of seismic profiles. The interpretation of profile FIRE4, modified from the present structure (Patison et al. 2006), is the assumed palaeosetting at 1.87 Ga. Thick black lines are thrust zones, thin lines indicate the general structural pattern. Interpretation of profile Pr–10 (without interpretation of crustal components) is a modification from Daly et al. (2006). Solid black lines are reflective layers, broken lines are fault zones. Profile 1–EU is a simplification of the one presented by Mints et al. (2014). Thick black lines are thrust zones. Stars denote eclogite occurrences.

Province boundaries

The definition of tectonic provinces – lithospheric blocks that were once separated from each other by oceanic lithosphere – implies that the province boundaries are marked by sutures. Sutures are cryptic zones that can usually be vaguely inferred due to orogenic reworking of the crust. In Figure 2a, tectonic province boundaries are interpreted to ca. 20 km crustal depth to give a three-dimensional impression. The interpretation to depth is based on reflection seismic data (Lapland – Kola – Karelia, Karelia – Svecofennia; Korja et al. 2006, Patison et al. 2006, Sorjonen-Ward 2006, Korja & Heikkinen 2008) and isotopic data (Karelia – Svecofennia; e.g. Huhma 1986; Patchett & Kouvo 1986, Lahtinen & Huhma 1997).

The foreland frontal thrusts are shown where they can be identified. Metamorphism in the Svecofennian orogen is characterized by fairly uniform 4–6 kbar pressures (Korsman et al. 1999, Hölttä & Heilimo, this volume), corresponding to 10–15 km crustal depth; thus, the Svecofennian frontal thrusts are comparable with deeper sections of similar thrusts in modern collisional orogens. The position of province boundary at various crustal depths is schematically presented in Figure 2b.

The Lapland – Kola – Karelia boundary is shown by a frontal thrust, dipping 10–20° NE. The shallow dip is well constrained by reflection seismic data (Fig. 3b). The province boundary at 20 km depth is at the intersection of seismic reflections: to the northeast, the reflections dip moderately SW.

The Norrbotten Province contains the Ylläs nappe, the extent of which is poorly constrained – hypothetical towards the north – but a frontal thrust can be defined for ca. 100 km length. The Norrbotten – Karelia boundary is inferred to dip to the west.

The Svecofennia – Karelia boundary, studied for decades, has been demonstrated to be complex. The boundary may be located fairly accurately to 10–20 km depth by reflection seismic data (Korja & Heikkinen 2008), and to Moho depth by refraction seismic data (Luosto et al. 1984, Korja et al. 1993). In the centre of the Savo belt, the suture is interpreted to be subvertical to 10–15 km depth, and to dip shallowly towards ENE at deeper levels (Fig. 4c). Further southeast, the Northern Karelia nappe complex overlies the Archaean crust to 10–15 km depth (Fig. 4d; Sorjonen-Ward 2006). Overall, the structure is interpreted to be a wedge of Archaean crust, underlain and partly overlain by Svecofennian crust (Korja & Heikkinen 2008).

It is difficult to assess the location of the boundary between the Western Finland and Southern Finland Subprovinces because of structural overprinting. In the east, the boundary is arbitrarily set to follow the frontal thrust of a late Svecofennian allochthonous unit (Southern Savo nappe system, Fig. 2a). However, rocks considered to be part of the Western Finland Subprovince are exposed as a tectonic window within the Southern Savo nappe system, implying that the boundary is actually further south. Continuation to the west is also ambiguous: in the centre, the boundary is defined by shear zones, and in the west the subprovince boundary was interpreted on a lithological basis. Reflection seismic data (Korja & Heikkinen 2008) suggest that in the central part, the boundary is subvertical (cf. Figs. 2a and 4e).

TECTONIC EVOLUTION FROM THE NEOARCHAEAN TO THE CENOZOIC

The following model is aimed to give an overall tectonic framework for the Geological Map. Nevertheless, it necessarily extends beyond the national boundaries of Finland and incorporates tectonic evolution of the present Fennoscandian Shield. Two periods fundamental to the evolution are emphasized: 1) the break-up of the Neoarchaean continent (Karelia craton) at 2.1–2.05 Ga; and 2) the assembly of four lithospheric blocks (Karelia, Lapland–Kola, Norrbotten and Svecofennia) at 1.92–1.86 Ga to form a new Palaeoproterozoic continent (protocontinent Fennoscandia).

The model (Figs. 5–6, 8–10) is presented so that the Karelia Province is the ‘fixed block’, and the other crustal components move with respect to it. The coordinates in the text refer to present directions. The numbers in parentheses [ ] refer to numbered rock associations in the map legend. The palaeogeographic reconstructions are outlined.

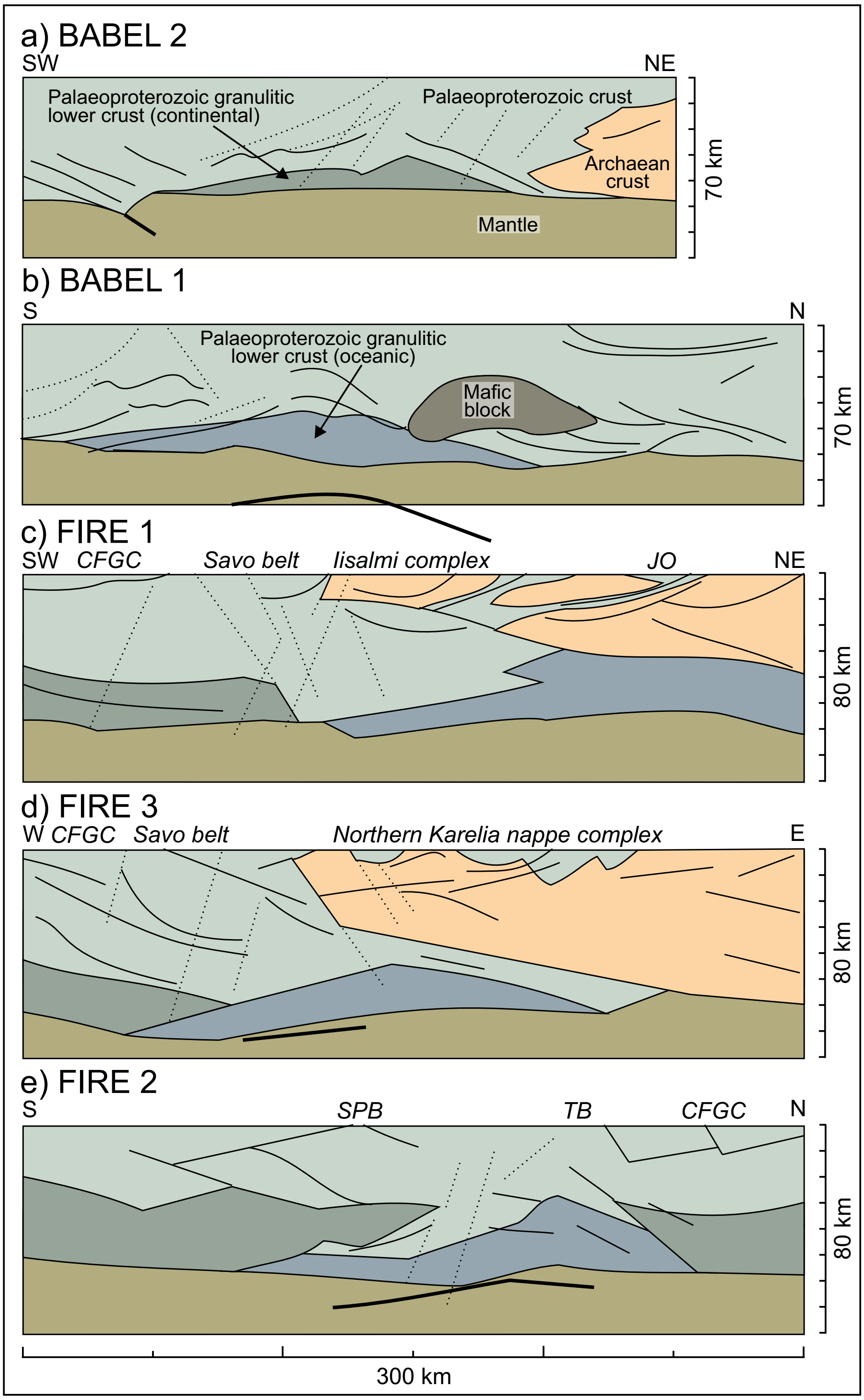


Fig. 4. Selected sections along BABEL and FIRE deep seismic reflection profiles (simplified from Lahtinen et al. 2009a). No vertical exaggeration. Crustal reflections are shown as thin black lines, mantle reflections as thick black lines, and faults/shear zones as broken lines. CFGC = Central Finland granitoid complex, JO = Jormua ophiolite, TB = Tampere belt, SPB = Subprovince boundary. For the profile locations, see Figure 1.

Assembly of the Neoarchaean continent (3.1–2.68 Ga)

The Archaean bedrock of the Karelia Province has been extensively studied during the past 15 years (e.g. Slabunov et al. 2006, Hölttä et al. 2012a, Mints et al. 2014). Previously scattered information (mainly in Russian) on the Archaean terranes in the Lapland–Kola Province has recently been compiled (Daly et al. 2001, Daly et al. 2006), whereas little is known of the Archaean bedrock in the Norrbotten Province.

The komatiitic and basaltic rocks of the Kuhmo greenstone belt resemble geochemically modern oceanic plateau basalts, and Hölttä et al. (2012b) suggested that the komatiites were erupted onto a rhyolitic-dacitic-tholeiitic oceanic plateau. In contrast, the metavolcanic rocks of the Ilomantsi greenstone belt probably represent arc magmatism within an attenuated continental margin. Overall, the geochemical data from Finland suggest the evolution of Archaean rocks in various geodynamic settings. The oldest Archaean terranes within the Fennoscandian Shield are Mesoarchaean in age (the 3.5–3.1 Ga Vodlozero microcontinent; Slabunov et al. 2006). Two core areas of the Neoarchaean assembly were the Karelia and Murmansk cratons, and the Belomorian belt was an orogenic belt between these cratons. Eclogitic bodies in Neoarchaean mélanges evidence Mesoarchaean (2.87 Ga; Mints et al. 2010) and Neoarchaean (2.79–2.73 Ga; Dokukina et al. 2014) eclogite facies metamorphic events in rocks of oceanic origin, and the metamorphic events as well as regional-scale nappe complexes have been associated to subduction and collision (Slabunov et al. 2006, Mints et al. 2009, Mints et al. 2014). Terrane accretion initiated at 3.1 Ga (Slabunov et al. 2006), but in Finland the exotic terranes probably only accreted at ca. 2.83–2.75 Ga. Collisional crustal stacking that resulted in the formation of a new Neoarchaean continent occurred at 2.73–2.68 Ga (Hölttä et al. 2012a). The continent included the blocks represented by the tectonic provinces Karelia and Lapland–Kola. The palaeogeographic setting of the Norrbotten Province at this stage is unknown.

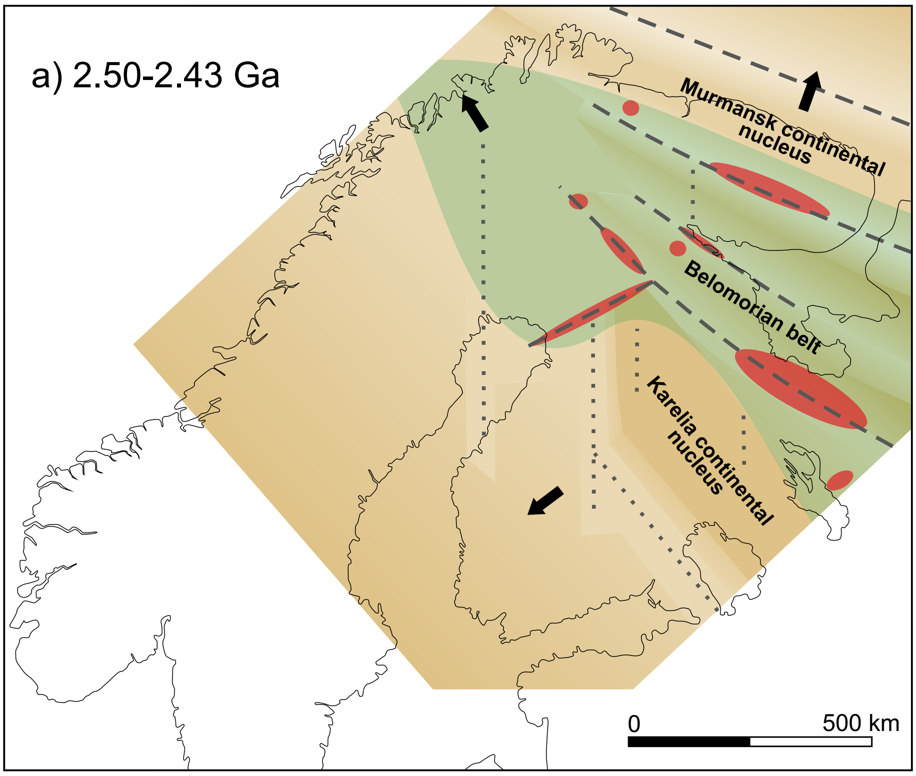
In palaeogeographic reconstructions the 2.7 Ga accretions have been assigned to assembly of the supercontinent Kenorland (Williams et al. 1991). Bleeker (2003) proposed the existence of separate supercratons Superia, Sclavia and Vaalbara instead of a single supercontinent. Based on palaeomagnetic evidence, at 2.7–2.6 Ga Karelia (i.e. Archaean rocks of the Karelia Province) was located at high latitudes (80–60°; Mertanen & Korhonen 2011).

Cratonic stage with intermittent extensional episodes (2.68–2.1 Ga)

After collisional orogeny, the new continent stabilized to form a craton, referred to as the Karelia (or Karelian) craton. The shear zones in at least N–S and ENE–WSW directions in the Karelia Province have a long history: they possibly developed during amalgamation of the Archaean terranes and were reactivated during subsequent extensional events. An indication of such a long history is the 2.61 Ga Siilinjärvi carbonatite [83] in east-central Finland (O'Brien et al. 2005): it occurs as a N–S-trending vertical tabular body, was probably emplaced in a Neoarchaean rift, and is presently delimited by Palaeoproterozoic shear zones.

The depositional age of quartzites and arkosites in Central Lapland [87] and quartz-feldspar paragneisses in the Kainuu belt [92] have been interpreted as Neoarchaean (Lahtinen et al. 2015a). If this interpretation is correct, the first extensional rift basin(s) developed in the Neoarchaean continent already during 2.6–2.5 Ga. The first unequivocal examples of Palaeoproterozoic extension are the 2.50 Ga layered mafic intrusions in the Kola Peninsula, associated with crustal uplift and erosion (Fig. 5a; e.g. Amelin et al. 1995, Bayanova et al. 2009).

A major extensional event at 2.44–2.43 Ga resulted in emplacement of layered mafic intrusions, felsic intrusions and intermediate–felsic volcanic rocks of the Sumi system [82-80] in intracontinental rift basins in northern Finland (Hanski & Huhma 2005, Hanski & Melezhik 2013) and basalts in Russia (Bogina et al. 2015). The layered intrusions and metavolcanic rocks occur in NW-SE trending zones, and in an almost orthogonal zone at the Archaean–Proterozoic boundary in the Peräpohja and Kuusamo belts (Fig. 1; Iljina & Hanski 2005, Hanski & Huhma 2005). The assumption here is that these intrusions were originally emplaced in an ENE-WSW-trending extensional zone (Fig. 5a). These two directions suggest large-scale extension in the present northern Fennoscandia, probably as the result of a mantle plume upwelling (Hanski & Huhma 2005, Melezhik & Hanski 2013). Basalts (Kulikov et al. 2010) and basaltic dykes and sills in the Archaean basement (Vuollo & Huhma 2005,



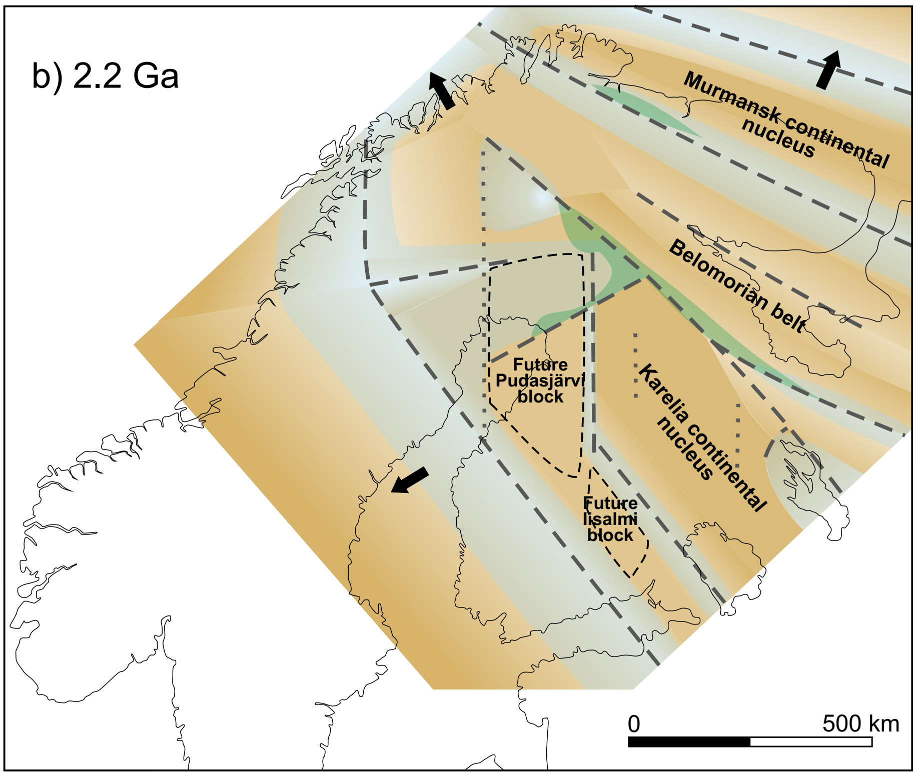


Fig. 5. a) Archaean continental crust at 2.50–2.43 Ga (modified from Melezhik and Hanski 2012). The present location of 2.50–2.43 Ga mafic plutonism is shown schematically by red areas. The inferred extent of continental flood basalt magmatism is shown by green shading, old deformation zones are shown by dotted lines and active deformation zones by broken lines. Note that the active deformation zones are drawn according to the magmatic centres in their present settings, not in their palaeosettings during 2.50–2.43 Ga. Directions of tectonic transport are shown by black arrows. b) Archaean continental crust at 2.2 Ga. Variation in crustal thickness is shown by a variable intensity of colouring (darker = thicker crust, lighter = thinner crust). Mafic volcanism is shown by green shading, sedimentary basins by blue shading.

Stepanova & Stepanov 2010) suggest the formation of a large flood-basalt province (Fig. 5a; cf. Melezhik & Hanski 2013).

The deposition of Sumi system rocks was followed by a period of weathering in semi-arid conditions, and the removal of much of the deposits during rift inversion (Laajoki 2005, Karinen 2010). Immature sedimentary rocks [78], including glaciogenic rocks, represent the Sariola system and are found at the margins of the Höytiäinen, Kainuu and Peräpohja belts (Fig. 1). Ultramafic and mafic rocks, occurring in the Kuusamo belt and in central Lapland [77], were deposited upon the sedimentary Sariola rocks or directly on Archaean gneisses. The Sariola rocks were probably deposited in reactivated rift basins during 2.43– 2.35 Ga.

The occurrences of a palaeosol and a major unconformity imply intense weathering and deep erosion in a warm and humid climate after the deposition of the Sariola rocks (Laajoki 2005). The subaerial palaeosol may have covered large areas of the continent, with a low topographic relief during the deposition of the Jatuli system sediments.

The beginning of Jatuli has been set at 2.3 Ga (Hanski & Melezhik 2013). Quartzites and arkosites of the Jatuli system [76] are voluminous in the Peräpohja belt, Kuusamo belt, and Central Lapland greenstone belt; Laajoki (2005) proposed a relative rise in the epicontinental sea level in the Karelia craton and the deposition of transgressive fluvial and deltaic sediments. The quartzites and arkosites are intruded by 2.2 Ga sills and dykes that evidence an extensional event within the Karelia craton (Vuollo & Huhma 2005), although the volume of mafic magmatism was probably less than during 2.44–2.43 Ga (Fig. 5b).

Palaeomagnetic studies indicate the drift of Karelia to near-equatorial palaeolatitudes by ca. 2.50–2.45 Ga (Mertanen & Korhonen 2011 and references therein, Pesonen et al. 2012). Based on palaeomagnetic evidence from dyke swarms, Bleeker and Ernst (2006) suggested that Karelia was attached to the Superior craton at 2.45 Ga, and that both were part of the supercraton Superia. However, a more recent palaeomagnetic study of dykes in eastern Finland (Salminen et al. 2014) does not support such an assembly.

Attenuation and break-up of the craton (2.1–2.05 Ga)

The quartzites [74], deposited after 2.2 Ga, and an increasing amount of metasedimentary carbonate rocks [73] record a shift from rift-controlled, fluvial-dominated system to open sea conditions, with development of carbonate platforms (Fig. 5b; Laajoki 2005, Melezhik & Hanski 2013). Graphite-sulphide paraschists [72-71] in the Lapland greenstone belt suggest the development of a separate euxinic basin.

The final break-up of the Karelia craton initiated at 2.1 Ga (Fig. 6a; see Lahtinen et al. 2010). Extension is evidenced as 2.1 Ga granites in northern Finland [62] (Ahtonen et al. 2007, Lauri et al. 2012), and especially as ca. 2.1 Ga tholeiitic dyke swarms that extend from eastern Finland to Russia (Vuollo & Huhma 2005, Stepanova & Stepanov 2010). Mafic intrusions in northern and central Finland [61] and ultramafic-mafic volcanic rocks in central Lapland [70] are of 2.06–2.05 Ga age. Emplacement of the 2.1 Ga dykes and 2.06–2.05 Ga magmatic rocks has been associated with mantle plume activity (Hanski & Huhma 2005, Lahtinen et al. 2015b). Moreover, the cratonic break-up is coeval with end of the 'Lomagundi-Jatuli isotopic excursion', an increase in $\delta^{13}C$ values of Jatulian carbonate rocks during 2.2–2.1 Ga, and drop at 2.06 Ga (Karhu 2005, Hanski & Melezhik 2013). The relationship between these two events is unclear.

A divergent triple point is modelled on top of a plume head, with continental break-up and development of a failed rift in northern Finland (Fig. 6a). An unknown amount of continental mass drifted away, continental ribbons and smaller extensional blocks were separated from the attenuated continental margin, and a volcanic margin developed in the southwest. In Figure 6a, a flood-basalt province is outlined in the continental nucleus. Part of the Kaleva system rocks [67] possibly represent sedimentation in the newly formed marginal basins.

Daly et al. (2006) modelled the opening of a narrow oceanic basin between the Karelia and Murmansk continental blocks as the result of 2.5–2.1 Ga rifting and final break-up. Palaeoproterozoic (1.98–1.94 Ga) juvenile crust, found as magmatic rocks of the Lapland granulite, Umba and Tersk belts (Fig. 3) was formed, presumably in an island-arc setting. The volcanic-sedimentary rocks of the Pechenga belt represent a continental rift environment, with attenuation of the crust between 2.06 Ga and 2.02 Ga (Fig. 6a; Melezhik et al. 2007, Hanski et al. 2014).

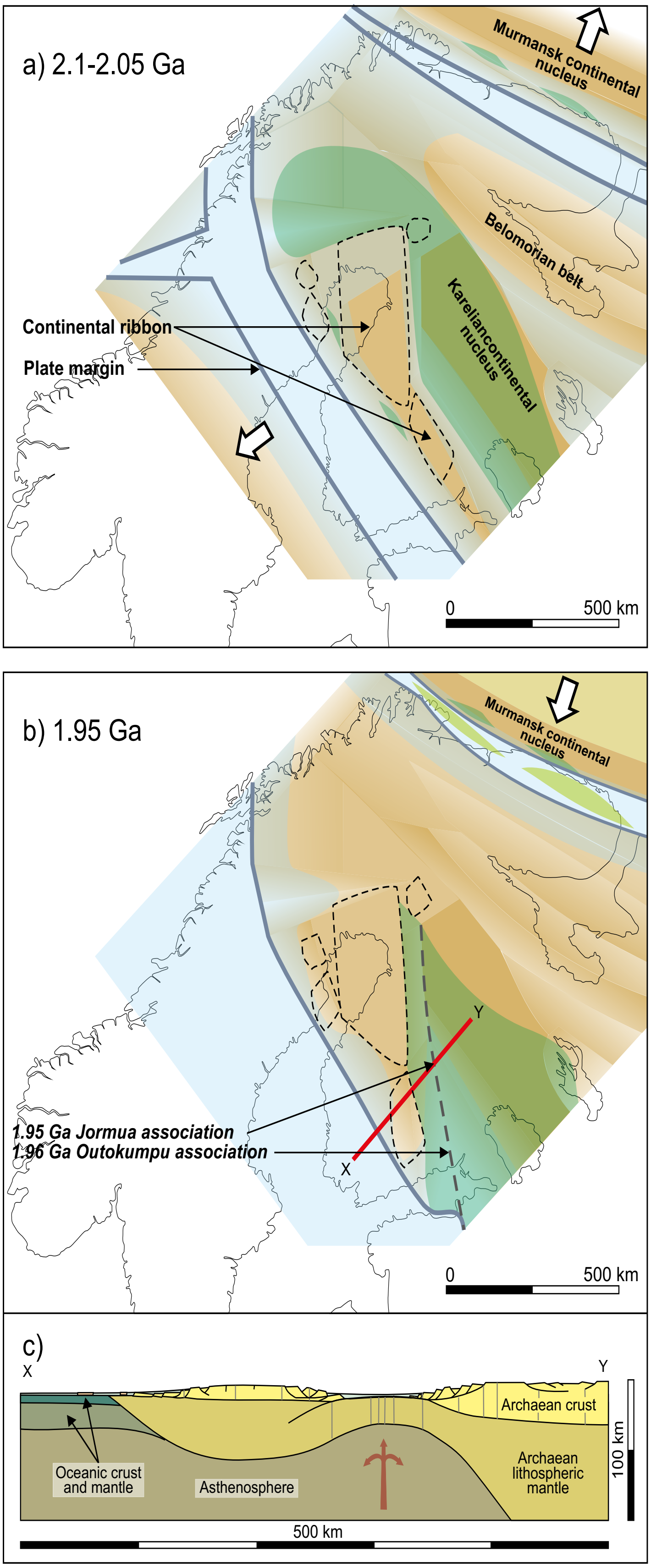


Fig. 6. a) Break-up of Archaean continental crust at 2.1–2.05 Ga. Newly separated continental ribbons and smaller extensional blocks are shown. b) Margins of the remnant Archaean continent at 1.95 Ga. Two ophiolite complexes (Outokumpu, Jormua) have developed in a V-shaped basin at the southwestern margin, and accretion begins at the northeastern margin. Rift-related volcanism is marked by darker green, arc volcanism by lighter green shading . c) Cross-section (red line in Fig. 6b) including the site of the Jormua complex upon exhumed continental mantle. No vertical exaggeration. Modified from Peltonen (2005).

A global rise in atmospheric oxygen would be expected in association with the break-up of a supercontinent (due to an increase in shelf areas). Bleeker and Ernst (2006) suggested the break-up of the supercontinent Superia at around 2.0 Ga, whereas according to Bradley (2008), the break-up occurred earlier, at around 2.3 Ga. The reasons for the global rise in atmospheric oxygen at 2.3–2.1 Ga, and the 2.3–2.06 Ga Lomagundi-Jatuli isotopic excursion remain unresolved.

Change from divergent to convergent tectonics (2.05–1.92 Ga)

Dyke swarms and sills with ages around 1.98–1.95 Ga (Vuollo & Huhma 2005, Lubnina et al. 2016), as well as carbonate rocks and metabasalts (‘Ludicovian system’; Hanski & Melezhik 2013) indicate that rifting, sedimentation and magmatism continued in the remnant continent with the development of a flood-basalt province (Fig. 6b). At 1.95 Ga, protoliths of the future ophiolite complexes Jormua and Outokumpu [55] were formed. In addition to lava rocks, sheeted dykes and gabbros, the main part of the Jormua complex consists of subcontinental lithospheric mantle. Peltonen et al. (2003) concluded that Jormua represents a seafloor that developed in an initial stage of continental break-up; a mantle diapir caused extreme thinning of the crust along detachment zones and uplift of the Archaean subcontinental mantle at the surface (Fig. 6c). The Outokumpu complex, consisting of numerous mantle tectonite massifs and associated polymetallic sulphide deposits, is not as complete as Jormua, but Peltonen (2005) suggested a common origin to the Jormua complex, with a more oceanic setting; later, Peltonen et al. (2008) presented an analogy to modern sulphide deposits in slow-spreading oceanic ridges. The present basin set-up is adopted from Kohonen (1995): extreme thinning of the continental crust led to the development of a northward-propagating V-shaped basin and a continental ribbon (Iisalmi block; Fig. 6b), similar to present continental ribbons and smaller fragments at the margins of the Atlantic Ocean (Péron-Pinvidic & Manatschal 2010). In the present model, the Jormua association represents the incipiently opened northern part of the basin, whereas the Outokumpu association developed closer to the continental margin.

Apart from the 1.95 Ga ophiolite complexes in eastern Finland, and the 1.95 Ga granitoid rocks and associated extrusive rocks in northern Sweden (Knaften; Wasström 2005), there are no reliably dated rocks in the Palaeoproterozoic bedrock of Fennoscandia in the age range 1.95–1.93 Ga. Rather poorly constrained age data come from northern Finland: 1.95–1.93 Ga ages have been obtained from intrusive rocks in northernmost Finland (Meriläinen 1976), and the youngest detrital zircons in the metasediments of the Lapland granulite complex have ages around 1.94 Ga (Tuisku & Huhma 2006). Daly et al. (2006) proposed the onset of accretion at 1.95 Ga between the Lapland-Kola and Karelia continental blocks. Initial accretion, coeval with extension in southwestern margin of the remnant Archaean continent, is shown in Figure 6b. Docking of the continent Laurentia with the Murmansk continental nucleus is modelled as the reason for accretion. The possible connection between contractional and extensional tectonics in opposite parts of the Karelia continental nucleus is discussed by Lahtinen et al. (2010).

Main collisional stage (1.92–1.87 Ga)

In contrast to the scarcity of properly dated rocks in the age range 1.95–1.93 Ga, considerably more age data on 1.92 rocks exists (Lahtinen & Huhma 1997, Lahtinen et al. 2002), and 1.92 Ga presumably marks the prelude to the main Palaeoproterozoic collisional period that led to the development of a new lithospheric block – a predecessor of the Svecofennia Province.

Plate tectonic models for the western part of the Lapland–Kola orogen involve 1) subduction of an oceanic crust northwards and closure of the ocean with thrusting of the Lapland–Kola orogen upon the Karelia Province (Barbey et al. 1984, Daly et al. 2006), and 2) subduction southwards, with the metasediments and magmatic rocks of the Lapland granulite belt representing a back-arc basin fill (Berthelsen & Marker 1986, Lahtinen et al. 2005). The Lapland granulite belt, in the orogenic core, is here interpreted as a crustal pop-up structure with opposing structural vergences (Fig. 3b), although other interpretations exist (e.g. Perchuk et al. 2000). The structure along the seismic profile 1-EU suggests a Palaeoproterozoic overprint on Neoarchaean structures, with Palaeoproterozoic subduction towards the northeast. It is easier to envisage burial of the metasediments in the Lapland granulite belt to relatively high pressures (5–9 kbar; Tuisku et al. 2006) and back to the surface in a subduction zone than in a back-arc environment. Therefore, the model favoured here is with subduction towards the northeast. In this model, the Pechenga–Varzuga belt represents a rift basin in the overriding plate.

Two main tectonic models have been presented for the Svecofennian orogeny. In the simplest model, sediments were accumulated and volcanic rocks were erupted in a widespread basin inboard an active continental margin (Rutland et al. 2001, 2004, Williams et al. 2008). In more detailed versions of a single active continental margin, several island arcs were accreted during continuous subduction, with retreat of the subduction zone to the southwest (Gáal & Gorbatschev 1987, Gorbatchev & Bogdanova 1993, Bogdanova et al. 2015), or with longer periods of subduction retreat and shorter periods of advance, leading to extensional and compressional cycles in the overriding plate (Hermansson et al. 2008, Saalmann et al. 2009). The second model includes the collision of arc complexes (microcontinents) with the Archaean continent (Nironen 1997). A refined model (Lahtinen et al. 2005, Lahtinen et al. 2009a) consists of several orogenic stages and

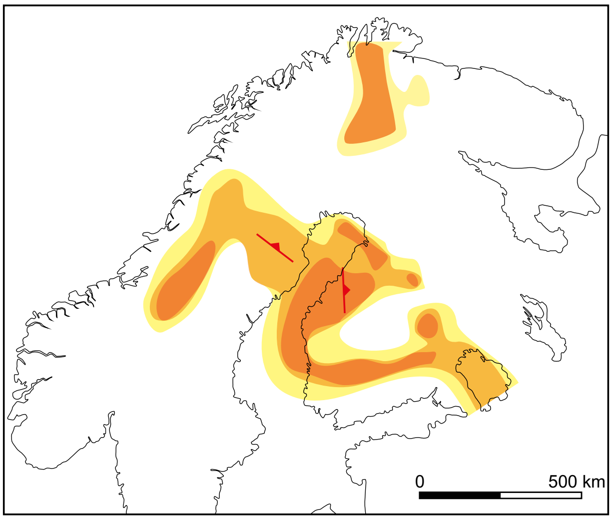


Fig. 7. Fennoscandian crustal conductance pattern at 0–60 km depth (simplified from Korja et al. 2002). Orange ≥4 $\log_{\mathrm{Siemens}}$, light orange 3.5–4 $\log_{\mathrm{Siemens}}$, yellow 2.5–3.5 $\log_{\mathrm{Siemens}}$. Dip directions from Korja et al. (1993).

orogenies, including microcontinent accretion, continental extension, continental collision, and finally orogenic collapse before crustal stabilization. The existence of microcontinents comes from Nd and Hf isotopic evidence, suggesting a ≥2.0 Ga crustal component in central and southernmost Finland and in central Sweden (Lahtinen & Huhma 1997, Rämö et al. 2001, Andersson et al. 2011). In subsequent modifications of the second model, the configuration of the microcontinents was reinterepreted (Lahtinen et al. 2009b), and in order to explain the curving structural and metamorphic zoning pattern in supracrustal rocks and in crustal conductance (Fig. 7), Lahtinen et al. (2014) presented a model in which an originally linear orogen along the Archaean continental boundary was buckled into a coupled orocline. The model presented here is a refinement of the model involving several collisional events during the Svecofennian orogeny (Nironen 1997, Lahtinen et al. 2005).

At 1.93–1.92 Ga, blocks of Archaean crust and an oceanic basin (containing protolith sediments of the Lapland and Umba granulite belts and magmatic rocks of the Tersk belt; Fig. 3) were being assembled between the Karelia and Murmansk continental blocks (Fig. 8a). Lahtinen et al. (2010) proposed a scenario in which the growing mountain belt provided detritus that was transported south, into the passive margin, to form the main part of the Kaleva sediments. Partly simultaneously with

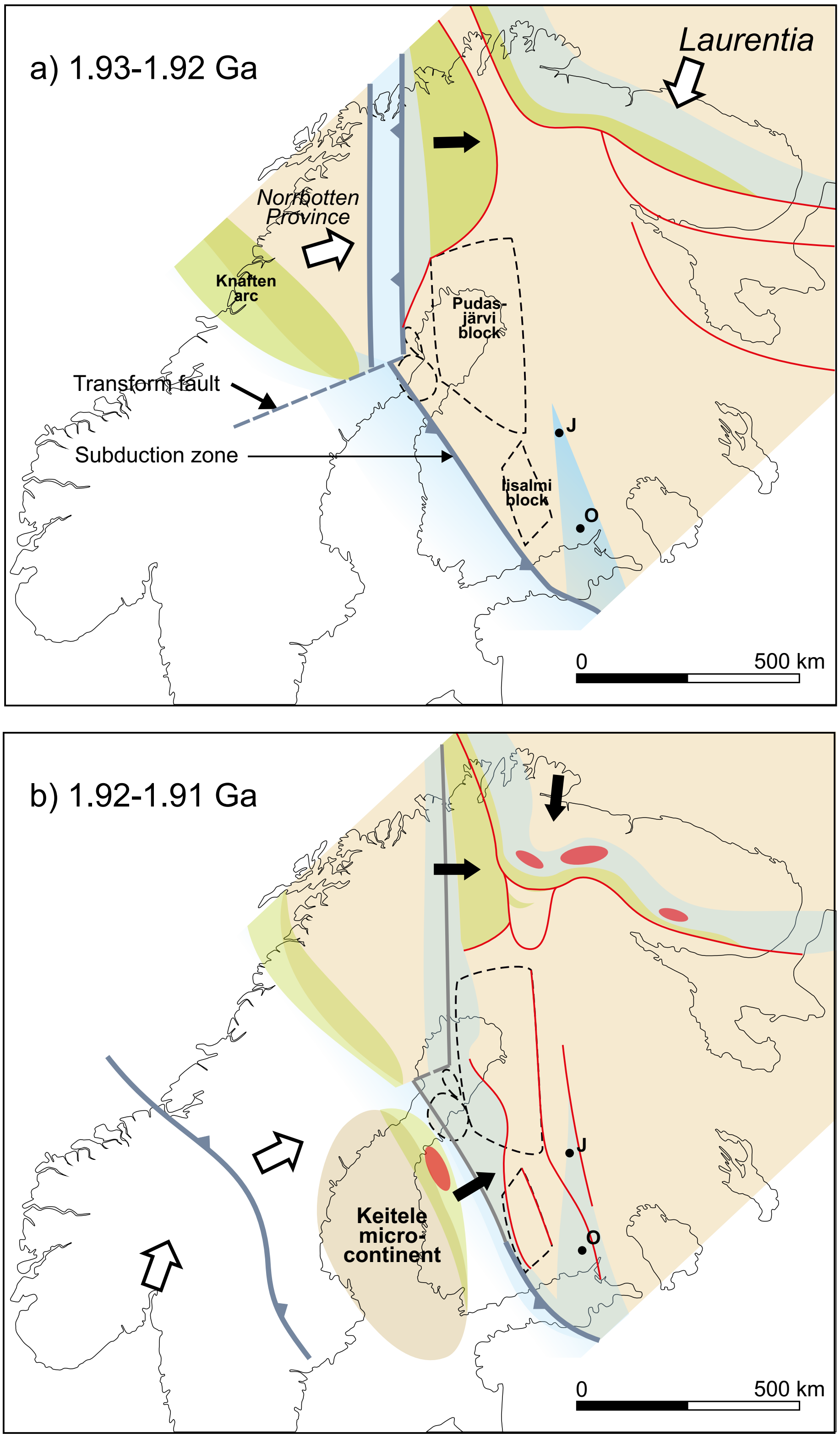


Fig. 8. a) Initiation of the main collisional stage of the Svecofennian orogeny (including Lapland–Kola area) at 1.93–1.92 Ga. Archaean crustal units are shown by a light-brown colour, Palaeoproterozoic microcontinent and areas dominated by arc-type volcanism are shown in darker brown and light green, respectively. Sedimentary belts mainly consisting of passive margin sequences are shown in blue; deposits related to continental rift are not shown. Relative plate motion is shown by a white arrow, the direction of tectonic transport by black arrow. Red lines are active deformation zones. J = Jormua association, O = Outokumpu association. b) Collision at 1.92–1.91 Ga, with jump of the subduction zone outboard of the Keitele microcontinent and subduction flip. Magmatism is shown by a red colour.

the Lapland – Kola – Karelia collision, a NNW–SSE-trending active continental margin closed at 1.92 Ga, and the Svecofennian orogeny initiated by collision of the continental blocks Karelia and Norrbotten; a volcanic arc (Knaften arc) had been attached to the Norrbotten block before continental collision (cf. Lahtinen et al. 2005). The reason for subduction towards the southwest is that there is little evidence of subduction-related magmatism in the Karelia continental margin. Remnants of oceanic crust that had existed between the two Archaean continental blocks [58–57] were sliced between passive margin sequences, and this package was thrust eastwards during collision (Kittilä allochthon–parautochthon, presently a component of the Central Lapland nappe complex; Fig. 2a). The orogenic belt developed diachronously so that at 1.92 Ga, foreland sediments of the Karelia – Norrbotten collision [25] were deposited simultaneously with accretion of a microcontinent (Keitele microcontinent) and attached volcanic arc to the Karelia continental margin (Fig. 8b). Accretion of the Keitele microcontinent caused slab break-off, subduction zone jump outboard of the accreted microcontinent, and reversal of subduction polarity along the margin of the Norrbotten block and attached magmatic arc (Knaften arc; Fig. 8b). Accretion caused a metamorphic event that culminated at ca.1.91 Ga. Kaleva sediments and tectonically enclosed fragments of ophiolitic bodies [56–55] were thrust upon the continental margin, leading to development of the Kainuu nappe complex (Figs. 3a and 8b). Sediments from the southwestern plate [67, 64] were mixed with the passive margin and early foredeep sediments to form allochthonous packages of the Northern Karelia nappe complex and Northern Ostrobothnia nappe system. Continental blocks of varying size were attached to the attenuated continental margin. Whether the blocks were continental ribbons (Pudasjärvi and Iisalmi blocks) or smaller blocks, their mantle components were detached from the crust during attachment (Fig. 4).

To explain the development of the 1.89–1.88 Ga Tampere belt (Fig. 1), with a rather simple E–W-trending basin structure (Kalliomäki et al. 2014 and references therein), Nironen (1997) and Lahtinen et al. (2005) modelled a change in plate movement direction (Figs. 8b, 9a). Another microcontinent (Bothnia microcontinent) approached from the south, and a transform fault developed between the two microcontinental blocks. Subduction in opposite directions caused gradual subduction of the oceanic plate in the east (Fig. 9b). A third microcontinent (Bergslagen microcontinent) approached from the south, leading to orthogonal collision of the Berslagen and Keitele microcontinents (Fig. 10a). In the west, a change in subduction polarity towards north is modelled to explain the north-dipping mantle reflector in the BABEL 1 profile (Fig. 4b; cf. Korja & Heikkinen 2005).

Age data indicate magmatism and deformation already occurring at 1.89 Ga, but the peak of early Svecofennian deformation, metamorphism and magmatism occurred at 1.88–1.87 Ga, when the two microcontinents Bergslagen and Keitele collided (Fig. 10a). As the result of this collision, the Pudasjärvi and Iisalmi blocks were thrust northwards, and foreland sequences [24] were deposited in front of the thrust zones. As modelled by Pajunen et al. (2008), the Keitele microcontinent started to rotate dextrally, coevally with mafic-felsic magmatism [43–39]. The Bothnia microcontinent docked at 1.87 Ga, finishing subduction in central Sweden (Fig. 10b). The oroclinal bend developed as the result of rotation of the Keitele microcontinent and docking of the Bothnia microcontinent.

Assembly of the lithospheric blocks to form the protocontinent Fennoscandia (1.87–1.86 Ga)

At 1.87 Ga, the continental and microcontinental blocks and remnants of oceanic crust as well as intervening arc and passive margin sequences were united to form a coherent continental block – the protocontinent Fennoscandia. The term protocontinent Fennoscandia means here the continental block before attachment to Volgo-Sarmatia.

Figure 10b shows the configuration of the microcontinental blocks at 1.87 Ga. The northern suture explains the curving structural-metamorphic pattern in supracrustal rocks and in crustal conductance (cf. Fig. 7). The blocks are not everywhere in contact with each other, but remnants of oceanic crust and volcanic-sedimentary arc material are squeezed between and overlying the continental blocks, following the interpretation of seismic profiles (Fig. 4). The Keitele microcontinent extends northwest as a thin layer at the bottom of the crust and is almost in contact with the Bothnia microcontinent (Fig. 4a). The boundary between the Western and Southern Finland Subprovinces roughly follows the suture between the Keitele and Bergslagen microcontinents.

Svecofennian collisional orogenic evolution during 1.87–1.86 Ga was diachronic. Peak metamorphic

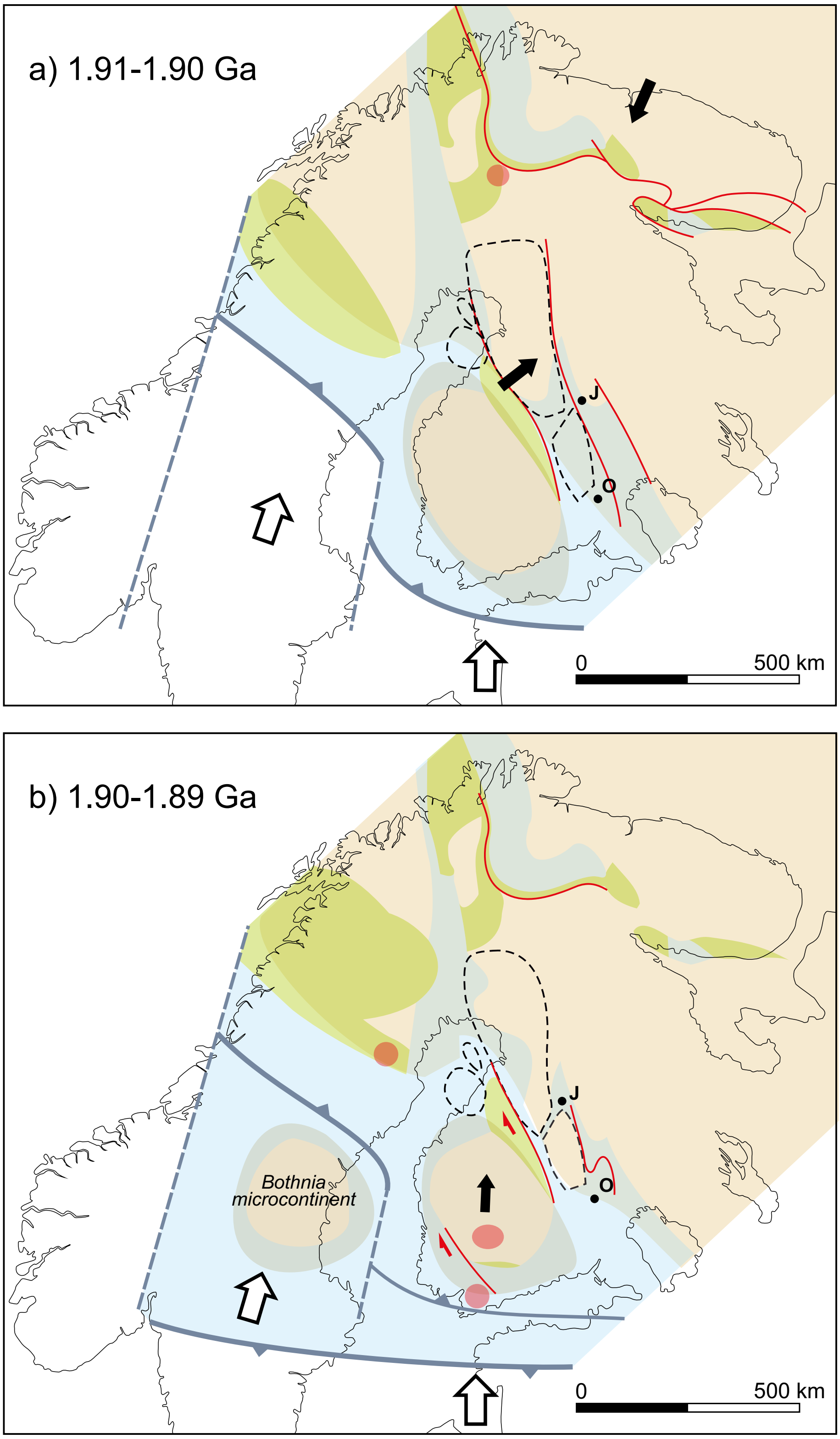


Fig. 9. Early Svecofennian accretion. a) 1.91–1.90 Ga. b) 1.89 Ga. Thick and thinner blue-grey lines denote an active subduction zone and inactive zone (suture), respectively. For colours and other symbols, see Figure 8.

conditions were attained in central Sweden and Finland at 1.88–1.87 Ga, with the development of the metamorphic-intrusive Vaasa complex [37-36] (Figs. 1 and 10b; Högdahl et al. 2012, Mäkitie et al. 2012, Kotilainen et al. 2016). Contractional deformation in central Finland changed into transtensional at ca. 1.87 Ga, with lateral spreading and thinning of the middle crust (Korja et al. 2009) and emplacement of an A-type granitoid suite [38] along transtensional shear zones (Nironen 2005),

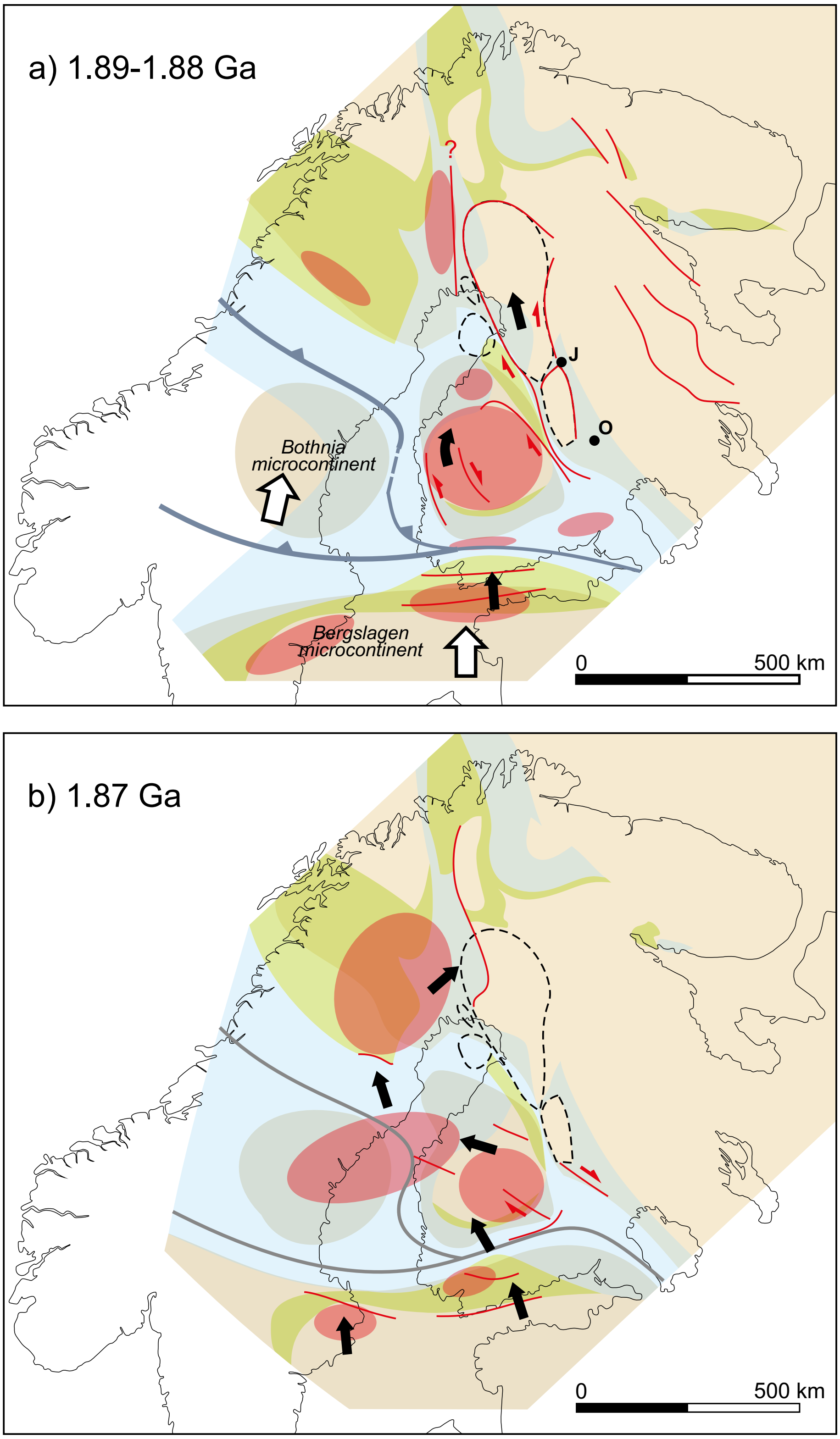


Fig. 10. Early Svecofennian accretion a) 1.89–1.88 Ga. b) 1.87 Ga. For colours and symbols, see Figure 8.

while contractional deformation still prevailed in southern Finland (Väisänen et al. 2002, Skyttä et al. 2006). In south-central Sweden, the metamorphic peak was only attained at 1.86 Ga (Stephens & Andersson 2015).

Fennoscandia attained its maximum crustal thickness during the 1.92–1.87 Ga collisions. The thickest crust developed in the area extending from the Savo belt to the Bothian Sea between Finland and Sweden, e.g. in the area where the microcontinents accreted (Fig. 10), and the crustal thickness in this area is still > 50 km (Lahtinen et al. 2009a, Bagherbandi et al. 2015).

In a global context, the main collisional period has been assigned to the amalgamation of the supercontinent Columbia (also referred to as Nuna or Hudsonland) at 1.9–1.8 Ga (e.g. Zhao et al. 2004, Rogers & Santosh 2009, Evans & Mitchell 2011). A recent study of dykes in central Finland (Klein et al. 2016) suggests that at 1.87 Ga, Fennoscandia (Baltica in the palaeomagnetic literature) was at low latitudes (ca. 20°) and had not yet been assembled with Laurentia to form Columbia.

Intra-orogenic stabilization and late Svecofennian crustal extension, continued accretion in the south (1.86–1.83 Ga)

Metasandstones, including orthoquartzites [20], have a scattered occurrence in southern Finland, and similar rocks are found in south-central Sweden (Fig. 11a). Their depositional age may be constrained by detrital zircon data between 1.87 Ga and 1.83 Ga (Bergman et al. 2008). The occurrence of ultramature quarzite (Lahtinen & Nironen 2010) implies upper crustal stabilization and deposition of quartz sands in a continental environment.

The period referred to as late Svecofennian initiated at 1.84 in southern Finland by crustal extension and associated mafic to felsic magmatism (Nironen 2005, Pajunen et al. 2008). The Late Svecofennian period is characterized by high-T metamorphism and associated granite magmatism [16]. The high-grade metamorphism and magmatism are thought to be the result of crustal extension, leading to high heat flow from the mantle (Korsman et al. 1999, Lahtinen et al. 2005), or of the combined effect of crustal thickening and radioactive heat production (Kukkonen & Lauri 2009).

Again, evolution was diachronic: at 1.83 Ga when crustal extension prevailed in southern Finland and quartz sands were redeposited in intracontinetal rift valleys (Fig. 11a; Skyttä & Mänttäri 2008, Nironen & Mänttäri 2011), a volcanic arc (the Oskarshamn–Jönköping belt in southern Sweden) was developing at a continental margin (Fig. 11b; Mansfeld et al. 1995). This volcanic arc probably has a continuation in Lithuania (Skridlaite & Motuza 2001, Siljauskas & Skridlaite 2016). Following the general idea of Gorbatschev and Bogdanova (1993), Lahtinen et al. (2005) proposed retreating of an Andean-type active margin to explain this southwestward crustal growth.

Little is known of tectono-metamorphic evolution in northern Finland during 1.86–1.83 Ga. A granite in the Central Lapland granitoid complex (Fig. 1) yielded a 1.85 Ga age (Ahtonen et al. 2007), and overgrowths in detrital zircons indicate a metamorphic event at 1.86–1.85 Ga in western Finnish Lapland (Lahtinen et al. 2015b). Both crustal contraction and extension can explain these observations.

Late collisions, orogenic collapse and formation of the continent Baltica (1.82–1.76 Ga)

Late Svecofennian deformation, characterized by NW–SE trending shear zones (Fig. 11b), has been attributed to transpression with bulk compression towards the NW (Fig. 11b; Väisänen & Skyttä 2007 and references therein). Deformation was most intensive in southeastern Finland, where an allochthonous unit developed (Southern Savo nappe system, Fig. 2a). A broad, dextral shear zone developed in southern Fennoscandia, extending from Estonia to the archipelago of SW Finland and possibly to central Sweden (Fig. 11; Torvela et al. 2008, Högdahl et al. 2009). The amount of displacement along this zone is unknown.

Lahtinen et al. (2005) modelled continental collision at 1.84–1.80 Ga (Svecobaltic orogeny) to explain the late Svecofennian deformation and metamorphism in southern Finland. Oblique collision between two protocontinents Fennoscandia and Volgo-Sarmatia caused transpression in southern Finland; transpressional deformation initiated earlier but collision occurred at 1.82–1.80 Ga (Fig. 11b). Together, Fennoscandia and Volgo-Sarmatia formed the continent Baltica (or East European Craton; Gorbatschev & Bogdanova 1993, Bogdanova et al. 2015). Hereafter, Fennoscandia refers to part of the continent Baltica. Southward–southeastward accretionary growth of Fennoscandia continued during and after the collision.

The late Svecofennian metamorphism and deformation partly overlap in age with voluminous magmatic activity that produced the N–S trending Transscandinavian igneous belt in Sweden (TIB;

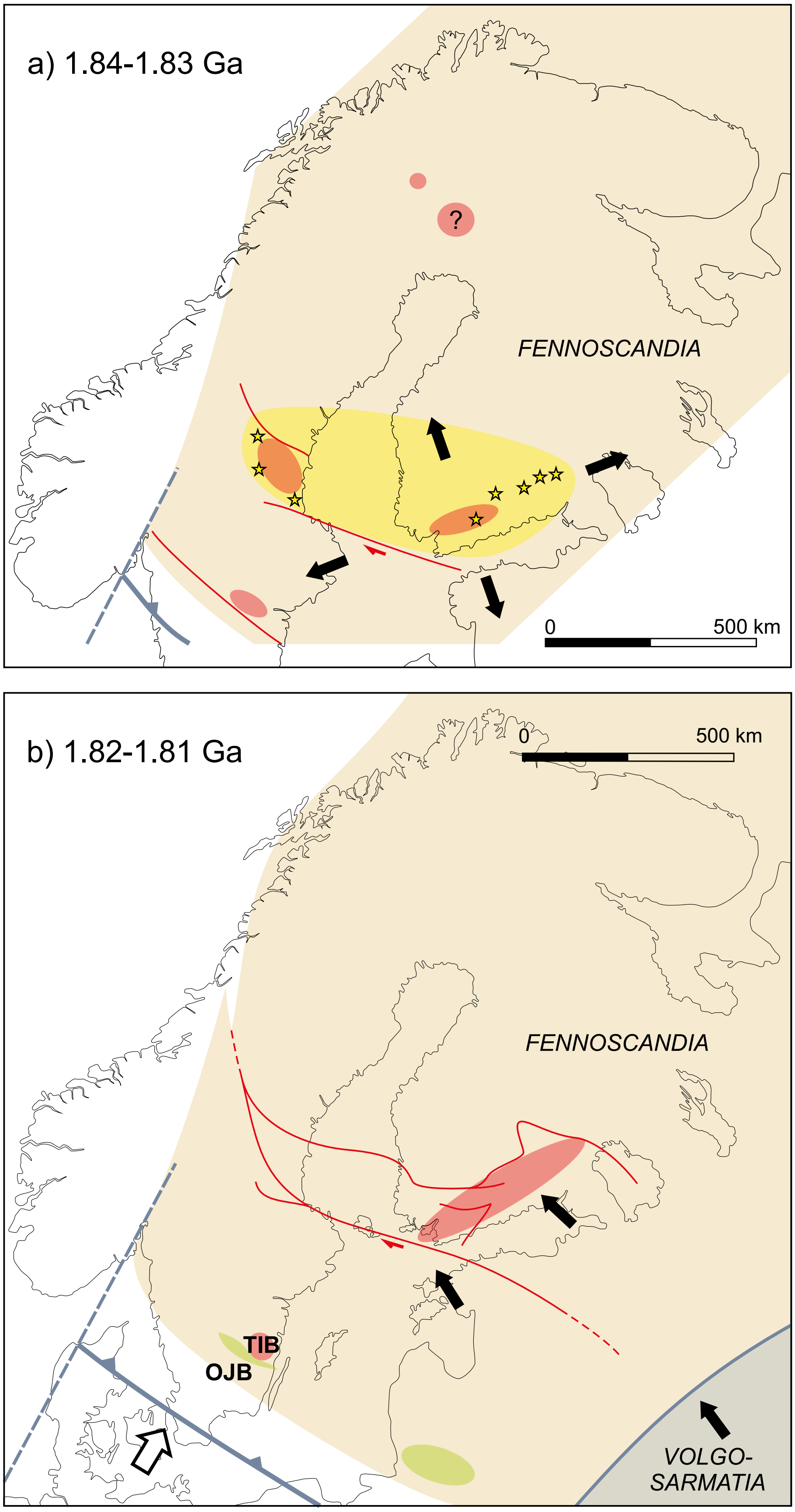


Fig. 11. a) Late Svecofennian extension (1.84–1.83 Ga). b) Late Svecofennian collision (1.82–1.81 Ga). Quartzite occurrences are shown by stars, inferred distribution of mature sands by yellow, (mainly granitic) magmatism by orange (from Åhäll and Larsson 2000, Pajunen et al. 2008, Lahtinen and Nironen 2010). Active deformation zones are shown as red lines (partly modified from Torvela et al. 2008, Högdahl et al. 2009). TIB = Transscandinavian igneous belt magmatism, OJ = Oskarshamn-Jönköping belt.

Gorbatschov and Bogdanova 1993). The TIB has been considered to represent magmatism in a convergent continental margin environment in three cycles: 1.81–1.77 Ga, 1.72–1.69 Ga and 1.68–1.66 Ga (Åhäll & Larson 2000). Lahtinen et al. (2005) proposed collision (Nordic orogeny) at 1.82–1.79 Ga between Baltica and Amazonia to explain TIB magmatism. Another possibility, presented by Lahtinen et al. (2009) and adopted here, is that the western margin of Fennoscandia was the convergent margin of an advancing Andean-type accretionary orogen (Fig. 12a). Models of subduction during TIB magmatism vary from a single curving zone (Andersson et al. 2004) to two zones (Lahtinen et al. 2005, this study); overall, the modelled plate kinematic arrangement at the northwestern margin of Fennoscandia (Figs. 11 and 12) is speculative because of the subsequent orogenic overprint.

In the model of Lahtinen et al. (2005), gravitational collapse that followed the two (proto)continental collisions, Fennoscandia–Volgo-Sarmatia and Fennoscandia–Amazonia, caused large-scale crustal extension, metamorphism and magmatism in the northern part of Fennoscandia. In northern Finland, a suite of mafic rocks [18] and another one of granites [17], and in southern Finland a suite of bimodal shoshonitic rocks [16], all in the age range 1.81–1.77 Ga, represent post-collisional magmatism (Fig. 12a; Nironen 2005, Ahtonen et al. 2007, Heilimo et al. 2009). Ages of 1.80–1.76 Ga have been obtained from pegmatites and migmatite leucosomes in Sweden, Finland and Russia (Lahtinen et al. 2005, Ahtonen et al. 2007), indicating late metamorphism that affected Fennoscandia. These late ages may be attributed to crustal extension: the FIRE4 reflection seismic profile reveals a horizontal, strongly reflective zone at the base of the crust in central Lapland (Patison et al. 2006), which is probably the result of lower crustal extension.

The palaeogeographic reconstructions for the supercontinent Columbia include an initial assembly of Laurentia, Baltica and Amazonia by 1.8 Ga (e.g. Johansson 2009). Here, the name Baltica is used to mean the terrane that was assembled during the Palaeoproterozoic (East European Craton), and was a part of various continental assemblages or a separate continental unit from the Palaeoproterozoic to the present (cf. Bogdanova et al. 2008).

Crustal stabilization (1.76–1.65 Ga)

During 1.72–1.66 Ga, accretionary orogenic activity continued at the southwestern margin of Fennoscandia and produced TIB magmatism (Andersson et al. 2004). Little is known of the interior of Baltica during the period 1.76–1.65 Ga, but an indication of crustal stabilization comes from the Suursaari island in the Gulf of Finland (Fig. 13), where an ultramature (quartz arenitic) conglomerate, containing quartz arenitic boulders, lies nonconformably upon Svecofennian basement (Pokki et al. 2013a). Correlative occurrences are found in southern Finland and central Sweden, and together these suggest deep erosion of the Svecofennian crust (migmatitic basement) and development of a large peneplain (quartz arenite) in the interior of Baltica before the emplacement of the oldest rapakivi granites at 1.65 Ga (see below). The depositional age of the Suursaari conglomerate can be bracketed between 1.65 Ga and 1.63 Ga. Deposition of the conglomerate marks a shift from tectonically stable conditions to incipient intracontinental rifting.

A problem still unresolved is that the Svecofennian metasedimentary rocks generally yield 4–6 kbar pressures, corresponding to 10–15 km depth, and yet there is little evidence as to when and how these rocks were exhumed. Exhumation occurred between 1.80 Ga and 1.65 Ga, and preferably in the earlier part of this period considering the tectonically stable conditions in the later part. Was the mechanism large-scale normal faulting and associated erosion during orogenic collapse? Where is the eroded material?

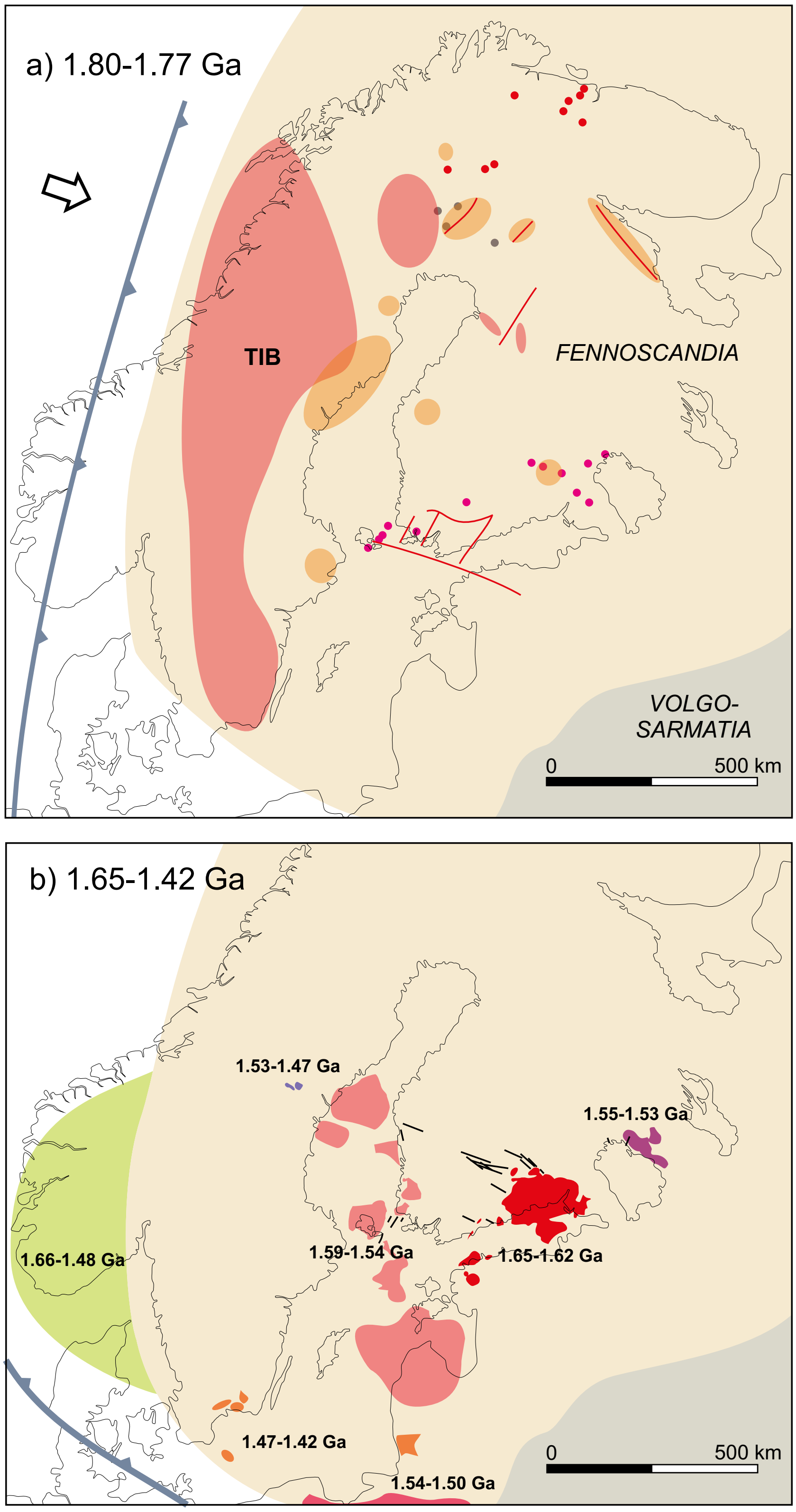


Fig. 12. a) Magmatism in Fennoscandia during 1.80–1.77 Ga (post-collisional magmatism in Finland). Plutonic bodies shown by points (magenta = bimodal, brown = mafic, red = granitic; Haapala et al. 1987, Eklund et al. 1998, Eklund and Shebanov 2005, Ahtonen et al. 2007, Heilimo et al. 2009). Red areas show granitic magmatism (Åhäll and Larsson 2000), orange areas sites of metamorphism and intrusion of pegmatites (Romer and Smeds 1994, 1997, Alviola et al. 2001, Bibikova et al. 2001, Ahtonen et al. 2007). TIB = Transscandinavian igneous belt. Active deformation zones are shown by red lines. b) A-type magmatism in Fennoscandia during 1.65–1.42 Ga (Laitakari et al. 1996, Koistinen et al. 2001, Bogdanova et al. 2008, Brander and Söderlund 2009). Plutons with red and bluish colours are rapakivi granites, plutons with an orange colour are related to Hallandian–Danopolonian orogeny. Age ranges for each colour are given. The green area represents Gothian and Telemarkian accreted units (Bingen et al. 2008) before the Sveconorwegian orogeny.

Intracontinental rifting and magmatism, orogenic activity at the continental margin (1.65–0.9 Ga)

There is evidence of rifting and magmatism in the interior of Baltica during 1.65–1.1 Ga, and orogenic activity in the southwestern margin during 1.66–1.42 Ga. A bimodal association of rapakivi granites [13–12], gabbro-anorthosites [14] and dykes is found in onshore and offshore southern Finland and central Sweden (Fig. 13). The age of rapakivi magmatism spans 1.65–1.47 Ga, with four age groups (Fig. 12b; Rämö & Haapala 2005, Rämö & Mänttäri 2015). The rapakivi granites are part of a more extensive anorthosite-mangerite-charnockite-granite (AMCG) suite of that includes the 1.54–1.50 Ga bimodal Mazury complex in Lithuania and northeastern Poland. The mafic dyke swarms in southern Finland have two main orientations: the WNW-ESE-oriented dykes are coeval with the oldest (1.65–1.62 Ga) granites, whereas the NNE-SSW-oriented ones are associated with younger granites. The established concept is that the rapakivi magmas were derived in an extensional setting from the lower crust, whereas the mafic magmas had a variably crustal-contaminated mantle origin. However, the ultimate cause of the bimodal magmatism is controversial (Rämö & Haapala 2005).

Sandstone [11], found in the western coast of Finland but mainly occurring as fillings in offshore basins and Lake Ladoga, flank or overlie the magmatic rocks (Fig. 13). Based on the BABEL 1 seismic profile, Korja et al. (2001) concluded that the sandstone reaches 3–4 km thickness in the Bothnian Bay area (see northern part of Fig. 4b), and suggested that the basin initiated as a cauldron subsidence on top of the rapakivi intrusions. Rifting, sedimentation and magmatism probably occurred intermittently (Pokki et al. 2013b).

Mesoproterozoic clastic sedimentary rocks [9] are preserved in a fault-bounded basin in the western coast of Finland (Fig. 13), and continue into the Bothnian Bay area (Kohonen & Rämö 2005, Paulamäki & Kuivamäki 2006). Drilling at the 75 Ma Lappajärvi meteorite impact site [1] (Fig. 13) revealed a 20-m-thick pile of Mesoproterozoic sedimentary rocks [9] below and around the impact rocks, suggesting that Mesoproterozoic sediments covered much wider areas than the preserved occurrences. Late Mesoproterozoic evolution involved short extensional periods, as exemplified by the few 1.3–1.1 Ga mafic dykes found in northern Finland, as well as the 1.27 Ga dolerite sills and dykes in southwestern Finland [10].

Partly coeval with rapakivi magmatism, several allochthonous terranes, presently comprising the Sveconorwegia Province (Fig. 1), were accreted to the western margin as two events, first at 1.66–1.52 Ga (the Gothian event; Åhäll & Connelly 2008), and at 1.52–1.48 Ga (the Telemarkian event, Bingen et al. 2008). A third event, referred to as the Hallandian-Danopolonian orogeny (Bogdanova et al. 2008), extended from southern Sweden to Lithuania and Poland and resulted in AMCG magmatism during

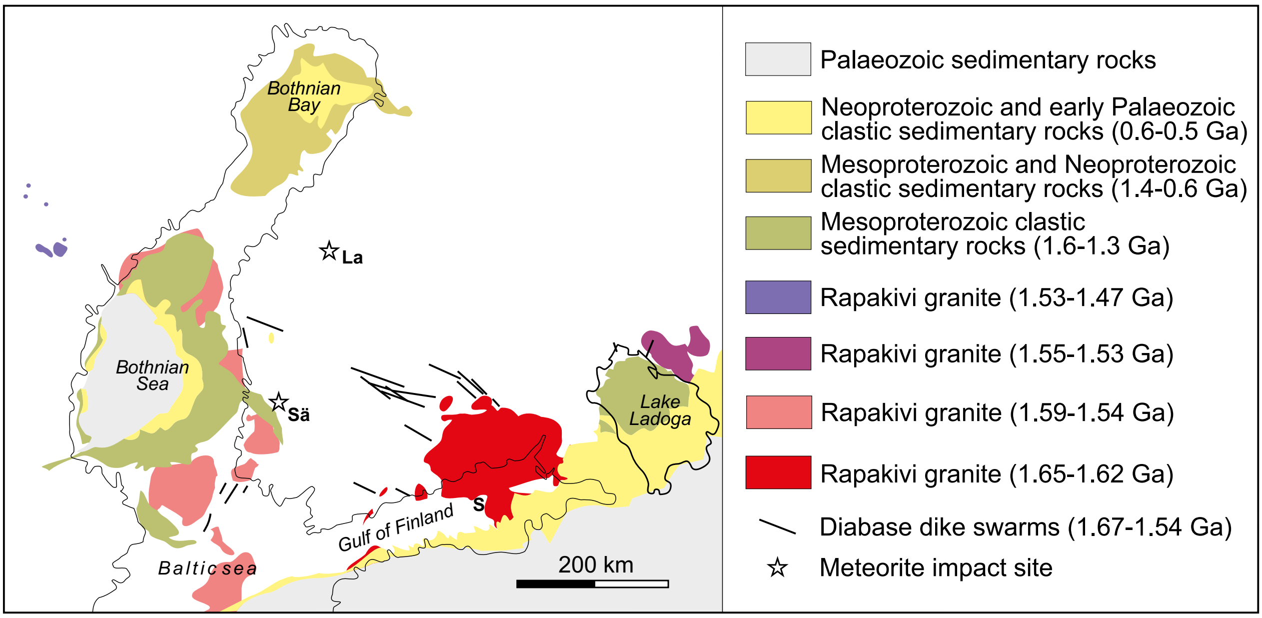


Fig. 13. Mesoproterozoic and younger lithological units in the eastern part of the Fennoscandian Shield (generalized from Koistinen et al. 2001). Dyke swarms associated with rapakivi magmatism are shown crudely. S = Suursaari island, La = Lappajärvi impact site, Sä = Sääksjärvi impact site.

1.47–1.42 Ga. In Figure 12b, a subduction zone is delineated to explain the Gothian, Telemarkian and Hallandian–Danopolonian events. The orientation of subduction would match with development of the two dyke swarms associated with rapakivi magmatism (older parallel, younger orthogonal). The episodic activity and different orientations of subduction in southwestern Fennoscandia could explain inboard rapakivi magmatism and the non-linear age distribution, as suggested by Åhäll et al. (2000).

As postulated above, a shallow basin probably developed in central Fennoscandia during the rapakivi magmatic event. Emplacement of the 1.27–1.1 mafic dikes and sills preceded the 1.14–09 Ga Sveconorwegian (–Grenvillian) orogeny that was prominent in the area of southern Norway and southwestern Sweden (Bingen et al. 2008, Roberts & Slagstad 2015). The dykes, sills and normal faults bounding the present occurrences of Mesoproterozoic cover rocks are probably expressions of foreland extension during the initial stage of the Sveconorwegian orogeny. During the orogeny, the basin deepened into a foreland basin that received huge masses of detritus from the orogenic front area (Fig. 14a; Kohonen & Rämö 2005). Extension of the basin to the east is speculative.

In some palaeogeographic reconstructions (e.g. Zhao et al. 2004), AMCG magmatism in Baltica (1.65–1.45 Ga) was part of the initial fragmentation of the supercontinent Columbia, whereas in other ones the maximum assembly of Columbia was achieved as late as 1.5 Ga (Salminen et al. 2017). The final break-up probably occurred at 1.2 Ga. Plate organization during the break-up of Columbia and re-assembly into the supercontinent Rodinia at 1.1–1.0 Ga, with Baltica as one component, appears to include a complex set of continental extensions, accretions and collisions, including the Sveconorwegian orogeny (cf. Bogdanova et al. 2008, Johansson 2009, Pisarevsky et al. 2014, Roberts & Slagstad 2015). The degrees of freedom in the palaeomagnetic method are evident in the variable reconstructions of the Columbia – Rodinia reorganization (Meert 2014).

Neoproterozoic uplift and denudation (900–640 Ma)

Early- and Mid-Neoproterozoic (Tonian–Cryogenian, 1000–640 Ma) rocks are missing in onshore Finland, but exist in the Bothnian Bay area (Fig. 13). In Estonia, late Neoproterozoic (Ediacaran or 'Vendian') or Cambrian sedimentary rocks occur directly upon the crystalline Svecofennian basement (Puura et al. 1996). Based on deep drilling, a kaolinitic palaeosol, with a thickness of 0.5–2 m, covers the Svecofennian basement, indicating an ancient peneplain. In addition to Estonia, evidence for the peneplain, referred to as Pre-Vendian, Sub-Vendian or Sub-Cambrian, has been detected in southern Norway, southern Sweden, southern Finland, and in the Kola Peninsula area (Riis 1996, Kohonen & Rämö 2005, Lidmar-Bergström et al. 2013, Hall 2015).

The peneplain indicates crustal uplift, removal of most of the foreland sediments that had been deposited during the Sveconorwegian orogeny, and exposure of the crystalline basement. Gradual uplift and denudation occurred during most of the Neoproterozoic and resulted in a large, virtually flat shield area at the end of the Cryogenian Period (Fig. 14b). The northwestern margin of Baltica was a rift margin, and shallow rift basins (including the Bothnian Bay basin) formed or were reactivated in northwestern Baltica, whereas Mesoproterozoic aulacogens in the east (present East European Platform area) were filled with near-shore and shallow-marine sediments (Grachev & Nikolaev 2006, Pease et al. 2008). The northeastern margin of Baltica was a passive margin throughout the Neoproterozoic, filled with a km-scale pile of sediments.

The position and orientation of Baltica in the supercontinent Rodinia in the Neoproterozoic is controversial (e.g. Meert & Torsvik 2003, Cawood & Pisarevsky 2006). In the palaeogeographic reconstruction of Li et al. (2008), Baltica was within moderate southern latitudes during the break-up of the supercontinent Rodinia at 750–600 Ma.

Late Neoproterozoic and early Palaeozoic subsidence and platform sedimentation (640–430 Ma)

Late Neoproterozoic (Ediacaran) and Palaeozoic rocks are virtually missing in onshore Finland: the Lauhavuori sandstone [8] in western Finland is possibly Early Cambrian (Paulamäki & Kuivamäki 2006), and Cambrian sedimentary rocks [4] overly the Archaean basement in the northwestern tip of Finland. In contrast, an Ediacaran to Devonian sequence covers Precambrian basement rocks in the

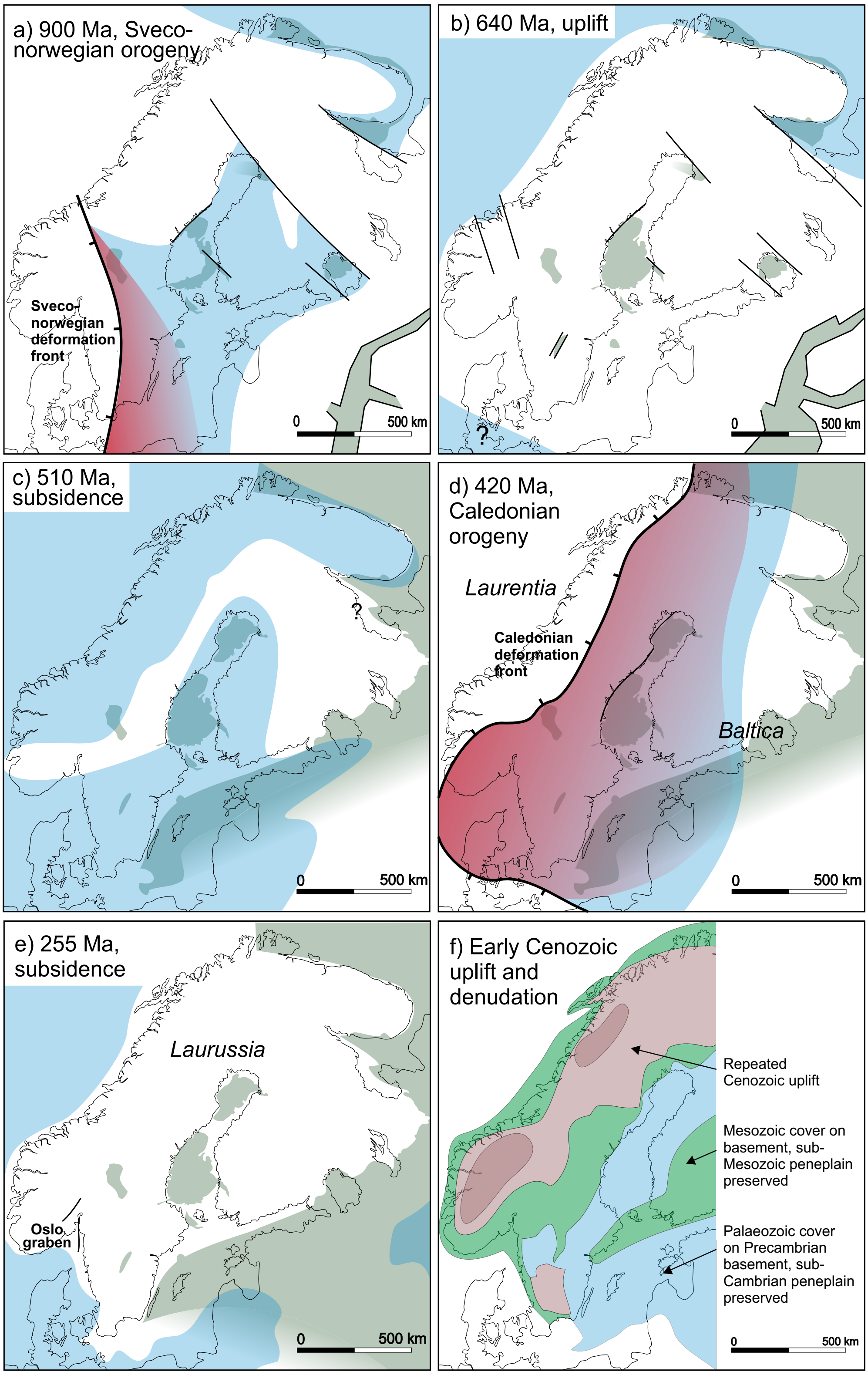


Fig. 14. Model of a few stages in the evolution of the platform cover in Fennoscandia. Light greenish areas indicate the present distribution of cover rocks that had been deposited during each palaeogeographic snapshot, transparent blue areas show the inferred extent of the epicontinental sea or oceanic shelf, red areas represent orogenic depositories. Black lines denote inferred faults. a) 900 Ma, end of Sveconorwegian orogeny. Modified from Kohonen and Rämö (2005). b) 640 Ma, final stage of crustal uplift in Fennoscandia. Modified from Vidal and Moczydlowska (1995) and Bogdanova et al. (2008). c) 510 Ma, maximum flooding stage. Modified from Nielsen and Schvovsbo (2011). d) 420 Ma, Caledonian orogeny. Modified from Kohonen and Rämö (2005). Note that the Caledonian frontal thrust is drawn where it is now; it was probably located elsewhere at 420 Ma. e) 255 Ma, Permian subsidence. Modified from Ruebsam et al. (2017). f) Early Cenozoic uplift and denudation. Modified from Lidmar-Bergström et al. (2013).

Baltic countries: the thickness of the sequence increases southwards from northern Estonia up to ca. 2000 m in Latvia, where some 800 m of Devonian rocks form the uppermost part (Puura et al. 1996). In the Bothnian Bay area (Fig. 13), the uppermost sandstone is probably Ediacaran in age (Paulamäki & Kuivamäki 2006). Cambrian sandstone and Ordovician limestone and shale are found in the Bothnian Sea area.

The Ediacaran and early Palaeozoic sedimentation has been assigned to the opening of the Iapetus Ocean and development of a passive continental margin in northwestern Baltica (Kohonen & Rämö 2005). During the Ediacaran, central Baltica slowly submerged under an epicontinental sea, the Palaeobaltic Basin, and Ediacaran sedimentation extended to (present-day) Estonia. Ediacaran sedimentation in the area of Finland is controversial: the sequences in northern Estonia suggest that sedimentation also occurred in southern Finland, whereas Ediacaran and Early Cambrian sediments in Estonia were supplied by detritus from the Precambrian basement and rapakivi granites, suggesting that most of Finland was land area during the Ediacaran and beginning of the Cambrian (Isozaki et al. 2014). During the Early Cambrian, transgression in Fennoscandia and regression in central Baltica included a series of subsidence and uplift events of the order of tens to a maximum of hundreds of metres (Nielsen & Schovsbo 2011); Figure 14c shows the interpreted Early–Middle Cambrian maximum flooding stage.

During the Ordovician and Silurian a carbonate platform extended from southern Norway to the St. Petersburg area, with a deeper shelf that opened southwest to the surrounding ocean. The Cambrian and Ordovician rocks in the Bothnian Sea area are tectonically preserved remnants of an originally extensive Cambrian–Ordovician sequence that covered much of Finland. It is speculative whether the carbonate platform extended to the area of Finland during the Silurian (cf. Baarli et al. 2003, Kohonen & Rämö 2005).

The early Palaeozoic subsidence has been assigned to the isolation of Baltica from Laurentia and opening of the Iapetus Ocean at 600–550 Ma (Pease et al. 2008, Li et al. 2008). Palaeomagnetic and geological data suggest that Baltica was at high southern palaeolatitudes during the early Ediacaran (Li et al. 2008), and drifted northwards to low palaeolatitudes during the Cambrian and Ordovician; during the mid-Silurian (425 Ma), Baltica was within tropical latitudes (Cocks & Torsvik 2005). From 450 Ma onwards, continental collisions occurred at the western margin of Baltica (see below).

Caledonian and Variscan orogenies and development of the Permian basins (430–250 Ma)

Late Palaeozoic rocks have mainly been recognized in southwestern Fennoscandia: Silurian to Devonian sedimentary rocks occur in Latvia, and Permian rocks are found in the Oslo graben in Norway. However, fission track studies (e.g. Cederbom et al. 2000) suggest that late Palaeozoic deposits covered large areas of Fennoscandia, presumably as a result of the Caledonian orogeny. The Caledonian orogeny initiated in the early Ordovician (490–470 Ma), but the main, Scandian phase lasted from the Silurian to the Devonian (430–390 Ma; Roberts 2003, Gee et al. 2008). The foreland fold and thrust belt sequence, with eastward lateral transport of allochthonous units for several hundreds of kilometres, dominates the geology of Norway, but barely extends to the northwestern part of Finland (Fig. 2). The allochthonous nappe units [7–5] build up the Finnish part of the Caledonides (Kohonen & Rämö 2005).

As the result of the Caledonian orogeny, a foreland basin formed and received detritus from the growing mountain belt (Fig. 14d). Detritus probably buried the foreland basin, including most of Finland, with an estimated thickness of >2.5 km in western Sweden, thinning to 1.5–0.5 km in Finland (Larson et al. 1999).

The Variscan (or Hercynian) orogeny formed a continuation with the Caledonian orogeny, with initiation set at 400 Ma and ending at 300 Ma (e.g. Kroner & Romer 2013). The orogeny severely modified the crust in the present central and western Europe south of the Trans-European Suture Zone (Fig. 1b), whereas the effects in Baltica were mainly restricted to the southwestern margin as transpressional deformation in the Trans-European Suture Zone. Fission-track analysis suggests a late Carboniferous (314–307 Ma) uplift and exhumation event in southern Sweden (Jaspen et al. 2016). Post-Variscan extension caused development of the intracontinental Permian Basins that encompassed the present Denmark, northern Germany and Poland areas and reached Latvia at the end of the Palaeozoic Era, but most of Baltica was presumably land area (Fig. 14e; Ruebsam et al. 2017).

Baltica remained an independent continental block until the Iapetus Ocean started to close: it was docked firstly with Avalonia at the end of the Ordovician, and with Laurentia to form Laurussia during the Silurian (Cocks & Torsvik 2005, Torsvik et al. 2012). Docking with Laurentia caused the Caledonian orogeny, and plate convergence continued during the Variscan orogeny. Fennoscandia was foreland to both orogenies. These orogenies were parts in the assembly of the supercontinent Pangea.

Mesozoic and Cenozoic uplift and subsidence events, and development of the Fennoscandian Shield (250–0 Ga)

The virtual lack of Phanerozoic sedimentary rocks in Finland indicates considerable uplift and erosion, but keys to the timing are few. According to Kohonen and Rämö (2005), the occurrence of clastic dykes of Cambrian sandstone in southwestern Finland and the preservation of the 560 Ma Sääksärvi impact structure (Fig. 13) indicate that the present erosional level in southern Finland is close to the Sub-Vendian (Sub-Cambrian) peneplain. As mentioned above, a pile of Mesoproterozoic sedimentary rocks are found below and around the 75 Ma Lappajärvi meteorite impact site [1] (Fig. 13). The preservation of them is explained by downfaulting of the precursory sediments during the impact in the late Cretaceous (Kohonen & Vaarma 2001). Since the thickness of the sedimentary rock package is only 20 m, most of the pre-existing sediments had been eroded by the late Cretaceous.

Geological correlation and landscape analysis (Riis 1996, Lidmar-Bergström et al. 2013) suggest uplift in the early Mesozoic, during which most of Scandinavia and central Finland was exposed to denudation and the development of a peneplain in the Jurassic. Uplift was followed by transgression, and during late Cretaceous, almost entire Fennoscandia was below sea level. Early Cenozoic opening of the North Atlantic Ocean, or more specifically the Norwegian Sea, caused major but differential late Cenozoic uplift in Fennoscandia, during which the present Fennoscandian Shield was exhumed (Fig. 14f). The estimated Cenozoic uplift decreased from 1000 m in Norway to less than 200 m in southern Finland (Riis 1996).

Amalgamation of the supercontinent Pangea was complete by 250 Ma. Opening of the North Atlantic Ocean initiated at ca. 60 Ma as part of the break-up of Pangea.

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Bedrock of Finland at the scale 1:1 000 000 – Major stratigraphic units, metamorphism and tectonic evolution
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METAMORPHIC MAP OF FINLAND

by

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Hölttä, P. & Heilimo, E. 2017. Metamorphic map of Finland. *Geological Survey of Finland, Special Paper 60, 77–128, 34 figures and 2 appendices.*

The metamorphic map of Finland was constructed mainly on the basis of the observed metamorphic features in peraluminous metasedimentary rocks, especially mineral assemblages, and the onset and degree of partial melting that characterize a particular zone. The PT fields of these assemblages are shown in the PT pseudosections with a colour corresponding to the same colour in the map.

The GIS map contains several layers. In the first one, the bedrock is classified into low, medium and high metamorphic grade domains. The second layer is based on the metamorphic facies. The third layer shows metamorphic zones based on the stable mineral assemblages in the PT pseudosections, wherein the assemblages are classified into low-pressure (LP), medium-pressure (MP) and high-pressure (HP) series. The pseudosection map has additional layers showing pre-peak and overprinting metamorphic events, wherever such classification is possible.

Most of the Archaean bedrock was metamorphosed during 2.70–2.60 Ga in high amphibolite facies at low to medium pressures around 6–7 kbar. There are only a few low- to medium-pressure granulite facies areas. The Archaean greenstone belts were metamorphosed in mid-amphibolite facies at medium pressures, in Ilomantsi at around 5–6 kbar, but in the Kuhmo and Oijärvi greenstone belts, pressures close to 10 kbar or even higher are possible.

The Archaean areas were overprinted by Proterozoic metamorphism, which can be seen as local rehydration (epidotization, chloritization), especially close to shear zones. In the Rautavaara and Tuntsa areas, the Proterozoic overprint was pervasive, extending from several kilometres to tens of kilometres in width. This retrogression was obviously related to metamorphism of the Proterozoic cover sequences of the Karelia Province, which were metamorphosed in greenschist to mid-amphibolite facies conditions. The cover sequences show low-pressure metamorphism (Peräpohja, Kiiminki), with andalusite and cordierite assemblages, to medium-pressure (North Karelia schist belt, Central Lapland) preserving kyanite.

Most of the Svecofennia Province was metamorphosed during 1.88–1.79 Ga in upper amphibolite and granulite facies at low pressures of around 4–6 kbar. Within the abundant metatexitic and diatexitic migmatites, there are lesser low- to mid-amphibolite facies zones with low-pressure andalusite, sillimanite and cordierite assemblages in peraluminous schists. These commonly have tectonic boundaries with the surrounding higher-grade metamorphic rocks. In the Southern Finland Subprovince, the majority of the lower grade rocks are situated at the northern boundary of the subprovince. In the Western Finland Subprovince, there is a prograde increase in metamorphic grade from andalusite-bearing schists to diatexitic migmatites towards the contacts of the Vaasa complex.

Keywords: metamorphism, metamorphic belts, Fennoscandian Shield, Proterozoic, Archean, Finland

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INTRODUCTION

Bedrock mapping of Finland has had a long history since the foundation of the Geological Survey of Finland (GTK) in 1886. The early maps were mostly lithological, but thematic maps have also been developed, such as stratigraphic and metallogenic maps. Metamorphism is a bedrock feature that can easily be mapped, reflecting tectonic processes such as subduction, collision and extension. The development of deformation and metamorphism of rocks are interconnected. Ductile deformation takes place in metamorphic pressure–temperature (PT) conditions in the crust, and brittle deformation postdates metamorphism and may cause metamorphic discontinuities now observed in the present erosion level. Magmatism, either local or and regional, often plays an important role in the evolution of metamorphism as a source and means of transfer of heat. As a whole, metamorphism is crucial in understanding the evolution of orogenies (Brown 2009). Metamorphism also has an important role in the development of large hydrothermal systems that often have economic importance (Oliver 1996, Oliver et al. 1998, Oliver et al. 1999, Cartwright & Oliver 2000), especially in the evolution of orogenic gold deposits (Phillips & Powell 2009, 2010).

After the fundamental work in the Orijärvi area by Eskola (1914, 1915), there was a long silence in the regional metamorphic studies on the bedrock of Finland. However, Hietanen (1947) described metamorphism and metamorphic reactions in her work in the Turku area, and Eskola (1952) studied the Lapland granulites. Korsman (1977) published his work on progressive metamorphism in the Rantasalmi–Sulkava area, and continued with his group at GTK on metamorphic studies, including metamorphic mapping of many areas.

The metamorphic map presented in this work is based on the earlier research at GTK and at other institutions, referred to later in the text. New fieldwork was carried out in 2011–2014 in areas where only limited data on metamorphism was available, using the 1:100 000 bedrock maps and map explanations as a basis. Observations were recorded from the exposures that have metamorphic index minerals or which are representative from the metamorphic perspective in a particular area. The geodatabase is available to those having access to the Geological Survey of Finland Gisdata menu. The open access version can be found on GTK's website http://gtkdata.gtk.fi/mdae/index.html, Layers/Exploration layers/Geological maps.

PRINCIPLES OF THE METAMORPHIC MAP

The metamorphic map has been produced at the 1:1 000 000 scale and the database is named metamorphic_1M.gdb. Roughly one-third of the Proterozoic bedrock in Finland consists of metagreywackes and metapelites, and consequently the Proterozoic part of the map is based on the metamorphic features of peraluminous metasedimentary rocks. Classification tools used in this study included mineral assemblages, grain size, preservation of sedimentary structures and the onset and degree of melting in metasedimentary, especially in metapelitic rocks. The standard grain size classification (fine-grained <1 mm, medium-grained 1–5 mm, coarse-grained 5–30 mm, very coarse-grained >30 mm) was used in the field classification.

Temperature (T) and pressure (P) are the most important factors in metamorphism. Metamorphic pressures and temperatures can be determined using either geobarometry and geothermometry, mainly based on net transfer or exchange reactions, or using phase diagrams and pseudosections. Geobarometry and geothermometry require mineral compositions, which are not always straightforward to interpret. Minerals are often zoned and their compositions may change in exchange reactions with changing metamorphic conditions, so that P and T values given by thermobarometry may not indicate those pressures and temperatures where the observed mineral assemblage equilibrated. Moreover, with changing PT conditions, mineral assemblages are also often partly or totally replaced by others, resulting in various kinds of metamorphic textures such as symplectites, coronas and pseudomorphs.

A pseudosection is a mineralogical map of stable mineral assemblages in the P-T space for a representative whole rock composition, and is a self-explanatory graphical tool for metamorphic classification. The pseudosections presented in this work (Figs. 1–4) were constructed using Perple_X 6.6.9 software (Connolly 1990, Connolly & Petrini 2002, Connolly 2005, Connolly 2009) (http://www.Perple_X.ethz.ch), with the Holland & Powell (1998)

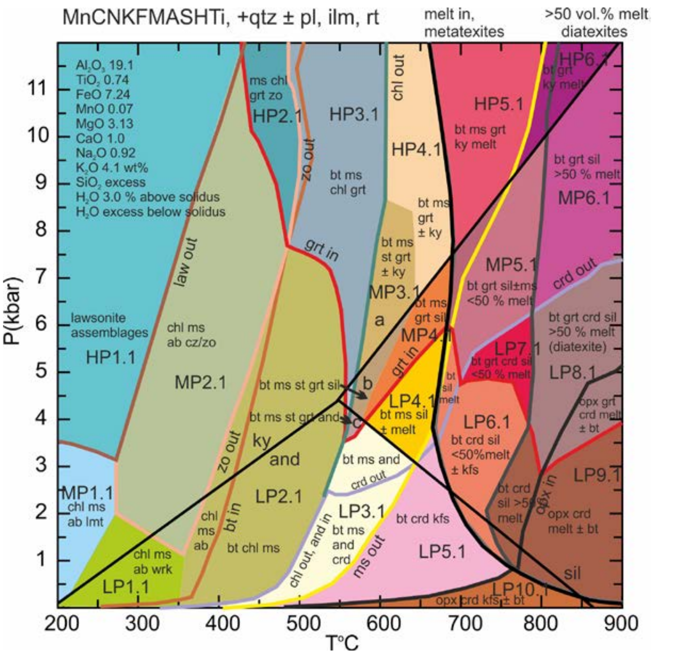

Fig. 1. A generalized PT pseudosection for an Al-rich pelitic rock.

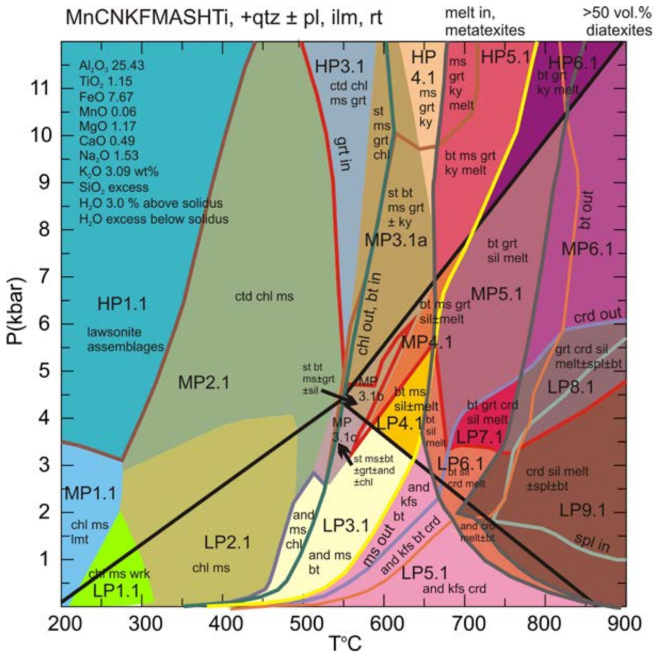

Fig. 2. A generalized PT pseudosection for a low-Ca, Fe- and Al-rich pelitic rock.

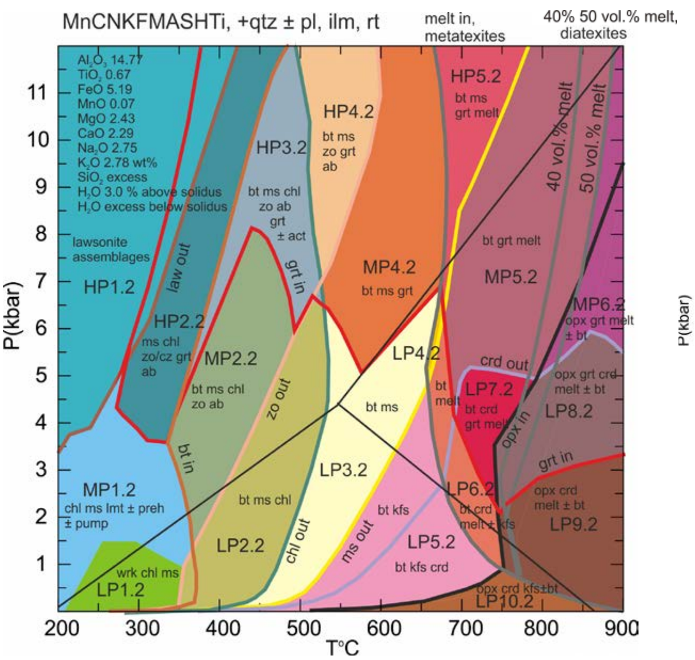

Fig. 3. A generalized PT pseudosection for an average Svecofennian metasedimetary rock.

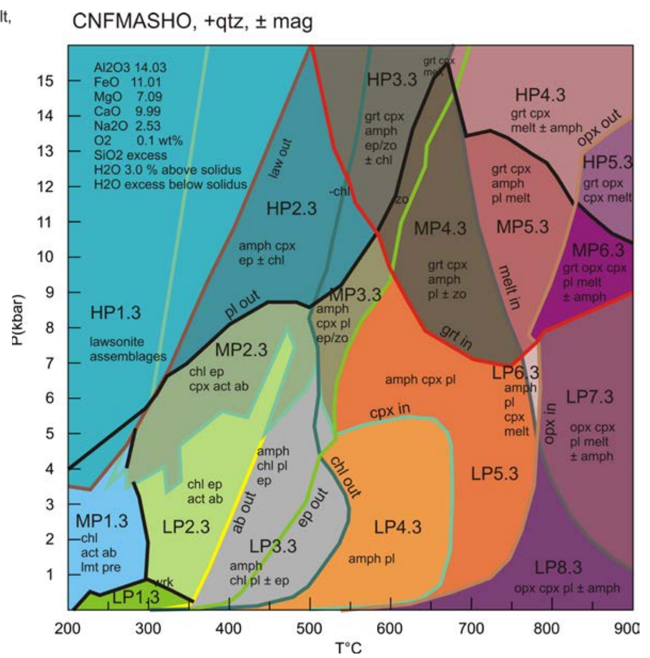

Fig. 4. A generalized PT pseudosection for an average Archaean amphibolite.

database revised by the authors in 2004 (hp04ver.dat).

Metapelites record low-variance mineral assemblages, which are more sensitive to PT changes than high-variance assemblages in mafic and felsic lithologies such as amphibolites, metapsammites or metagranitoids. In the Proterozoic part of the map, it is suggested that these rocks were metamorphosed under the same PT conditions as the adjacent metapelites. In the Archaean, the bedrock mostly consists of tonalitic-trondhjemitic-granodioritic (TTG) gneisses, and migmatites and metasedimentary rocks are only locally found. Therefore, the classification of the Archaean metamorphism is mostly based on mineral assemblages in mafic metamorphic rocks, apart from those areas where metasedimentary rocks are more abundant.

The metamorphic zones in the map are constructed on the basis of the observed mineral assemblages that characterize a particular zone. The PT fields of these assemblages are shown in the PT pseudosections (Figs. 1–4) with a colour corresponding to the same colour in the map (Fig. 8). The problem is that the width or presence of the stability field of a certain mineral assemblage in the PT space is sensitive to the whole-rock composition. However, in general, the compositional variation in most metasedimentary rocks is limited, so that only a few pseudosections are needed to explain most of the observed mineral assemblages, provided that the main factors of metamorphism have only been pressure and temperature.

Map levels

The GIS map contains several layers. In the first and simplest layer, the bedrock is classified into three metamorphic grades; these divide the bedrock into low-grade, medium-grade and high-grade areas (Figs. 5a, 6), following the classification of the IUGS Commission for the Management and Application of Geoscience Information (CGI) (http://resource.geosciml.org/vocabulary/cgi/201211/metamorphicgrade.html). The second layer is the metamorphic facies classification (Fig. 7), which also mainly follows the CGI recommendations. However, amphibolite facies is further divided into low, mid and high classes for detail (Fig. 5b). The metamorphic grade and facies mostly depend on the temperature conditions.

The third layer (Fig. 8) specifies the metamorphic zones, being based on the fields of stable mineral assemblages in the PT pseudosections, classified into low-pressure (LP), medium-pressure (MP) and high-pressure (HP) series. Figure 8 displays the metamorphic zones that represent the peak metamorphic conditions (generally maximum temperature), which best explain the textures of the rocks, for example the absence, presence and degree of partial melting without late metamorphic retrograde events. Figure 9 shows the areal codes of these metamorphic zones, cited later in the text.

Figure 10 displays those areas that have a significant late metamorphic overprint, either prograde or retrograde. Overprints are shown by metamorphic reactions and the growth of new minerals or mineral assemblages that represent PT conditions differing from those characterizing the prevailing assemblage. For example, in the Svecofennian migmatites, the common retrograde assemblage is andalusite-green biotite-quartz after cordierite, in which case a low pressure–high temperature assemblage is overprinted by a low pressure–low temperature assemblage. Fibrolitic sillimanite is found in some andalusite schists, in which case the LP-LT assemblage is overprinted by the higher temperature phase.

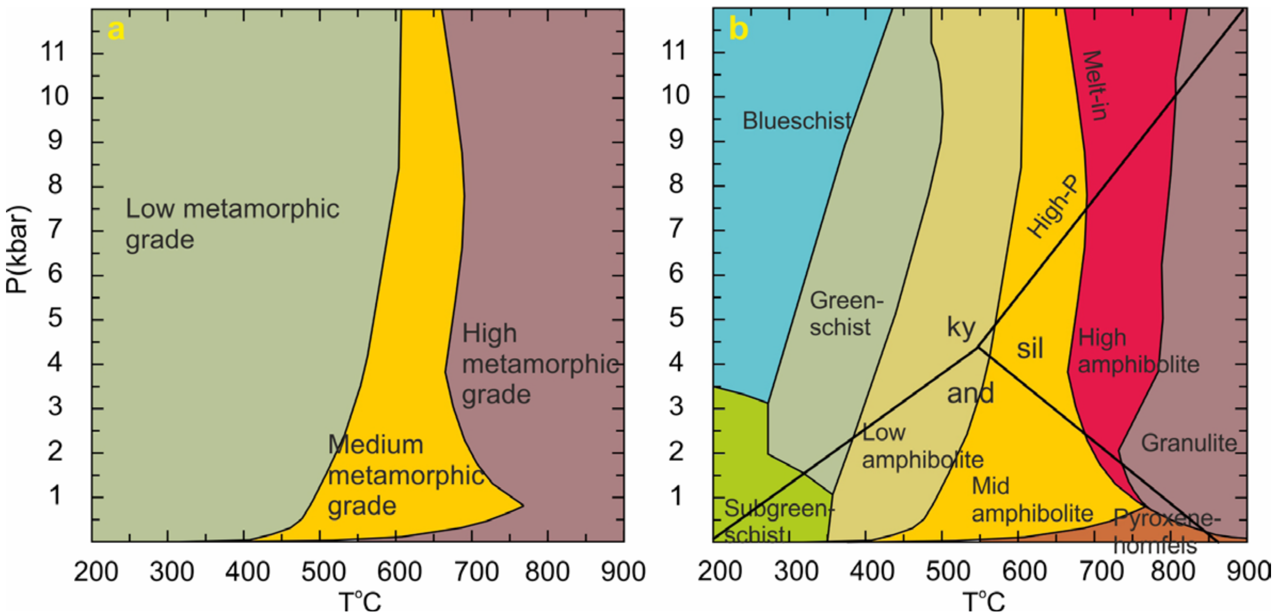

Fig. 5. a) PT fields of low, medium and high metamorphic grade, based on Fig. 1. b) PT fields of metamorphic facies, based on Fig. 1.

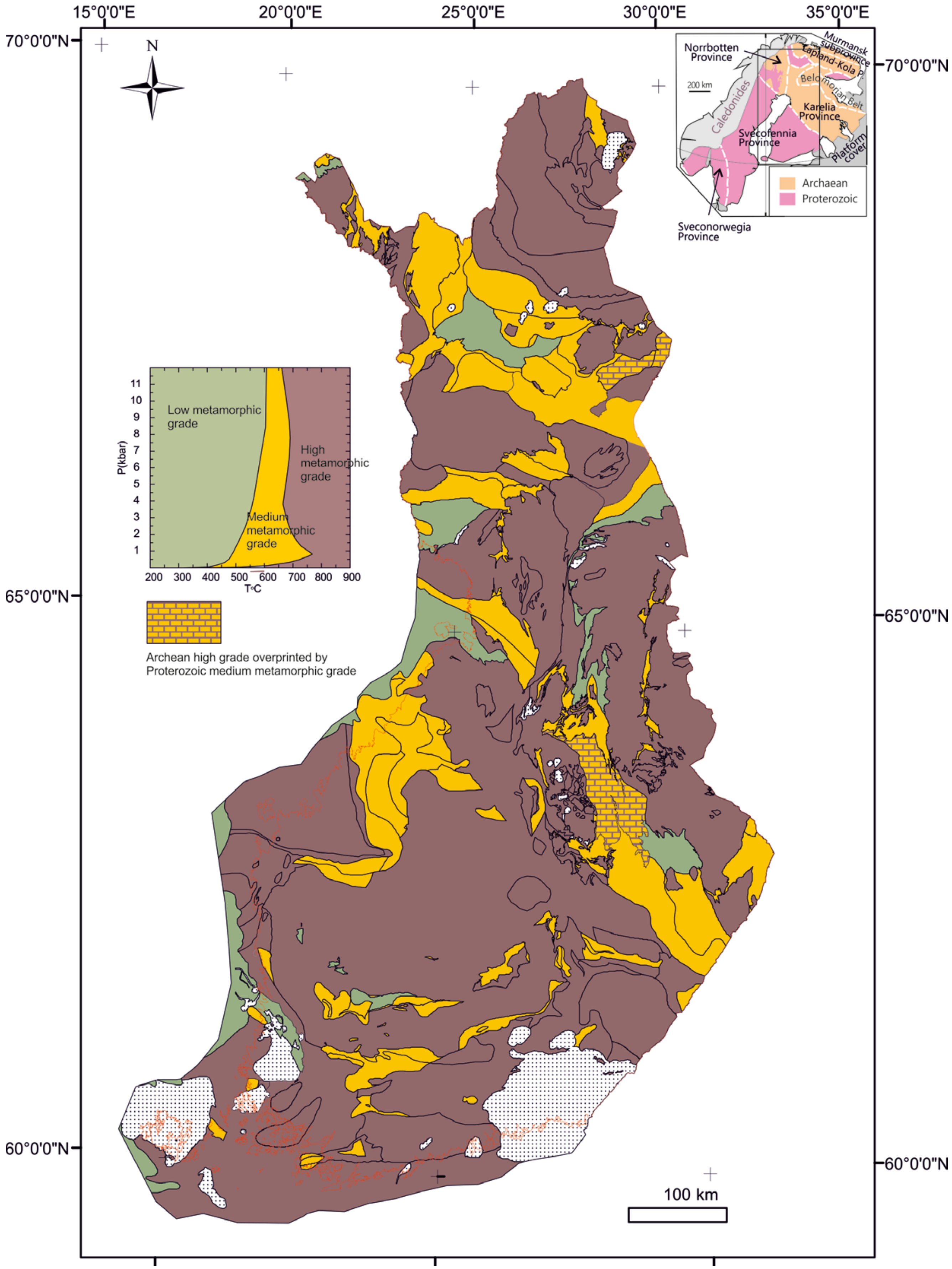

Fig. 6. Low-, medium- and high-grade areas. Stippled areas indicate undefined plutonic rocks. Updated 4.4.2022.

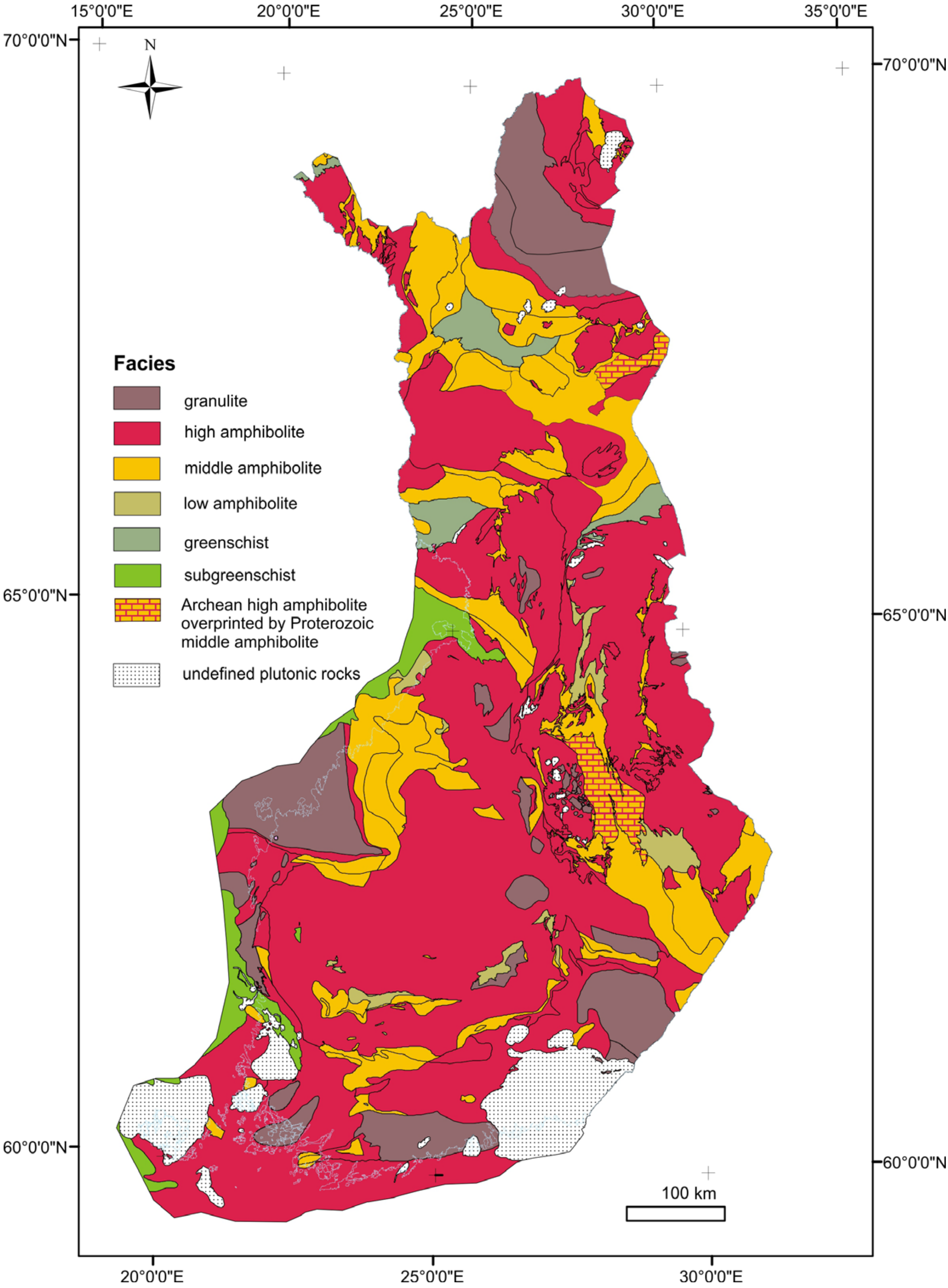

Fig. 7. Metamorphic map based on facies division. Updated 4.4.2022.

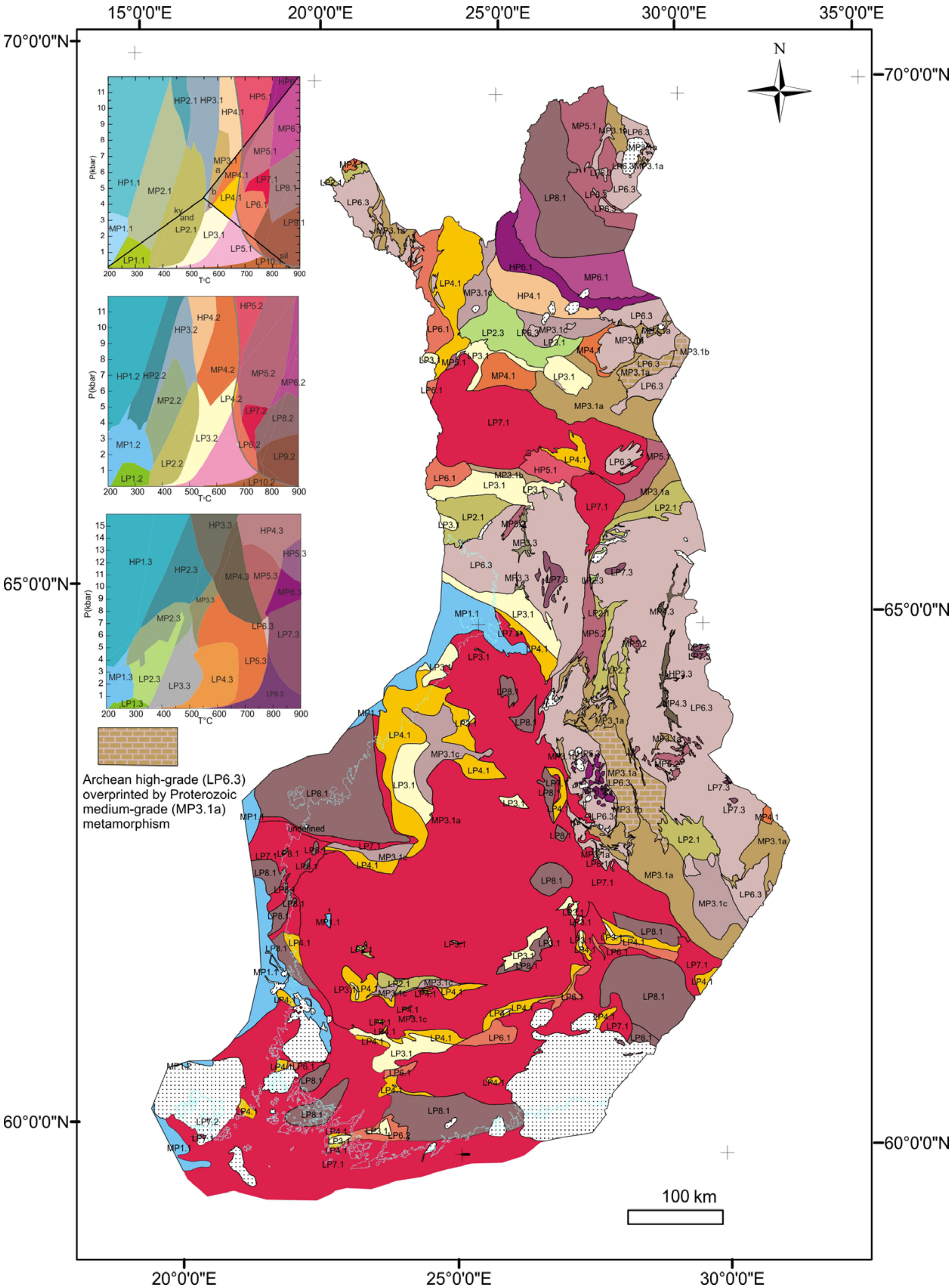

Fig. 8. Metamorphic map based on the fields of stable assemblages in generalized PT pseudosections (insets). Stippled areas indicate unclassified plutonic rocks. Updated 4.4.2022.

Database structure

The basic structure is the geodatabase (Fig. 12), at the scale 1:1 000 000 and entitled metamorphic_1M.gdb. The geodatabase contains a file geodatabase feature dataset entitled Metamorphic_Map_1.FDS. The file geodatabase feature dataset contains 12 classes: four of them are polyline type (boundary), another four are label type, and the remaining four are polygons combined from lines and data from the feature classes of the label file geodatabase. Each of them represents a different relative time of metamorphism: prepeak, peak, overprint and overprint2. At the moment, the prepeak and overprint classes are tentative and do not cover the whole bedrock.

The data consist of labels and polylines, as well as polygons, which use the same feature class properties as labels. The feature class properties are shown for labels and polygons in Appendix 1 and for polylines in Appendix 2. These appendices are found at http://tupa.gtk.fi/julkaisu/liiteaineisto/sp_060_appendix_1_2.xlsx.

Basis of the classification

Figure 1 is a pseudosection for an Al-rich, K-rich and Ca-poor metapelite. Figure 2 displays a pseudosection for an Al-rich, Ca-, Na- and K-poor metapelite, a typical composition, for example, of Proterozoic metapelitic schists in Central Lapland. The pseudosections have been calculated with excess H_2O in subsolidus conditions, assuming that dehydration reactions produce enough fluid to keep the system water-saturated. When melting begins, H_2O is strongly partitioned into melts and the system becomes H_2O-undersaturated; therefore, the suprasolidus parts of the pseudosections are calculated with 3.0 wt% H_2O. This is only an estimate, but, for example, reducing the H_2O abundance to 1.5 wt% would have little effect on the field where the garnet-cordierite-sillimanite-biotite-plagioclase-quartz assemblage is stable. However, the H_2O content has a strong influence on the stability of K-feldspar and on the volume of melt produced in melting reactions.

The pseudosections in Figures 1–2 are calculated in the MnCKFMASHTi system. The fields for Ti minerals (rutile, ilmenite) are not shown in the figures, although they are also important indicators of pressure and temperature. The reason for this is that rutile and ilmenite are mostly accessory minerals, which can often be reliably identified under a microscope, and the purpose is that the classification for the metamorphic map could already be carried out in the field using the generalised pseudosections.

Figure 3 presents a pseudosection for an average Svecofennian metasediment whose composition was calculated from the Rock Geochemical Database by Rasilainen et al. (2007). The composition is a greywacke type with relatively high CaO and Na_2O contents and moderate Al_2O_3, where in low- and mid-amphibolite facies between ~500–650 °C, garnet, muscovite and chlorite are almost the only index minerals in the obtained pseudosection, as also calclculated for the MnNCKFMASHTi system (fields LP2.2, LP3.2, LP4.2 and MP4.2 in Fig. 3). Cordierite is found at low pressures and orthopyroxene is stable at temperatures >7 50 °C. This reflects well the Svecofennian bedrock, where most metasedimentary rocks were metamorphosed at temperatures >500 °C, now being monotonous biotite schists and gneisses with occasional garnet and migmatites, often with garnet and cordierite and seldomly with orthopyroxene.

Figure 4 is a simplified pseudosection for an average Archaean amphibolite whose composition is calculated from the data by Hölttä et al. (2012). For simplicity, the chosen system is CNFMASHO, and 0.5 wt% of O_2 was added to the whole-rock composition to stabilize magnetite and epidote, which are commonly found in Archaean amphibolites. This pseudosection has many problems, especially because the chosen activity model for amphibole has drastic effects on the stability field of stable mineral assemblages, especially at lower temperatures. The model by Diener et al. (2007) was used in Figure 4. Apart from activity models, in different compositions the fields and existence of certain mineral assemblages are highly variable, especially in the low-T/high-P parts of the pseudosections. However, low-T/high-P rocks are lacking in the bedrock of Finland, and low-grade greenschist facies rocks with metamorphic temperatures <500 °C are rare in general, so this is not a major problem in these maps.

Criteria of the classes

In the diagrams in Figures 1–4, the fields named LP (MP, HP)X.1 represent pelitic Al-rich compositions, LPX.2 denotes greywacke-type compositions and LPX.3 amphibolites. The lowest grade rocks (LP1, MP1) have wairakite (wrk) assemblages at low pressure and laumontite (lmt), prehnite (preh) and pumpelleyite (pump) assemblages at medium pressure. With a temperature increase at low pressure, wairakite disappears and the assemblage biotite-white mica-chlorite-plagioclase becomes stable. Albite may coexist with these minerals in the low-T part of the LP2 field. In normal pelitic and greywacke compositions (Figs. 1 and 3), the assemblage bt-ms-chl-pl (LP2) has a wide field in the PT space extending to medium pressures. In low-Ca compositions (Fig. 2), chloritoid is, however, stable under medium pressure (MP) and the assemblage chl-ms is restricted to low pressure (LP).

The transition from LP2.1 to LP3.1 and MP3.1 is marked by the appearance of andalusite and staurolite in pelitic compositions, and by the disappearance of chlorite in Ca- and Na-richer compositions (Fig. 3), which do not contain Al_2SiO_5 minerals or staurolite at all. Chlorite can coexist with andalusite and staurolite in a narrow field at the breakdown boundary, depending on the composition. Cordierite is present in the low-pressure part of the LP3.

The stability of staurolite is shown by the MP3.1 field, which is divided into three parts, because staurolite-kyanite rocks represent higher pressures than staurolite-andalusite rocks. Therefore, combining all staurolite rocks together in the map is not justified, although staurolite has a rather limited field in the PT space, especially as regards temperature. Staurolite can coexist with kyanite in the MP3.1a field, with sillimanite in the MP3.1b field, and with andalusite in the MP3.1c field.

In the LP4.1 field, sillimanite is stable instead of andalusite, and small proportions of melt can be present in the high-temperature part of LP4.1-4.3. Within the PT limits of LP4, the grain size of metasedimentary rocks normally coarsens so that fine-grained schists change into medium-grained gneisses. Muscovite breakdown marks the transition from LP3 and LP4 into LP5 and LP6. The melt-in curve coincides with the muscovite-out curve at ca. 4–7 kbar, but the latter was chosen as a delimiter because, in the field, biotite-muscovite-sillimanite gneisses often have narrow leucosome veinlets as a sign of the onset of melting. In metapelitic and metagreywacke compositions, LP6 is characterized by the assemblage bt-melt(±sil) with cordierite in the low-pressure part, and LP7 by the assemblage grt-crd-bt-melt(±sil).

In mafic rocks, the presence of orthopyroxene has been considered to define the granulite facies. For Al-rich metasedimentary rocks, this is problematic, because in high-Al compositions such as in Figure 2, orthopyroxene is not stable below 900 °C, whereas in the greywacke composition (Fig. 3), orthopyroxene is stable over a wide range of pressures (0–9 kbar) at temperatures above 750 °C. In the Svecofennian metapelitic migmatites, orthopyroxene is rare, which is obvious on the basis of Figures 1 and 2. Existing data indicate that these migmatites were metamorphosed at ca. 5±1 kbar, and metamorphic temperatures seldom exceeded ~800 °C. Therefore, the PT conditions never reached the orthopyroxene field for these compositions. To tackle this problem, we used the degree of melting of Al-rich metasedimentary rocks for our classification.

Most metasedimentary rocks in Finland are migmatites, representing high-grade metamorphism with partial melting, which begins in metapelites at around 650 °C. With the temperature increase, the fraction of melt increases and primary sedimentary structures tend to disappear. Sawyer (2008) divided migmatites into two main groups on the basis of their morphology: metatexites, where the structures preceding partial melting are present, and diatexites, where the degree of melting is so high that primary structures are no longer visible. Therefore, instead of the orthopyroxene-in curve, for metapelitic rocks we have used the metatexite-diatexite classification of the migmatites. Indeed, it is quite easy to recognize in the field, and it describes the amount of melting and hence the metamorphic temperatures. Nevertheless, because the classification is structural, it cannot be directly shown in the pseudosections. In diatexites, there is normally more than ~40–50 vol.% neosome, which represents melt. The melt mode isopleths can be calculated using Perple_X software, and the 50 vol.% melt curve in the pseudosections has been used as a rough estimate above which migmatites are diatexitic. However, as a temperature indicator, the mode isopleth is inaccurate, because the observed neosome volume in the exposure may not be the same as the volume of melt produced due to the possible removal of melt from the source. Therefore, it is considered to give a sort of minimum temperature. The H_2O content also has a strong influence on the volume of melt, so that, for instance, reducing the H_2O wt% from 3.0 to 1.5 in the whole-rock composition of Figure 3, the temperature needed to produce 50 vol.% melt would be 70–80 °C higher. In the Archaean and Proterozoic migmatites, the reported metamorphic temperatures of >800 °C are rare, although the abundance of leucosome is often high. Therefore, the estimate of 3.0 wt% H_2O in Figures 1–4 may be justified.

In the average Svecofennian mica gneiss composition (Fig. 3), the opx-in and 40–50 vol.% melt curves are almost convergent; therefore, in these compositions, the appearance of orthopyroxene can also be used as a signature of the change from LP7 to LP8.

In medium- and high-pressure rocks, the lawsonite-out, zoisite-out and chlorite-out reactions are chosen to distinguish metamorphic zones under the low- to medium-temperature conditions. The garnet-in reactions at low and medium temperatures and cordierite-out reactions at high temperatures distinguish medium- and high-pressure rocks from low-pressure rocks. The exact location of both of these curves in the PT space is strongly dependent on the composition, and Figures 1–3 are thus only suggestive. However, using these three figures, rough estimates can be made for PT conditions and even PT paths for most mineral assemblages and associations observed in metapelites and metagreywackes. A generalized metamorphic map can be constructed based on these pseudosections, but for more detailed PT estimates, whole-rock and microanalytical data are of course needed on individual samples from each locality.

A pseudosection constructed for an average Archaean amphibolite is presented in Figure 4. Again, the high-P/low-T part of the pseudosection has little relevance for the classification of the Archaean bedrock, because it was metamorphosed in amphibolite to granulite facies at pressures seldom exceeding ~10 kbar. For most important reactions with increasing temperature, we have chosen the epidote-out, chlorite-out, clinopyroxene-in, garnet-in, melt-in and orthopyroxene-in. There are only a couple of cases where mafic granulites were metamorphosed at higher pressures than the stability field of orthopyroxene, or where garnet-bearing amphibolites are without plagioclase.

Regarding terminology, the term *mineral assemblage* in this paper refers to minerals that are stable in a certain PT field, whereas the term *mineral association* is used for all minerals observed in a thin section. The basis for the classification of the metamorphic zones is explained by describing typical mineral assemblages and associations, as well as textures, in the areas where published data do not exist and which are informative in a metamorphic sense. For other zones, the map is largely based on previously published studies.

In the following sections, metamorphism of the Finnish bedrock is described following the tectonic province division (Fig. 10) of Nironen et al. (2016).

KARELIA PROVINCE

Archaean

TTG migmatites and granulites

Because of the dominance of the mineralogically monotonous tonalitic–trondhjemitic–granodioritic (TTG) gneisses, suitable mineral assemblages for studying the pressure–temperature evolution of the Archaean rocks in the Karelia Province are not common. The high degree of melting and migmatization of felsic and mafic rocks implies that they were mostly metamorphosed in upper amphibolite and granulite facies conditions. Garnet is rare in amphibolites, but when it is present, the calculated pressures and temperatures given by geobarometry and geothermometry are ca. 6.5–7.5 kbar and 670–750 °C (Hölttä et al. 2012). However, because of the scarcity of garnet in amphibolites, the migmatite and TTG complexes are mostly classified as LP6.3 (Fig. 8).

Medium-pressure granulites, metamorphosed at ca. 9–11 kbar and 800–850 °C (MP6.3), are only found in the Iisalmi complex (areas 185–212, Figs. 8–10). These granulites are mostly mafic with grt-cpx-opx-pl-qtz assemblages, but without orthopyroxene in the northwestern part of the area (areas 209–212) (Hölttä & Paavola 2000, Hölttä et al. 2000). In the southwesternmost part of the Iisalmi granulite complex, there are rocks with a high Mg and Al content and with low abundances of alkalies and Ca, typical of hydrothermally altered rocks (Hölttä 1997). These Mg-Al granulites form interlayers a few metres thick within migmatitic mafic granulites, garnet-sillimanite gneisses and quartz-cordierite rocks. The outer silica-richer parts of the Mg-Al-granulite layers have grt-crd-opx-sil-qtz-rt±oam±phl assemblages, and the inner silica-deficient parts are orthoamphibole-rich with

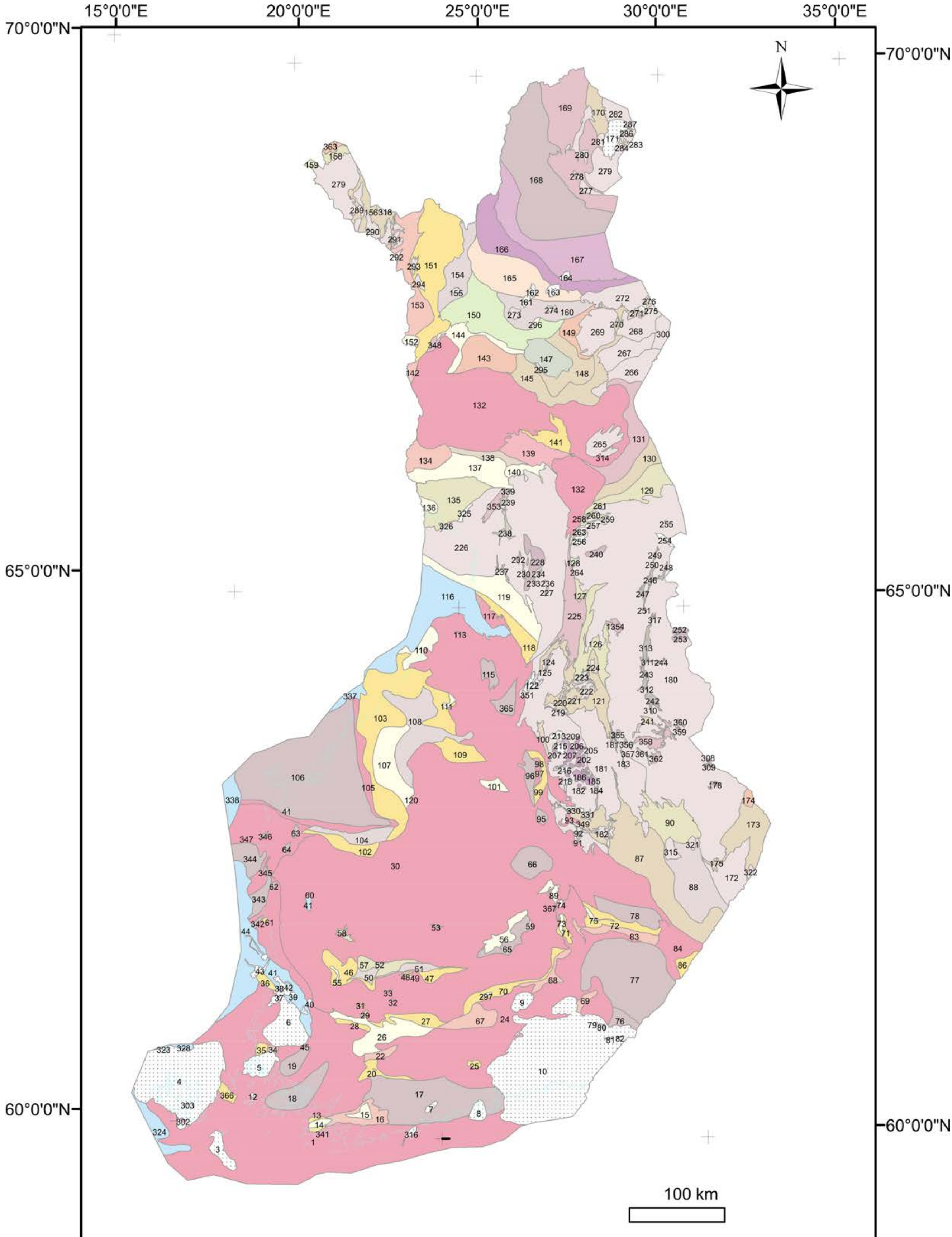

Fig. 9. The areal codes of the metamorphic zones presented in Fig. 8.

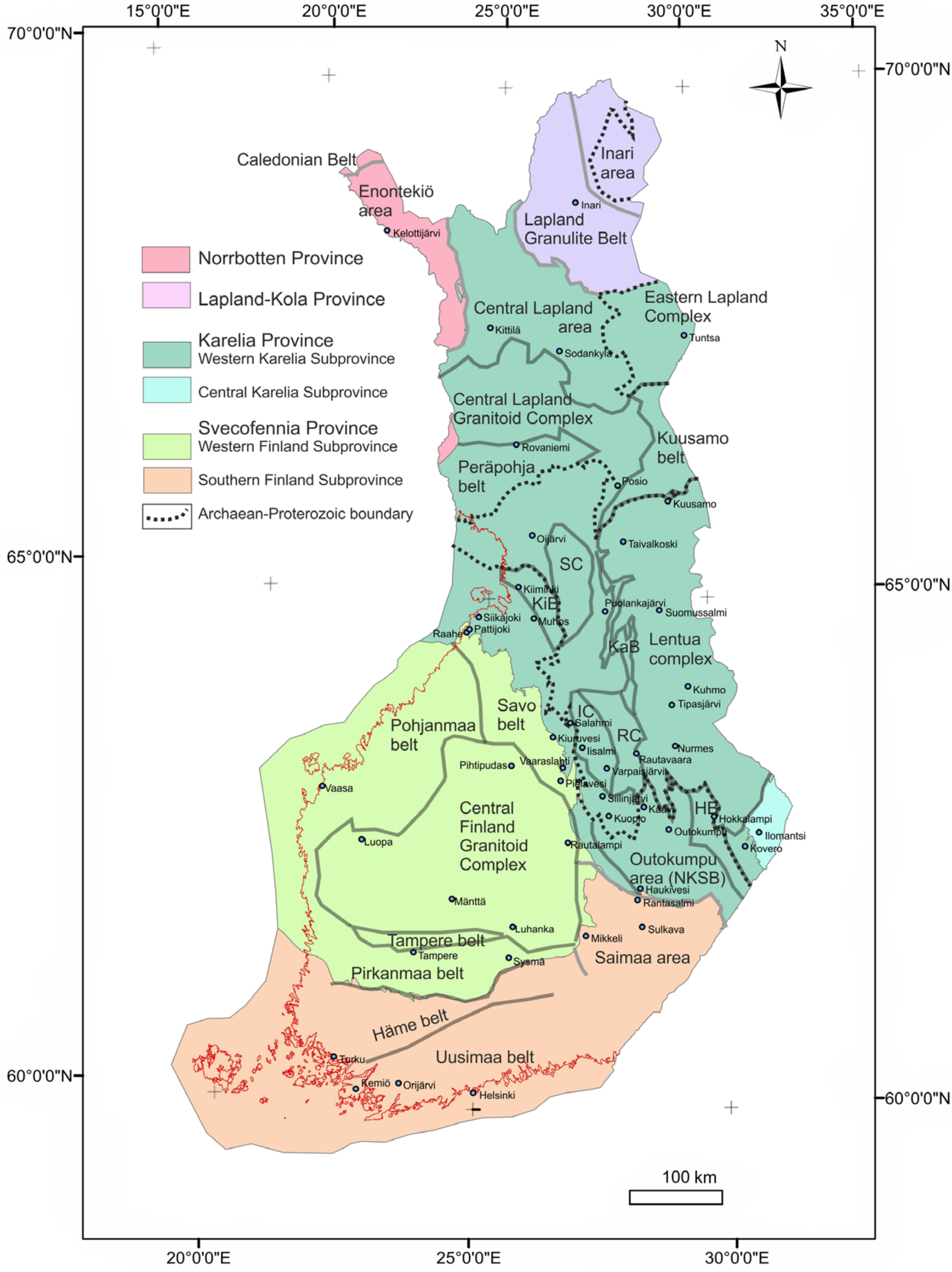

Fig. 10. Map showing the province division by Nironen et al. (2016) and the lithological-geographical areas defined by Nironen et al. (2002), cited in this paper. The Archaean complexes are from Hölttä et al. (2012). KiB = Kiiminki belt, KaB = Kainuu belt, SC = Siurua complex, IC = Iisalmi complex, RC = Rautavaara complex.

varying abundances of orthopyroxene, kornerupine, corundum, sapphirine, spinel and phlogopite. The prominent feature in the Mg-Al granulites is spectacular corona textures, and even multiple coronas in the mafic rock (Fig. 13). In the layers with an opx-sil assemblage, orthopyroxene, sillimanite and quartz have reacted, forming a corona of garnet and cordierite between the reactant minerals (Fig. 13d) (Hölttä & Paavola 1989). The mineral compositions indicate that this reaction took place at around 800-840 °C at 8.2-8.4 kbar, obviously indicating the onset of uplift near the peak temperatures (Fig. 13e).

The Siurua complex (Fig. 10) comprises mafic granulites (areas 227-235, Fig. 9) with hbl-cpx-opx-pl-qtz assemblages, for which maximum metamorphic pressures and temperatures of ca. 6 kbar and 750 °C have been calculated (Lalli 2002). Compared with the mafic pyroxene granulites of the Iisalmi area, garnet is rare in the Siurua mafic granulites, also indicating lower pressures, and they are therefore classified as LP7.3.

In the Lentua complex, the granulite area (area 240, Fig. 9) in Taivalkoski consists of orthopyroxene-bearing TTG gneisses without mineral assemblages suitable for pressure estimation. Sanukitoid suite granodiorites in the southeastern part of the complex locally contain orthopyroxene, but it is not clear whether the mineral assemblages in these rocks were metamorphic or magmatic (Halla & Heilimo 2009). Amphibolites and paragneisses near these charno-enderbites were metamorphosed in upper amphibolite and granulite facies at ca. 6.5–7.5 kbar and 670–750 °C. Pressures obtained for amphibolites elsewhere in the southern part of the Lentua complex are slightly lower, being 4.7–5.5 kbar (Hölttä et al. 2012).

Metamorphic pressures estimated by Hölttä et al. (2012) for the Nurmes paragneisses (areas 355–360, Figs. 9-10) and for the amphibolites are mostly around ca. 6.5–7.5 kbar, and corresponding temperatures ca. 650–740 °C. These rocks are normally migmatized, also indicating high metamorphic temperatures. Garnet is locally present, but cordierite was never found in metagreywackes, and they are therefore classified as MP6.2.

Greenstone belts

Low grade rocks having mid-amphibolite facies mineral assemblages are found in the inner parts of the greenstone belts, which often show well-preserved primary structures and only a few or no signs of partial melting. Garnet-bearing samples from supracrustal rocks in the Ilomantsi belt in the Central Karelia Subprovince (area 173, Figs. 9–10) typically have the association grt-bt-pl-qtz±ms, occasionally with andalusite and staurolite, but more often with their muscovite-filled pseudomorphs. Kyanite was found in one exposure in Ilomantsi (Sorjonen-Ward 1993, Hölttä et al. 2017). Grt-bt thermometry for these samples indicates in most cases crystallization at ca. 550–590 °C, similarly to the results of O'Brien et al. (1993) and Männikkö (1988), these temperatures being in accordance with the observed mineral associations. In the northwestern part of the Ilomantsi greenstone belt, sillimanite is also present in pelitic rocks (area 174, Fig. 9), and temperatures from grt-bt thermometry are also higher than in the southeast, being ca. 600–625 °C. Pressures indicated by the grt-bt-pl-qtz barometer are ca. 3.5–5.5 kbar in the central parts of the greenstone belt, but >6 kbar in the sillimanite-bearing rocks (Hölttä et al. 2012). The lower pressures are of the same order as those obtained by Männikkö (1988) using sphalerite barometry for samples from the Kovero greenstone belt, which is the southwesternmost continuation of the Ilomantsi belt. U-Pb ages on monazite show that the Ilomantsi belt underwent Proterozoic heating at ca. 1.83 Ga, and conclusions on the Archaean PT evolution, based on the thermobarometric data, must consequently be made with caution, because of the possible re-equilibration during the Proterozoic (Hölttä et al. 2017).

Previous studies on the Kuhmo greenstone belt in the Western Karelia Subprovince (Lentua complex, Fig. 10) have demonstrated an increasing metamorphic grade from inner to outer parts of the belt. According to Tuisku (1988), geothermometry suggests metamorphic temperatures as low as 500 °C for the inner parts and up to 660 °C for the outer parts of the belt. Garnet is locally found in mafic rocks, and the belt is therefore mainly classified as MP4.3. Pressures using the sphalerite barometer applied to sphalerite inclusions in pyrite are mostly 6–7 kbar, but in some cases as high as ca. 13 kbar (Tuisku 1988).

Still in the Lentua complex (Fig. 10), an interesting observation was made for a patch of garnet-bearing amphibolites east of the Kuhmo greenstone belt (area 311, Fig. 9). Noting the standard tholeiite basaltic whole-rock composition of these amphibolites, it is very surprising that they do not comprise any matrix plagioclase, but only minor albite and oligoclase inclusions in garnet. The observed ranges of the anorthite content in the plagioclase inclusions in two microanalyzed samples were An_{10}–An_{30} and An_1–An_{20}, indicating that some of the inclusions are almost pure albite. The garnet hosts are rich in grossular (X_{grs} 0.25–0.35, X_{grs} = Ca/(Fe+Mn+Mg+Ca)) and spessartine (X_{sps} 0.10–0.12), but Mg-poor (X_{prp} 0.05–0.09), indicating that the metamorphic temperatures were not very high during garnet crystallization. These rocks often contain epidote, sometimes only as inclusions in garnet, but occasionally also in the matrix. The P-T pseudosection in Figure 4 indicates pressures above 12 kbar. Using Thermocalc software, Hölttä et al. (2012) calculated average pressures of ca. 16–17 kbar at 600–700 °C for this rock, which is therefore classified as HP3.3. In the Oijärvi greenstone belt (area 238, Figs. 9–10), garnet amphibolites are rarely found, and relatively high average pressures of ca. 9.5 kbar were also calculated for these rocks using the grt-hbl-pl-qtz barometer (Hölttä et al. 2012), which were therefore classified as MP3.3.

Palaeoproterozoic metamorphic overprint in the Archaean bedrock

The Archaean bedrock in the western part of the Karelia Province underwent strong reheating during the Palaeoproterozoic Svecofennian orogeny. Most K-Ar ages on biotite and hornblende in the Archaean are 1.8–1.9 Ga, the only exceptions being the Varpaisjärvi granulite block and the Ilomantsi area in southeatern Finland, where K-Ar ages are Archaean. The heating of the Archaean crust is explained by burial under a massive nappe complex ca. 1.9 Ga ago (Kontinen et al. 1992).

Ductile shear zones developed in the Archaean bedrock during the Svecofennian orogeny. The width of these deformation zones varies from tens of metres to several kilometres (Kohonen et al. 1991). Apart from mylonitic and ultramylonitic shear zones, signs of Proterozoic metamorphism can be seen in most areas of the Finnish Archaean as rehydration reactions producing hydrous minerals (epidote, chlorite, micas, amphiboles). In some areas, this effect is weak, but there are at least two zones with a width of tens of kilometres that underwent pervasive Proterozoic metamorphism. In the Rautavaara complex, almost all Archaean rocks were ductilely deformed during the Svecofennian orogeny, which is well shown by the deformation of the dolerite dykes (Paavola 1999, Kontinen 2002). All Palaeoproterozoic 2.3–2.1 Ga dykes are deformed, and many of these have strong stretching lineations dipping mostly to the SW. The same foliations and lineations are also visible in the surrounding Archaean rocks, where Proterozoic metamorphism destroyed the Archaean mineral assemblages and new minerals crystallized as a response to changing PT conditions (Mänttäri & Hölttä 2002). A similar reaction history can be seen in the Tuntsa area, which represents the Belomorian belt in northeastern Finland.

Rautavaara complex

Local retrogression of granulites can be seen in the Iisalmi complex. In the mafic granulites, epidotization is common, and in the Mg-Al granulites, ferromagnesian minerals are retrogressed along rims and fractures, forming chlorite, talc, tiny needles of staurolite and kyanite and up to 1 mm andalusite. Retrogression is pervasive in the Rautavaara complex (area 181, Fig. 9), so that the relic granulite facies assemblages are only found in a few localities, and the size of staurolite, chlorite and Al_2SiO_5 minerals is often coarser, generally being medium-grained. Early garnet grains, obviously crystallized during the Archaean high-grade metamorphism, have almost exclusively broken down, either partly or completely, into cordierite. Geothermobarometry indicated that this took place at ca. 540-630 °C at 3-6 kbar (Mänttäri & Hölttä 2002). Therefore, according to the classification, the area has an MP3.1a to MP3.1c overprint (Fig. 11). In the zircon grains dated from the Rautavaara supracrustal rocks, the same age populations are found as in the Iisalmi granulites (Huhma et al. 2012), which suggests that the Rautavaara rocks were metamorphosed together with the Iisalmi granulite complex. However, TIMS U-Pb dating of monazite gives a Proterozoic age of 1.89 Ga (Mänttäri & Hölttä 2002), which in turn indicates retrogression during the Svecofennian orogeny.

In the Rautavaara complex (Fig. 10), the main supracrustal rock types are quartz rocks, garnet-cordierite-orthoamphibole rocks, garnet-cordierite-biotite gneisses, biotite-chlorite gneisses and amphibolites. SiO_2-rich quartz rocks are light in colour, resembling quartzites or cherts in appearance but being compositionally Al-richer. Common mineral associations observed in these rocks are qtz-pl-ky-rt±ms±and±sil±bt±pin and qtz-crd-chl-bt±ky±st±tur±rt. One variety of this rock type is quartz-albite rock, which is found in a few localities (Paavola 1999). This rock contains ca. 50-65 modal % quartz and 15-30 modal % sodic plagioclase, the rest being Al-silicates (andalusite, kyanite and fibrolitic sillimanite, and often all three), paragonitic

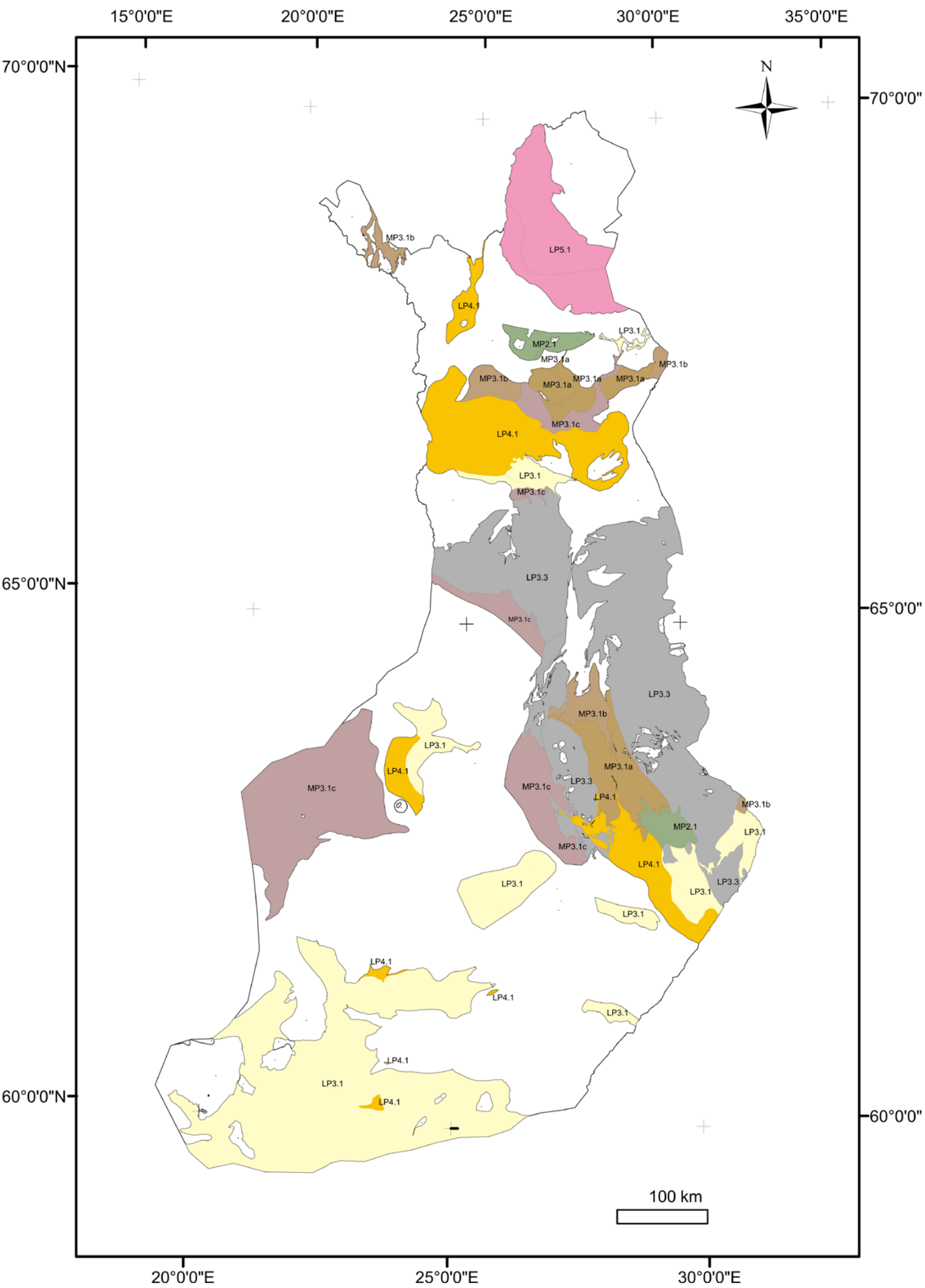

Fig. 11. A map showing the areas with a significant metamorphic overprint. The colours and symbols correspond to those in Fig. 1. White areas are either not classified or are not significantly affected by late metamorphic events.

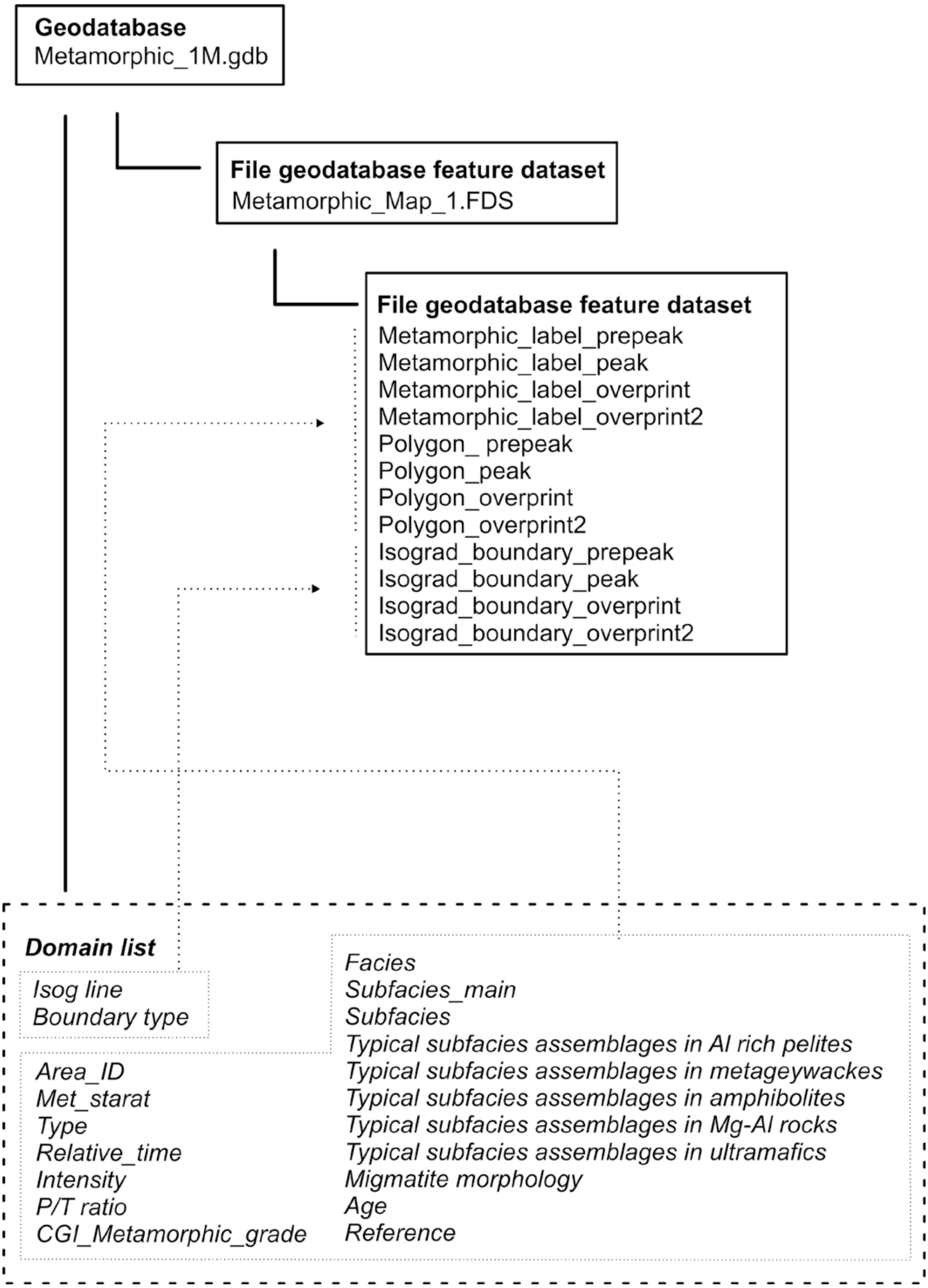

Fig. 12. The database structure.

white mica, phlogopite, rutile and cordierite. The process leading to the present compositions was probably premetamorphic alteration by saline fluids. Andalusite and kyanite occur as large elongated (1–10 mm) porphyroblasts. Andalusite grains are normally elongated along the foliation of the rock, whereas kyanite is more randomly oriented. The crystallization order of the Al-silicates is difficult to interpret, but fibrolitic sillimanite bundles are crystallized on the rims of andalusite and kyanite (Fig. 14), indicating that sillimanite crystallized later than the other two Al-silicates.

Garnet-cordierite-orthoamphibole rocks have the mineral association grt-crd-oam-qtz-st-chl-rt±bt±cum±pl±ky. These rocks are coarse-grained, with garnet and orthoamphibole grains up to 1–3 cm in diameter. The quartz content varies from almost quartz-free massive orthoamphibole rocks to more quartzose varieties. Garnet is always resorbed into cordierite and orthoamphibole or chlorite (Figs. 15a–b). Orthoamphibole, garnet and cordierite are commonly replaced by staurolite and chlorite, forming staurolite-filled pseudomorphs after orthoamphibole (Fig. 15c). Kyanite, when present, has reacted with orthoamphibole so that a cordierite corona is found between kyanite and orthoamphibole.

The common association in garnet-cordierite-biotite gneisses is grt-crd-bt-ky-sil-st-qtz±chl. Textures indicate decompression: for example, garnet is always decomposed into cordierite and biotite, commonly leaving only a pseudomorph with some garnet inclusions. There are some larger kyanites in the matrix, but kyanite, together with staurolite and chlorite, is commonly found as small (0.1-0.2 mm), randomly oriented prisms after cordierite. This texture suggests that decompression was followed by cooling to the kyanite field.

Biotite-chlorite gneisses are distinguished from garnet-cordierite-orthoamphibole rocks by the abundance of biotite and chlorite and absence or scarcity of orthoamphibole, which gives the rocks a more foliated, gneissose fabric. Compared to the quartz-bearing rocks, they differ in the smaller amount of quartz and higher amount of dark micas, which gives them a greenish-brownish colour. Biotite-chlorite gneisses have varying abundances of kyanite, andalusite, cordierite, orthoamphibole, white mica, staurolite and garnet. Cordierite rims are formed between Al-silicate (ky, and) and chlorite or biotite, whenever they were in contact (Fig. 15d). Garnet is sometimes replaced by staurolite in rims. Kyanite, andalusite and staurolite are locally altered into white mica. Chlorite always replaces other ferromagnesian minerals.

The common assemblage in amphibolites is hbl-pl-qtz±grt, sometimes with cummingtonite. Garnet is commonly decomposed from the rims to a second-generation hornblende and plagioclase.

Tuntsa suite

The Tuntsa suite in the Eastern Lapland complex in northeastern Finland (areas 267, 300) is considered to represent the northwesternmost part of the Archaean Belomorian belt of the Fennoscandian Shield (Figs. 6 and 9). Characteristic metamorphic features of the Belomorian belt are the presence of medium- to high-pressure, high-grade metamorphic rocks and a strong Proterozoic metamorphic overprint. Neoarchaean eclogites, metamorphosed at 14-17 kbar, possibly even at 30 kbar, have been described from the Gridino area on the White Sea coast (Volodichev et al. 2004, Mints et al. 2010a, Perchuk & Morgunova 2014, Balagansky et al. 2015, Li et al. 2015), and eclogites have also been found in the northern parts of the Belomorian belt, where they have been related to subduction of the Archaean oceanic crust (Mints et al. 2010a, 2010b, 2014, Shchipansky et al. 2012, Balagansky et al. 2015). The Belomorian belt underwent several high-pressure metamorphism events at 2.7-2.6 Ga (Li et al. 2015), and was in many places strongly affected by Proterozoic heating. This can be seen in the U-Pb age determinations on titanite and rutile, which have given ages of 1940-1750 Ma (Bibikova et al. 2001, Skiöld et al. 2001), and in ca. 1.9 Ga overgrowths on Archaean zircon in eclogites (Balagansky et al. 2015, Li et al. 2015).

The Tuntsa suite mainly consists of metasedimentary quartz-feldspar and mica gneisses, which are often migmatized. Strong deformation and recrystallization have obliterated the primary textures of the rocks, which are locally altered into augen gneisses or even-grained granitic gneisses containing ghost-like relics of metasedimentary rocks. Penetrative foliation, mostly with a subhorizontal dip, is the most prominent structural feature (Juopperi & Veki 1988). Rocks often exhibit leucosome veins up to several vol.%, indicative of partial melting. The thickness of the leucosome veins varies from <2 cm to more than ten centimetres, and they are locally broken and boudinaged. Metasedimentary rocks commonly have staurolite, kyanite and garnet porphyroblasts, which may be up to several centimetres in diameter (Figs. 16a–f). A typical mineral association in the Tuntsa metasedimentary rocks is

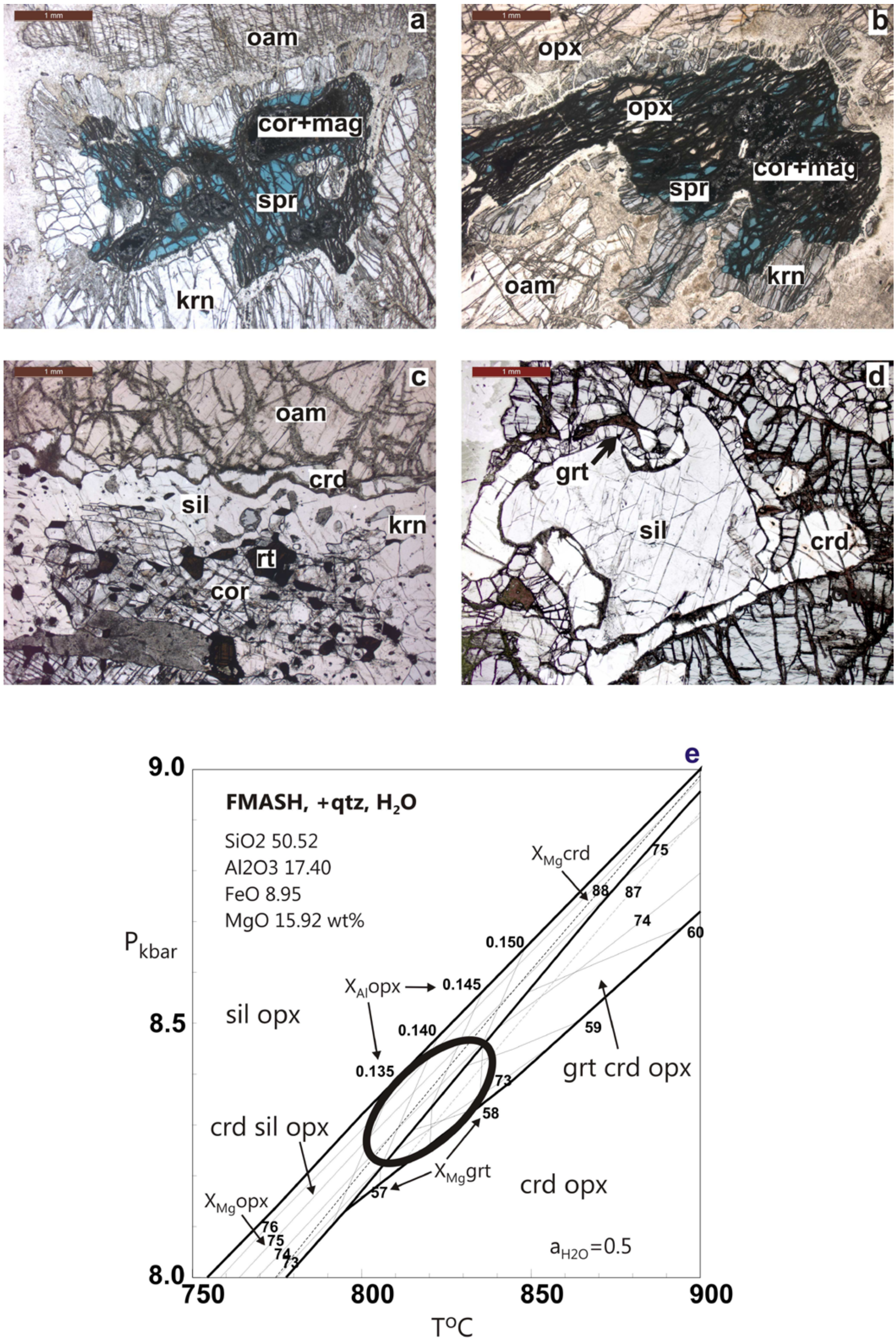

Fig. 13. Corona textures in the Mg-Al granulites in Varpaisjärvi: a, b) a sapphirine corona on an aggregate of corundum and magnetite, a kornerupine corona between orthoamphibole/orthopyroxene and sapphirine; c) a sillimanite corona on corundum, a cordierite corona between sillimanite and orthoamphibole; d) a garnet-cordierite corona between sillimanite and orthopyroxene; e) a PT pseudosection for a rock in Fig. 4d showing the the isopleths of mineral compositions and PT conditions where the reaction opx + sil + qtz = grt + crd took place. The pseudosection was constructed using Thermocalc 331 software.

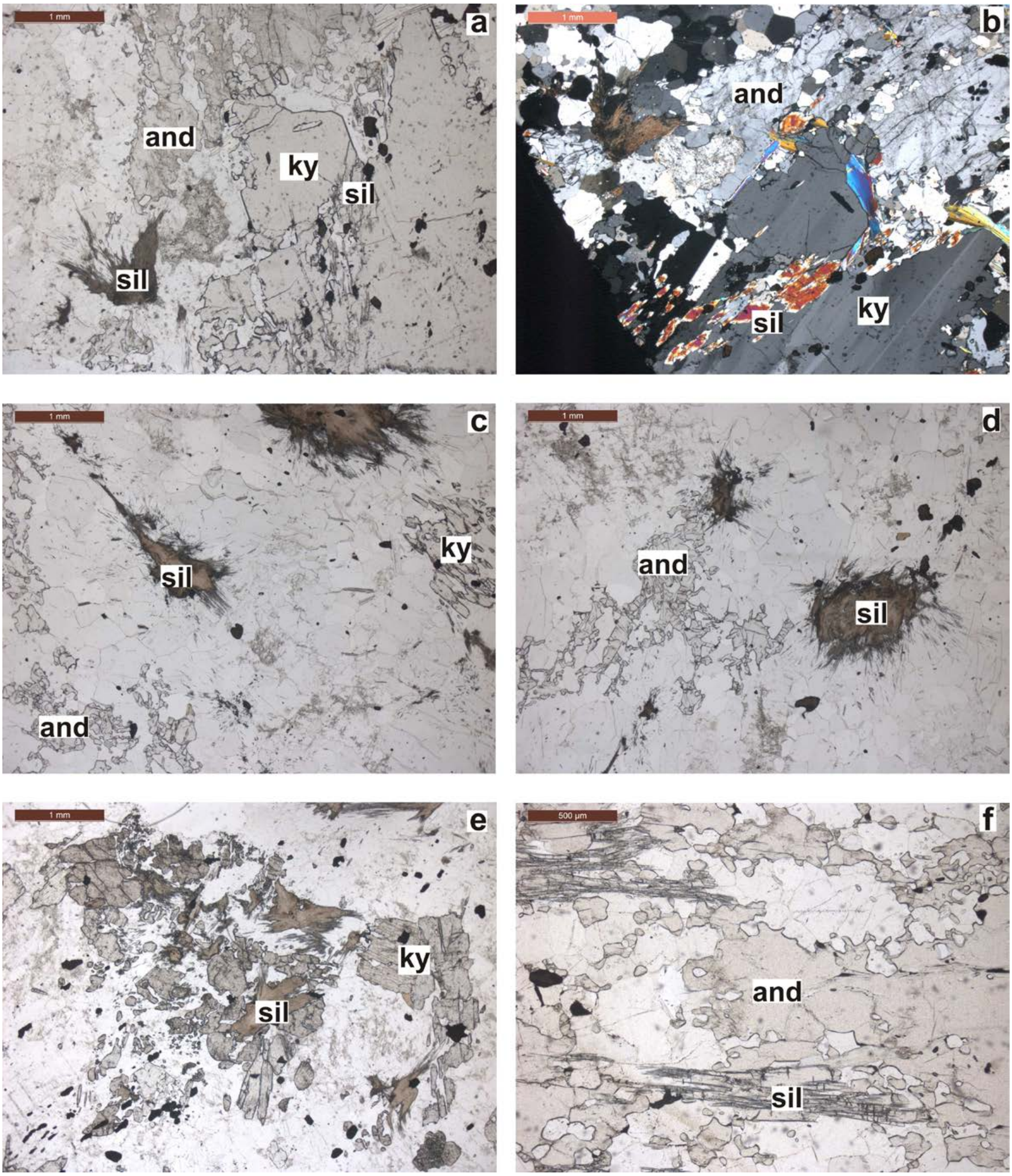

Fig. 14. Textures in the andalusite–sillimanite–kyanite rock in Rautavaara. Northing 7055574, easting 554356. Coordinates are given using the EUREF-FIN (UTM35) system.

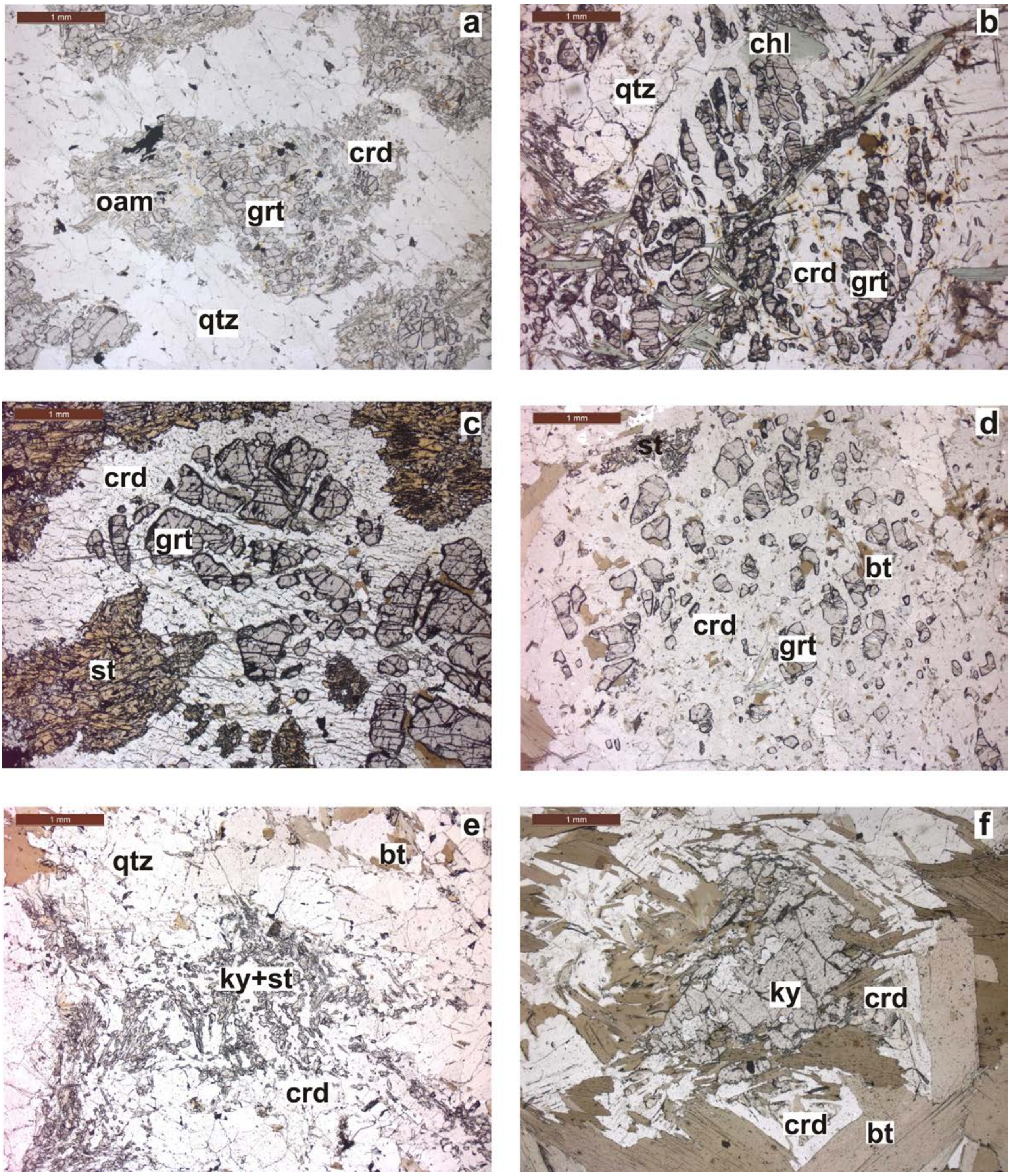

Fig. 15. Retrograde textures in the Rautavaara area: a) garnet altering into cordierite and orthoamphibole in the reaction grt + qtz = oam + crd; b) garnet altering to cordierite and chlorite in the reaction grt = crd + chl + qtz; c) garnet altering to cordierite and staurolite, possibly in the reaction grt + ky = crd + st; d) pinitized cordierite between kyanite and biotite, possibly formed in the reaction ky + bt + qtz = crd + K^+.

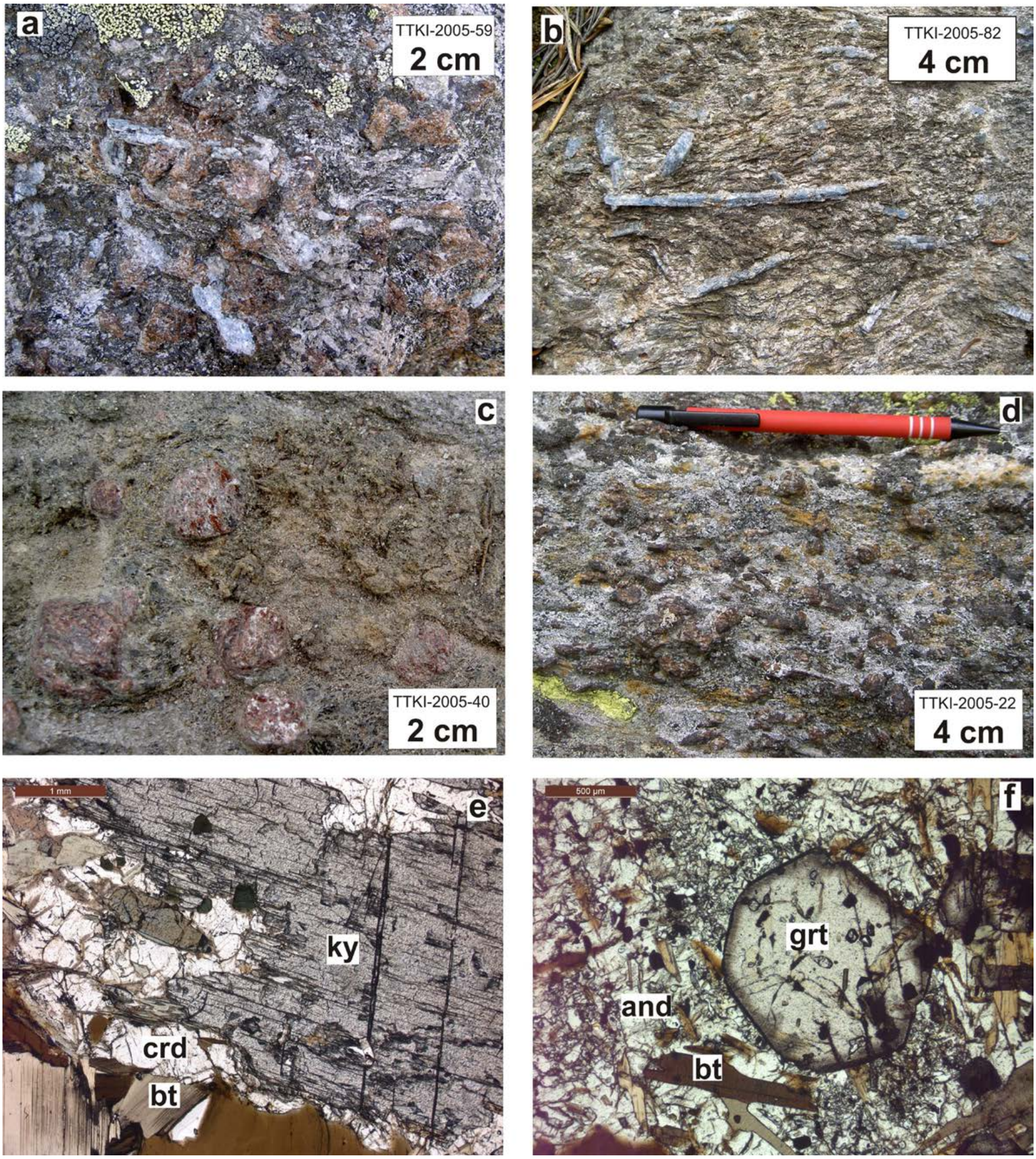

Fig. 16. Porphyroblastic rocks in Tuntsa: a) kyanite–staurolite gneiss; b) long kyanite crystals in biotite-rich gneiss; c) garnet crystals; d) staurolite crystals; e) reaction ky + bt = crd (+K^+) in the rock in Fig. 16b; f) euhedral garnet surrounded by andalusite.

st-bt-qtz-pl±grt±ky±chl±crd±ms. Andalusite (Fig. 16f) has been reported in two localities and sillimanite in four outcrops, both minerals in the eastern part of the Tuntsa suite (Kivisaari 2008). Andalusite, kyanite and sillimanite are also found in the Tulppio suite (area 271, Fig. 9), north of the Tuntsa suite (Virransalo 1985). Chlorite is common, but prograde muscovite is rare, and sericite is common in retrograded pseudomorphs, where it replaces staurolite, kyanite and andalusite.

The abundance of staurolite in the Tuntsa paragneisses contradicts the migmatisation, because staurolite should not be stable above the solidus in these compositions (Figs. 1–2). The garnet compositions also indicate maximum crystallization temperatures of ca. 600 °C, far below melting. This gives reason to conclude that the migmatisation is an earlier, obviously Neoarchaean event and the staurolite-garnet-kyanite assemblages were developed later. This is supported by the existing age determinations: titanites show both Archaean and Proterozoic U-Pb ages, and a slightly discordant monazite from a granite north of the Tuntsa suite gives a U-Pb age of 1.90 Ga (Juopperi & Vaasjoki 2001). Therefore, the area is classified as LP6.3, overprinted by MP3.1a–c (Figs. 8 and 10).

Garnet in Tuntsa is typically strongly zoned with a Ca-rich, Mg-poor core (X_{Ca} 0.16–0.20, XMg 0.06–0.09) and Ca-poor, Mg-richer rim (XCa 0.03–0.07, X_{Mg} 0.14–0.16), indicating decompression from ca. 8 kbar at 540–560 °C to 4.0–4.5 kbar at ca. 580–600 °C during the growth of the garnet (Kivisaari 2008). Reaction rims of cordierite between kyanite and biotite also indicate decompression, which probably followed the Proterozoic thrusting, producing clockwise PT paths typical for a tectonically thickened crust.

Palaeoproterozoic cover sequences

North Karelia schist belt

The Proterozoic supracrustal rocks in southeastern Finland form the North Karelia schist belt (NKSB), following the definition used by Kontinen et al. (2006) and Säntti et al. (2006), among others. This area covers the Höytiäinen belt and the Outokumpu area (areas 87, 88, 90, Figs. 9, 12) in the nomenclature of Nironen et al. (2002). It mostly consists of allochthonous upper Kaleva and autochthonous lower Kaleva metaturbidites, minor metavolcanic rocks, and Jatulian metasedimentary arkosites, conglomerates and quartzites at the Archaean-Proterozoic boundary (for an explanation of the names Kaleva and Jatuli, see Nironen, this volume).

The Jatulian rocks are characterized by medium-pressure metamorphism preserving andalusite-kyanite index minerals. Kyanite-bearing quartzites have been described from the NKSB, for example by Aurola (1959), Marmo (1988, 1992), Kohonen & Marmo (1992) and Pekkarinen et al. (2006). The mineral associations observed in this work in kyanite-bearing quartzites are:

ky-prl-ms-qtz±ctd±rt±tur±kao
ky-and-prl-ms-qtz-rt±tur±ctd±kao
and-qtz-ms

Chloritoid and kyanite are often in textural equilibrium (Fig. 17a), as also are andalusite and kyanite (Fig. 17b). In some cases, kyanite overgrows andalusite (Fig. 17c), suggesting that these two Al-silicates crystallized together; alternatively, kyanite may partly be a later phase, indicating an increase in pressure. Locally abundant retrograde pyrophyllite (prl) and kaolinite replace andalusite and kyanite from rims and fractures (Fig. 17d). The lower Kaleva metapelitic schists adjacent to the Jatulian rocks do not usually contain porphyroblasts, the common assemblage being bt-ms-chl-qtz±pl, although some schists have an Al_2O_3 content of up to ca. 20 wt% (Lahtinen et al. 2010). On this basis, the northern part of the NKSB (area 90, Fig. 9) is classified as LP2.1 with an MP2.1 overprint (Fig. 10). The maximum metamorphic temperatures are ca. 500 °C at pressures increasing from below to above ca. 3 kbar, shown by the pseudosection in Figure 17e, which was constructed using the composition of a kyanite quartzite such as presented in Figure 18a (Table 6, analysis 8 in Kohonen & Marmo 1992).

Andalusite, staurolite and cordierite are common porphyroblasts in the southern part of the NKSB (area 88, Fig. 9), where they can be found up to 2–5 centimetres in size in muscovite- and biotite-bearing mica schists (Figs. 18b–d). Andalusite and staurolite are locally found in contact, and some staurolites are crystallized on andalusite rims (Fig. 19a). In some specimens, andalusite, staurolite and cordierite are found in the same thin section. Because in most compositions staurolite and cordierite should not be a stable assemblage (staurolite represents higher pressures than cordierite; see Fig. 1), it is

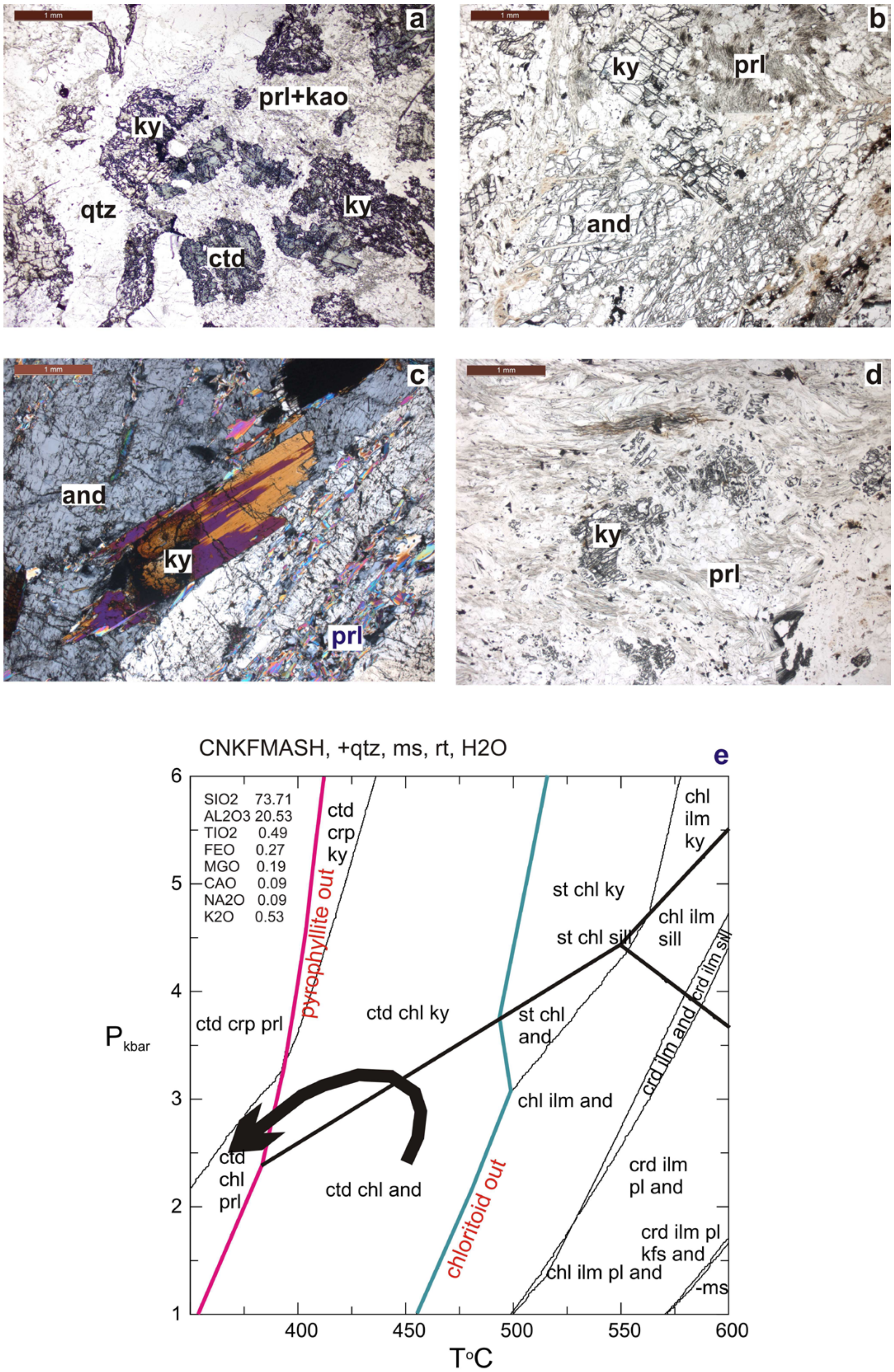

Fig. 17. Textures in the Hokkalampi kyanite quartzite in the North Karelia schist belt, northing 6973008, easting 650051: a) coexisting chloritoid and kyanite; b) andalusite and kyanite in textural equilibrium; c) kyanite overgrowing andalusite, d) kyanite altering into pyrophyllite; e) a PT pseudosection showing the possible PT path of the Hokkalampi rock. Coordinates are given using the EUREF-FIN (UTM35) system.

interpreted that the mineral assemblages record a decompressional PT path in which staurolite crystallized first and andalusite and cordierite later, so that the development of mineral assemblages records exhumation (Pattison et al. 1999). Therefore, the area (88) is classified as MP3.1c overprinted by LP3.1 (Figs. 8 and 10).

The metamorphic grade increases to the south and southwest so that the metasedimentary rocks become gneissic and sillimanite is found in many specimens (area 87, Fig. 9). The observed mineral associations in metapelitic rocks are st-grt-bt-ms-qtz±crd±and ±sil±chl±pl and bt-ms-and-qtz±sil. Staurolite is an early phase, and andalusite and cordierite replace staurolite, so that staurolite inclusions in andalusite are common, and in some samples andalusite coronas are found on staurolite (Figs. 19b–c). In the southwestern part of the zone, garnet is also commonly found as euhedral grains overgrowing other minerals as if there were two generations of garnet (Figs. 19a, 19d). Impure quartzite at Liperinsalo has the association st-bt-ms-qtz±and±crd±chl. In the Outokumpu deep drill core, Hölttä & Karttunen (2011) found all three Al_2SiO_5 polymorphs in the same thin section (Figs. 19e–f) in the association grt-st-and-ky-sil-bt-ms-pl-qtz.

The Outokumpu area is structurally complicated, showing multiple deformations with several thrusting and folding events (Koistinen 1981, Park & Bowes 1983, Park 1983, Park et al. 1984, Park 1988, Kontinen et al. 2006, Sorjonen-Ward 2006). Koistinen (1981) observed five deformation phases from D1 to D5 in the Outokumpu area. He related the biotite grade and garnet grade metamorphism to D1 and D2 deformations, respectively, associated with NNE–ENE-directed thrusting that caused recumbent folding as well as the formation and stacking of nappes. According to Koistinen (1981), the maximum temperature was reached during D3 deformation when open, asymmetric folds developed in the area.

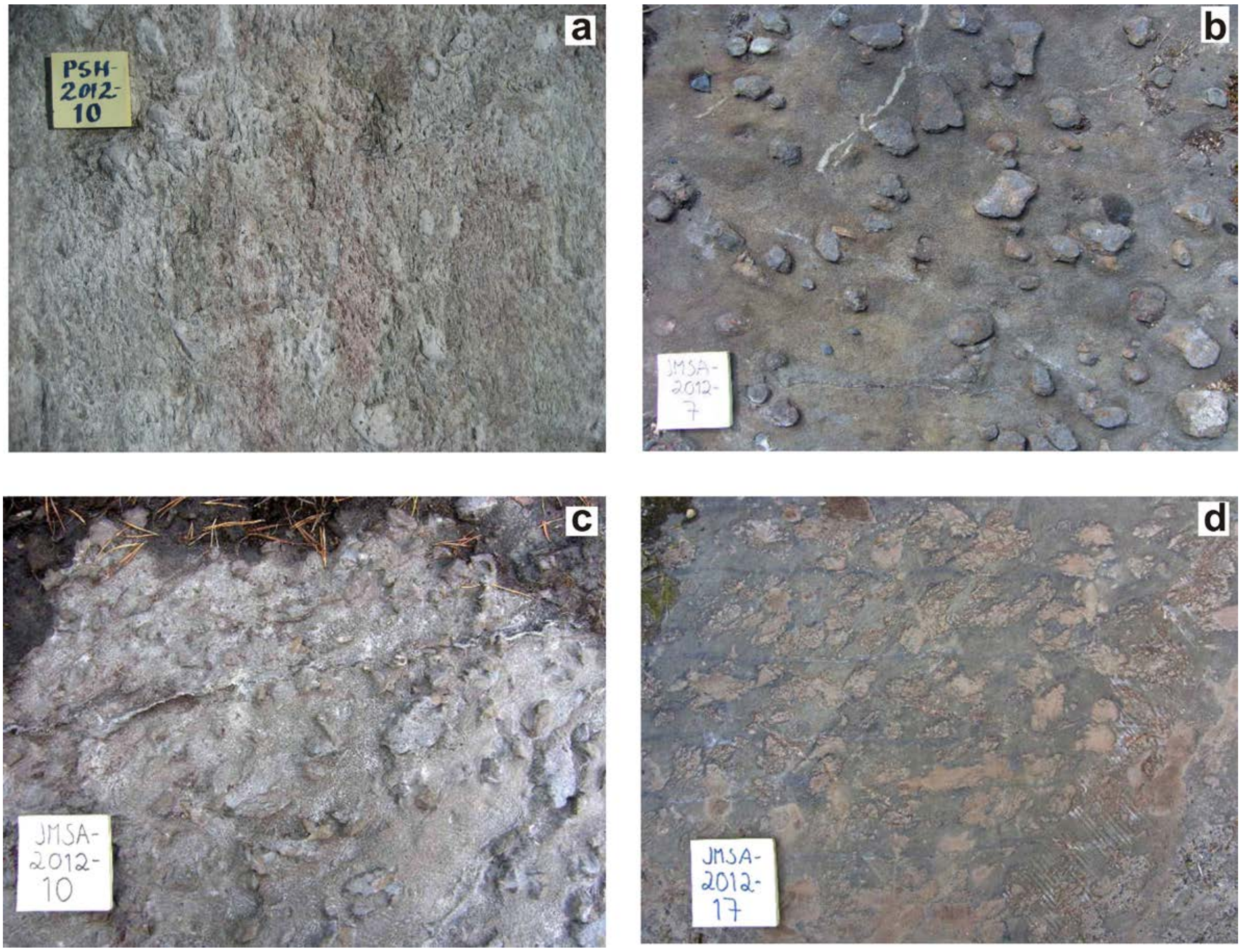

Fig. 18. Schists of the North Karelia schist belt: a) kyanite and andalusite (pink) bearing quartzite, Hokkalampi quarry, northing 6973008, easting 650051; b) andalusite porphyroblasts, exposure JMSA-2012-4, northing 6908080, easting 673135; c) andalusite and staurolite porphyroblasts, exposure JMSA-2012-10, northing 6894074, easting 677559; d) cordierite porphyrobla sts, exposure JMSA-2012-17, northing 6881227, easting 654671. The edge of the tag in each figure is 7.5 cm. All coordinates are given using the EUREF-FIN (UTM35) system.

Säntti et al. (2006) divided the upper Kaleva area in the NKSB into four N–S-trending metamorphic zones (A–D) based on mineral assemblages in ultramafic bodies within the metasedimentary rocks, with the grade increasing from east to west. The easternmost zone A is characterized by the mineral assemblage atg±ol±tr. The mineral assemblage in zone B is ol-tlc, whereas zone C is defined by the mineral assemblage ol-ath±cum±tlc. In the westernmost zone D, the mineral assemblage is ol-enst±ath±MgAl-spl. Säntti et al. (2006) estimated a temperature increase from 500-550° C in zone A to 725-775 °C in zone D, at 3-5 kbar, respectively. For the host rocks of the Outokumpu ore deposit, Treloar (1981) estimated the metamorphic conditions at Outokumpu to be 600 ± 50 °C and 3.5 ± 1 kbar, based on the mineral composition and assemblages in cordierite-orthoamphibole rocks within the ore body. The presence of cordierite was only reported in chemically altered cordierite-orthoamphibole rocks, in which the amount of alkalies and Ca is low (Treloar et al. 1981). Warrender et al. (1998) derived a pressure estimate of 3.4 ± 0.4 kbar for the Outokumpu ore using the sphalerite geobarometry.

The pressure estimates presented above are low compared with the observed mineral assemblages. Kontinen et al. (2006), Säntti et al. (2006) and Hölttä & Karttunen (2011) reported the co-existence of kyanite, sillimanite and andalusite in the mica gneisses, indicating a continuous decrease in pressure during various stages of metamorphism. Hölttä & Karttunen (2011) estimated the highest pressures in the Outokumpu area to be ca. 8.0-8.5 kbar, which is in accordance with the observed kyanite assemblages. Garnet-biotite thermometry gave temperatures of 600-620 °C for the same rocks for which Hölttä & Karttunen (2011), however, estimated metamorphic temperatures to ca. 670 °C, the onset of melting. This temperature is too high, because in the exposures close to the deep drill hole where the samples were taken, there are no signs of partial melting, and Hölttä & Karttunen (2011) erroneously interpreted felsic veins in the mica schist as leucosomes, although they are probably pegmatitic and quartz veinlets. Consequently, the shape of the PT path presented by the authors is not correct, although the rocks record a near-isothermal decompression from ca. 8.0-8.5 to 3-4 kbar at around 600 °C. Cordierite has not been reported in the mica schists in Outokumpu. However, Park (1983) described crd-grt-ms-pl-qtz and crd-grt-bt-pl-qtz assemblages in the mica schists of the Kaavi area, and also found sillimanite and andalusite in these schists. According to him, the rocks were metamorphosed at 600–680 °C and 2.5–3.5 kbar. Kaavi is located ca. 30 km northwest of Outokumpu, but is interpreted to represent the same metamorphic zone in this study. Therefore, these low pressures probably represent the late decompressional stage of the PT path. On the basis of mineral assemblages, reactions and published geothermobarometry, the zone is classified as MP3.1a, overprinted by LP 4.1 and LP3.1 (Figs. 8 and 10).

Staurolite grade rocks are also found in the Kuopio area (92 and surrounding areas, Fig. 9), at the southwestern margin of the Archaean Iisalmi complex. Kyanite was reported from quartzites at Siilinjärvi, north of the town Kuopio (Åker 1985, Lukkarinen 2008), and the Kuopio area is therefore classified in the same metamorphic zone as the Outokumpu area (87, Fig. 9). In the western part of the Outokumpu area, monotonous metagreywackes (Fig. 20a) become migmatitic as a result of partial melting. Locally, the amount of neosome may be up to tens of vol.%, but migmatites are still metatexitic, with the assemblage bt-pl-qtz in the palaeosome (Figs. 20b–c). Small garnet grains can be found, but they are rare. No clear change in metamorphic grade may be observed across the boundary between the Karelia Province and the Svecofennia Province. However, there is a change in lithology: in contrast to the monotonous metagreywackes of the Outokumpu area, in the westernmost part of the Karelia Province, migmatites contain pelitic layers showing garnet-cordierite-biotite-sillimanite assemblages with retrograde accessory andalusite, staurolite and kyanite (Fagerström 1990, Lukkarinen 2008). The latter three minerals are alteration products of cordierite. Southwest of Kuopio, Fagerström (1990) estimated crystallization pressures of 5-6 kbar using grt-sil-pl-qtz geobarometry, and the area is therefore classified as LP7.1, overprinted by MP3.1c (Figs. 8 and 10).

In the southwestern part of the Western Karelia Province, at Haukivesi (area 78, Fig. 9), granulite facies rocks are found. Metasedimentary rocks are diatexitic granulites with >50 vol.% neosome (Fig. 20d). Orthopyroxene-bearing gneisses, amphibolites and granitoids are common (Gaál & Rauhamäki 1971, Paavola 1976, Korsman & Pääjärvi 1988). Palaeosomes of the metapelitic migmatites commonly have the assemblage grt-crd-bt-kfs-pl-qtz±sil±spl. Sillimanite and spinel are found as inclusions in cordierite. Retrograde andalusite after cordierite is common. In palaeosomes of the migmatitic pyroxene gneisses, the assemblage

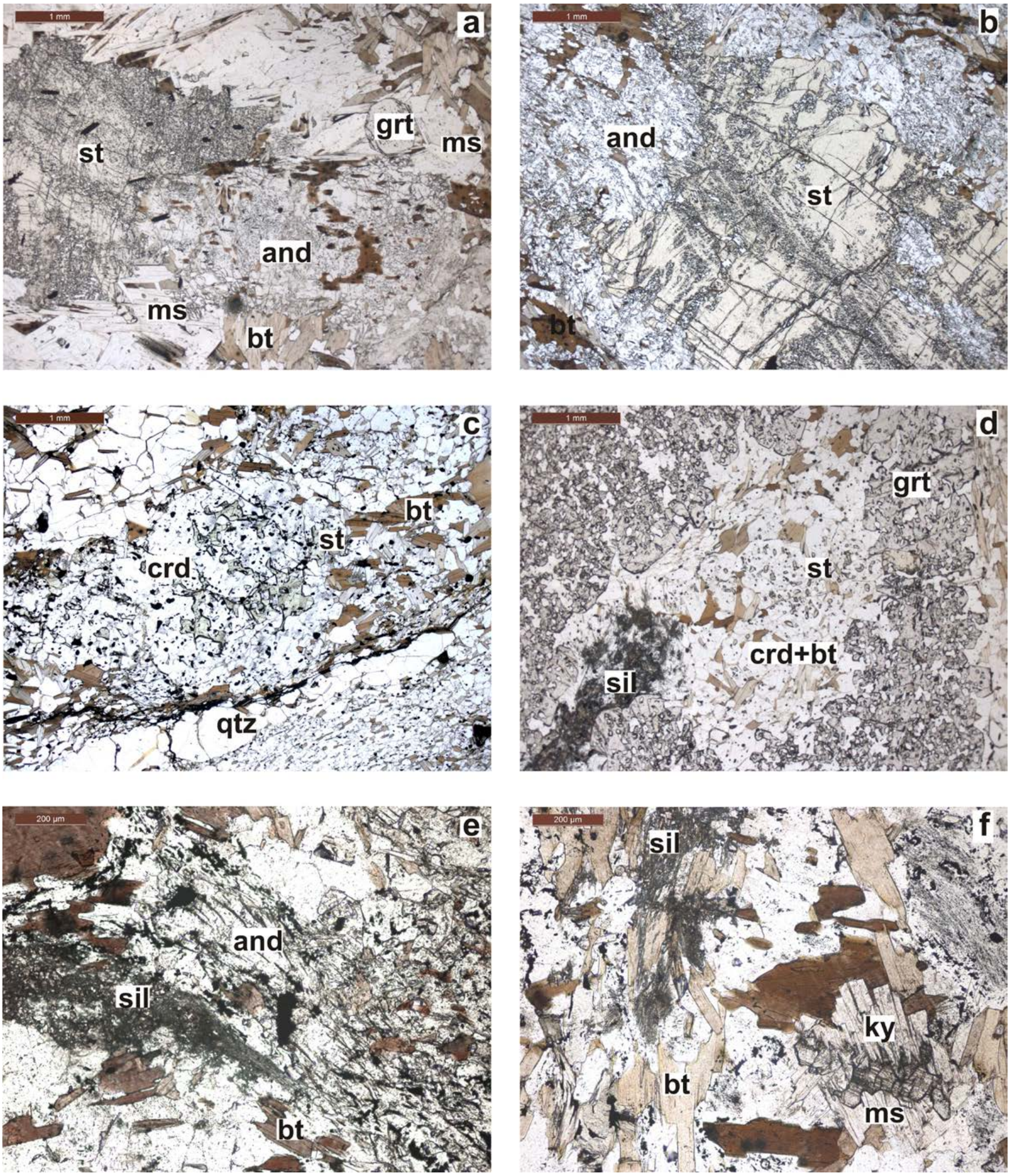

Fig. 19. a) Coexisting staurolite and andalusite, euhedral garnet overgrowing micas, in the southern part of the North Karelia schist belt, exposure JMSA-2012-4, northing 6908080, easting 673135; b) an andalusite corona on staurolite, exposure JMSA-2012-10, northing 6894074, easting 677559; c) staurolite decomposing into cordierite, exposure JMSA-2012-14, northing 6877400, easting 672615; d) staurolite decomposing into cordierite overgrown by garnet, which is also overgrowing sillimanite in the lower left corner of the figure, exposure JMSA-2012-14; e) coexisting andalusite and sillimanite and; f) coexisting kyanite and sillimanite in the Outokumpu deep drill core. Photos e) and f) are from the same thin section. All coordinates are given using the EUREF-FIN (UTM35) system.

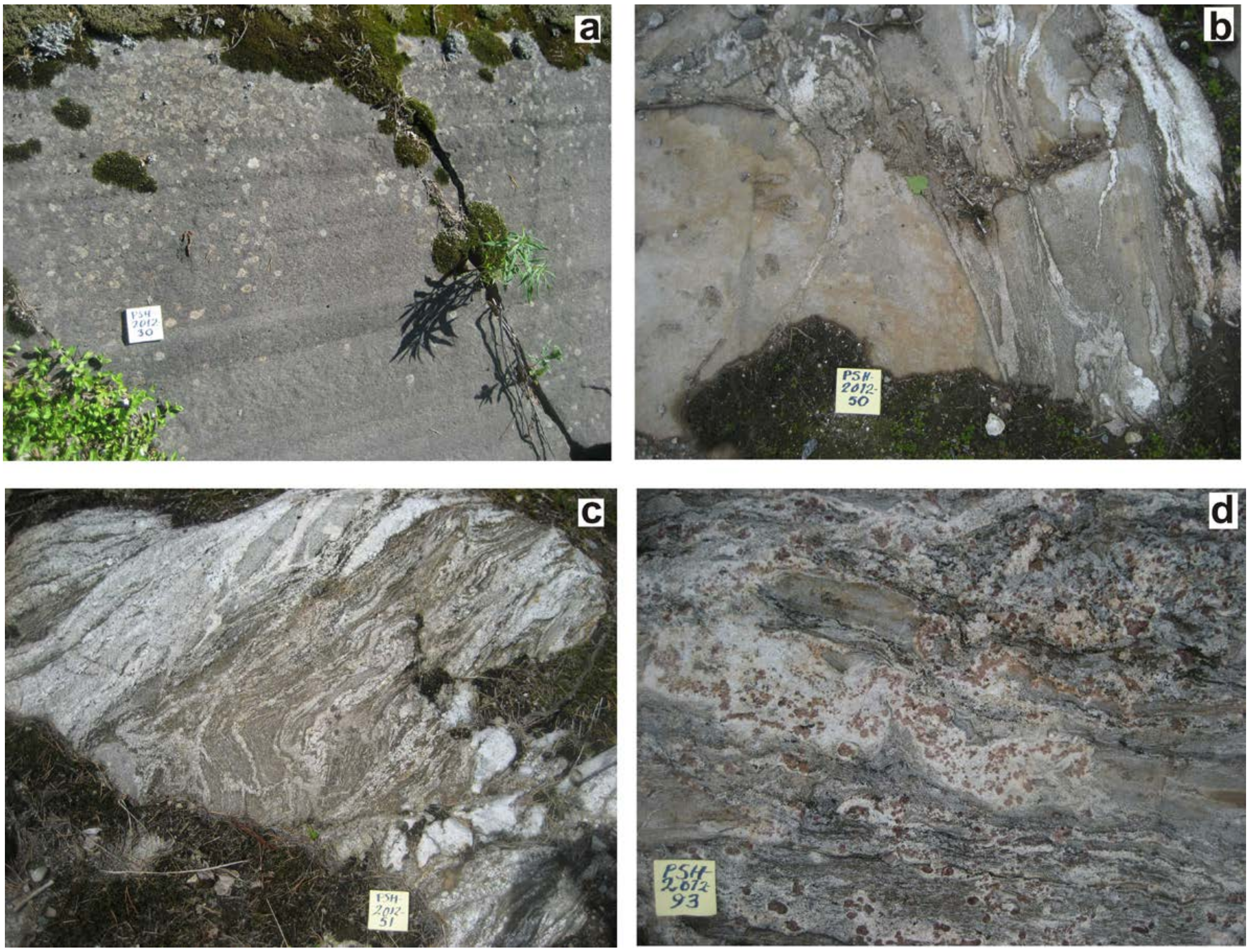

Fig. 20. The gradual increase in metamorphic grade in the Outokumpu area from a) a bedded monotonous metagreywacke, exposure PSH$-2012-30, northing 7064405, easting 350570 to b) the onset of melting in a metagreywacke, exposure PSH$-2012-50, northing 6919095, easting 579808, to c) diatexitic migmatite, exposure PSH$-2012-51, northing 6914414, easting 576327, to d) garnet-rich diatexite in the Haukivesi area, exposure PSH$-2012-93, northing 6892607, easting 564700. All coordinates are given using the EUREF-FIN (UTM35) system.

opx-bt-pl-qtz has been observed, and opx-cpx-bt-pl-qtz in pyroxene amphibolites (Korsman & Pääjärvi 1988). Consequently, the zone is classified as LP8.1, overprinted by LP3.1 (Figs. 8 and 10).

Salahmi and Kiiminki belts

The Salahmi and Kiiminki belts (areas 212 and 119, respectively, Fig. 9) are located next to the Archaean at its western boundary (Fig. 12). The Salahmi belt comprises conglomerates, quartzites and schists, locally with the mineral assemblage st-bt-ms-qtz±sil. Sillimanite is rare, found only as tiny needles. In more calcic schists, the assemblage grt-bt-ms-pl-qtz has been reported (Savolahti 1965, Hölttä 1988, Laajoki & Luukas 1988, Laajoki et al. 1988). The area is classified as MP3.1b.

The Kiiminki belt mostly consists of metagreywackes and mica schists (Honkamo 1988), but porphyroblastic rocks are relatively rare. In the northeastern part of the belt, there is a small area with andalusite, staurolite, cordierite and garnet porphyroblasts up to 2–3 centimetres in size (Figs. 21a, b), with the mineral associations:

bt-ms-chl-crd-grt-qtz
bt-ms-st-crd-grt-qtz±and±chl
bt-ms-st-grt-and-qtz.

Euhedral small garnet is overgrown by all other minerals and grain boundaries (Figs. 21c, d), so it appears that the early metamorphism took place under low pressure in the cordierite field, and the later event in elevated pressures in the garnet-staurolite field. The eastern part of the belt is therefore classified as LP3.1, with an MP3.1c overprint (Figs. 8 and 10).

In the southwestern part of the Kiiminki belt, the assemblage bt-ms-sil-pl-qtz is found in metapelites and the zone is classified as LP4.1 (area 118,

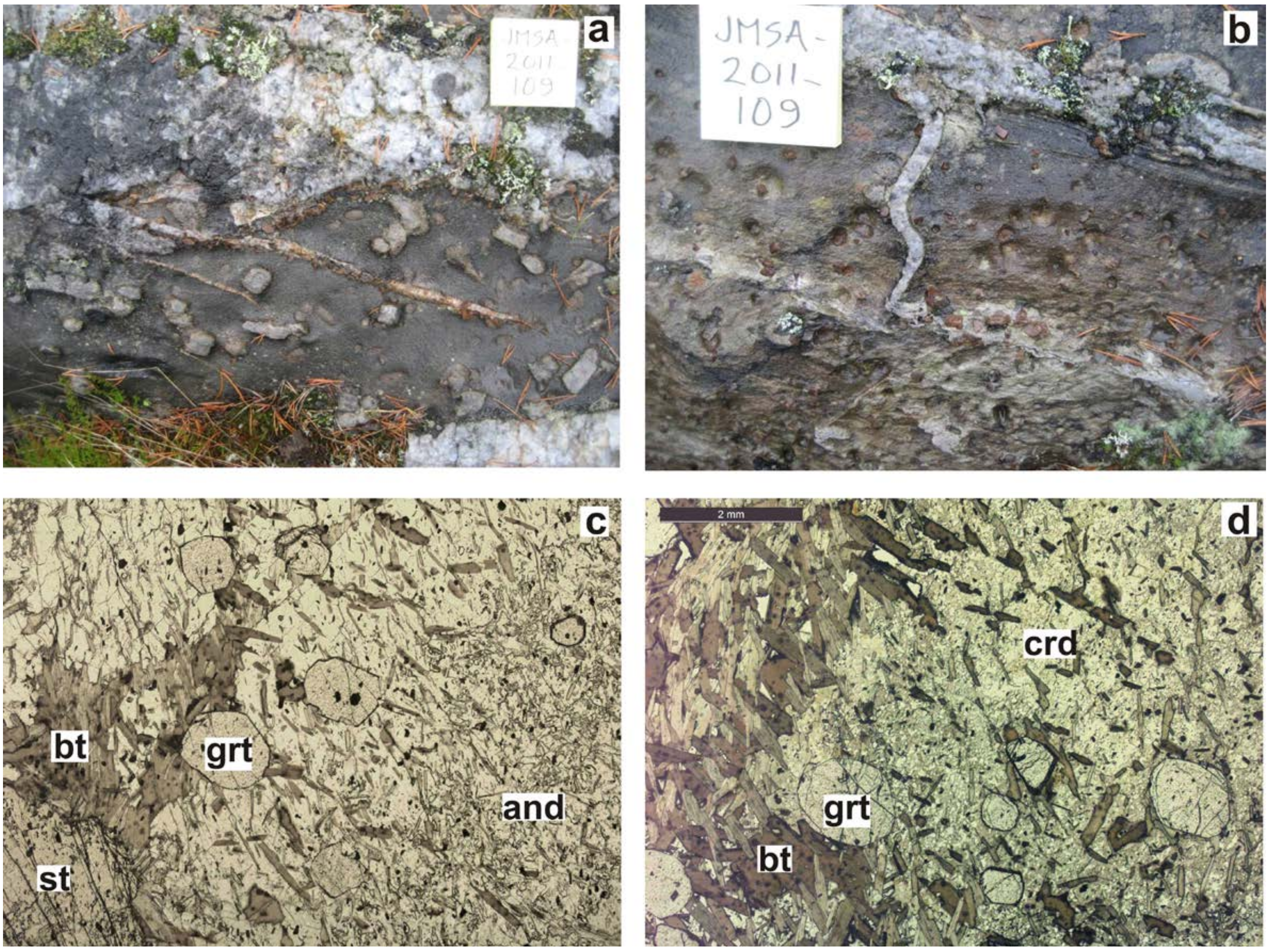

Fig. 21. Porphyroblastic schist in the Kiiminki belt: a) andalusite porphyroblasts; b) andalusite, staurolite and cordierite porphyroblasts; c) garnet overgrowing andalusite and biotite; d) garnet overgrowing cordierite and biotite. Exposure JMSA-2011-109, northing 7211739, easting 477829. The edge of the tag in figures a–b is 7.5 cm and all coordinates are given using the EUREF-FIN (UTM35) system.

Figs. 8 and 9). Further to the west, the rocks become migmatitic and the assemblages grt-bt-pl-qtz±crd and grt-crd-bt-sil-pl-qtz±kfs are found in many metatexitic migmatites and classified as LP7.1. No metamorphic boundary between the Karelian and Svecofennian migmatites was observed in outcrops of this area.

Kainuu belt

In the southern and western part of the Kainuu belt (KaB, Fig. 10), Al-rich metasedimentary rocks commonly contain garnet and staurolite porphyroblasts (area 121, Fig. 9). Tuisku & Laajoki (1990) described staurolite coexisting with kyanite, sillimanite and andalusite in the Puolankajärvi formation, and locally also cordierite being present. Based on paragenetic relationships and thermobarometry, Tuisku & Laajoki (1990) concluded that the Puolankajärvi formation underwent a clockwise PT path with early metamorphism in the kyanite field, probably at 6–7 kbar; the highest temperature was at ca. 550–600 °C in the sillimanite field and cooling continued down to the andalusite field at ca. 500 °C and 2–3 kbar. On this basis, the western and southern parts of the KaB are classified as MP3.1a with MP3.1b and LP3.1 overprints (Fig. 11). In the northern part, porphyroblasts are not found, although there is no change in the whole-rock composition of the schists (A. Kontinen, pers. comm.), and consequently the area is classified as LP2.1.

Kuusamo belt

The Kuusamo belt (Fig. 10) is mainly formed of mafic volcanic rocks and sedimentary quartzites and marbles (Silvennoinen 1991), other metasedimentary rocks being a minor constituent. The southeastern part of the Kuusamo belt (area 129, Fig. 9) was metamorphosed in greenschist facies. The sericite quartzites have the assemblage qtz-ms and in the mafic volcanic rocks ab-chl-ep (Silvennoinen 1991). Observed mineral assemblages in narrow fine-grained phyllite interlayers (Fig. 22a) are ms-cal/dol-qtz±chl and bt-chl-ms-qtz. This belt is classified as LP2.1 using the pelite classification and LP2.3 using the pseudosection for mafic rocks (Fig. 8).

In the northwestern part of the Kuusamo belt (area 130, Fig. 9), the grade increases to low amphibolite facies. Evins (2005) described schists with garnet and staurolite porphyroblasts close to Posio. East and northeast of Posio, there are several exposures of staurolite schists (Fig. 22b) with the association grt-st-bt-chl-qtz±ms, and ca. 25 km east of Posio, kyanite-bearing local boulders were found, with the association grt-st-bt-ms-ky-chl-qtz. Therefore, the zone is classified as MP3.1a (Fig. 8). In the northeastern part of the zone, there are garnet amphibolites with the assemblages grt-tre-bt-qtz, grt-bt-cum-qtz and grt-tre-chl, also indicating moderate pressures.

Sillimanite gneisses (Fig. 22c) are found in the northwestern part of the Kuusamo Belt (area 131, Fig. 9) with the associations bt-ms-sil-qtz±chl, bt-ms-sil-st-qtz, bt-sil-ms-grt-pl-qtz and bt-ms-sil-kfs-qtz. Staurolite, when present, is only a relict inclusion in muscovite. Leucosome veins are commonly found (Fig. 22d) in the mica gneisses, and this area is therefore classified as MP5.1.

Peräpohja belt

The Peräpohja belt (Fig. 10) shows a significant increase in metamorphic grade from low-pressure subgreenschist facies rocks in the southwest (area 135, Fig. 9) to high-pressure kyanite-bearing migmatites in the northeast (area 139). The Peräpohja belt mostly consists of metasedimentary schist, gneisses and volcanic rocks. In the southern part, the metasedimentary rocks are fine-grained schists with well-preserved sedimentary structures (Fig. 23a) and with the assemblage bt-ms-chl-qtz. Tiny euhedral 0.5–1.5-mm garnet grains are seldom found in these schists (Perttunen 1991). This area is classified as LP2.1 (Fig. 8).

Close to the western border of Finland (area 136), cordierite is found in pelitic schists as euhedral porphyroblasts 5–15 mm in size (Fig. 23b) in a fine-grained bt-chl-ms-qtz matrix. To the north, there is an increase in the grain size of the schist, cordierite is locally abundant (Fig. 23c) and andalusite is also found in pelitic schists (area 137, Figs. 9, 23d), although it is not common (Lahtinen et al. 2015). These two zones are classified as LP3.1, but the southern part without andalusite evidently represents lower pressure, probably as low as ≤2 kbar.

In the eastern part of the Peräpohja belt, close to the Archaean rocks (area 140, Fig. 9), the mica schists also have and-bt-qtz, crd-bt-qtz±ms±and and crd-bt-chl-qtz assemblages, but euhedral garnet locally overgrows other minerals and the predominant foliation. This zone is classified as LP3.1, overprinted by MP3.1c (Figs. 8 and 10).

Further to the north, at the boundary of the Central Lapland granitoid complex (CLGC), the metasedimentary rocks become gneissic (Fig. 23e) with a coarsening of grain size (area 138, Fig. 9). The observed associations are:

grt-st-crd-sil-bt-pl-qtz
grt-st-crd-sil-ms-pl-qtz
and-crd-st-bt-ms-sil-pl-qtz±grt
and-bt-ms-sil-pl-qtz±st
and-bt-ms-pl-qtz±crd
and-grt-bt-ms-qtz
and-grt-st-sil-bt-pl-qtz
and-crd-bt-ms-chl-qtz±st±sil
and-st-grt-bt-chl-pl-qtz
grt-bt-pl-qtz
bt-ms-kfs-pl-qtz
bt-sil-ms-pl-qtz
bt-sil-crd-pl-qtz
bt-ms-qtz-crd

In assemblages containing staurolite, cordierite and andalusite, staurolite is altered to andalusite and cordierite (Figs. 24a–b, e–f), and andalusite is sometimes altered to cordierite. Andalusite coronas on staurolite were first described by Perttunen et al. (1996). Locally, small euhedral garnet overgrows andalusite and staurolite (Fig. 24b), which may indicate a pressure increase after staurolite breakdown. Kyanite was not observed in this zone, and it is therefore classified as MP3.1b, overprinted by LP3.1 (Fig. 11). Lappalainen (1994) and Perttunen et al. (1996) interpreted that the pressure conditions were low, <4 kbar, but these pressures are probably related to the decompressional stage.

In the northeastern part of the Peräpohja belt (area 139), kyanite is in contrast a common mineral, sometimes found as prisms up to several centimetres in size (Fig. 23f). It is found both in metapelitic rocks and in quartzites (Perttunen et al. 1996). Metasedimentary rocks are migmatitic with up to

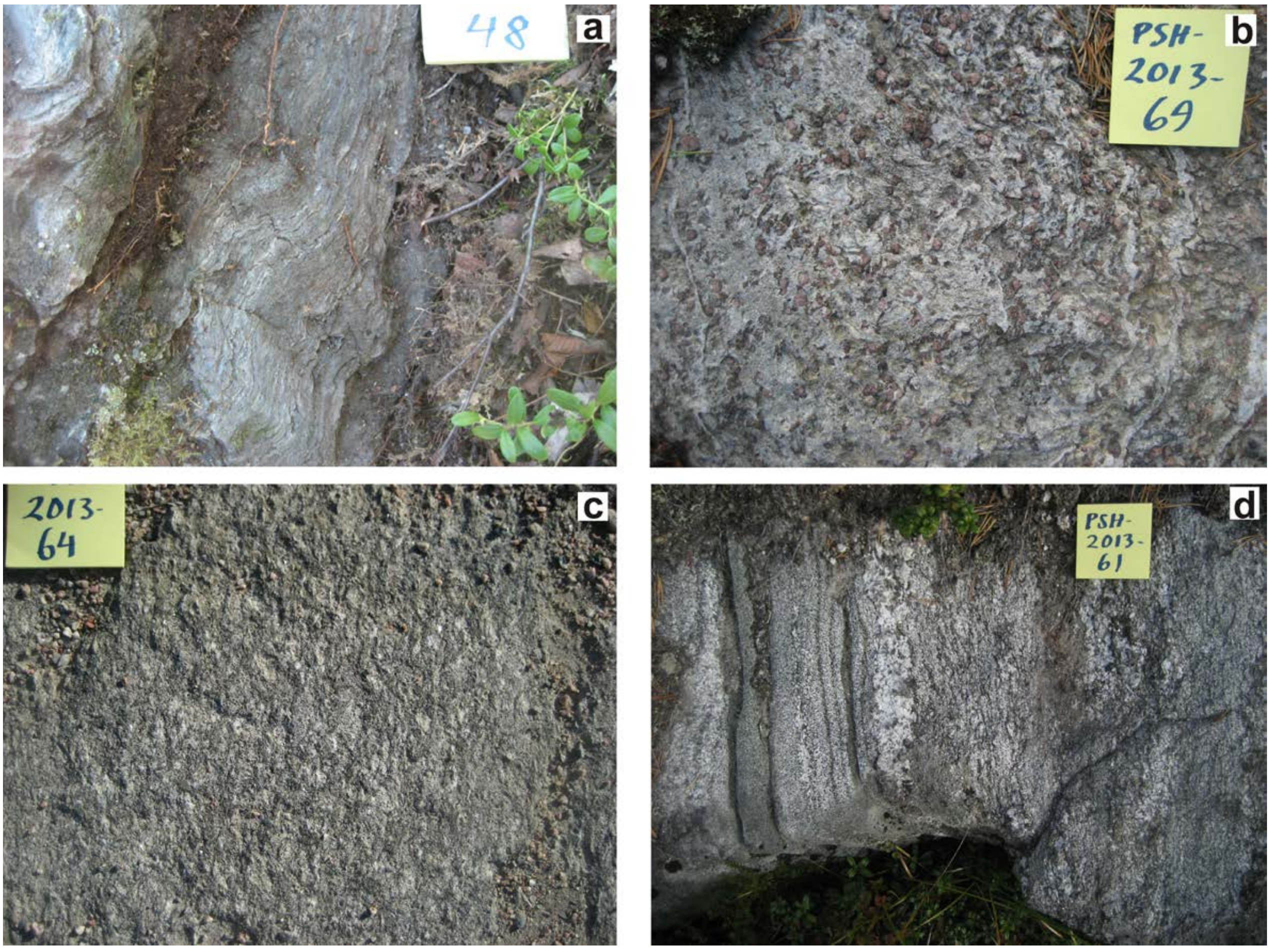

Fig. 22. Increase in metamorphic grade in the schists and gneisses of the Kuusamo belt: a) fine-grained greenschist facies schist, exposure PSH$-2013-48, northing 7328316, easting 602221; b) garnet-staurolite gneiss, exposure PSH$-2013-69, northing 7335733, easting 556385; c) sillimanite gneiss, exposure PSH$-2013-64, northing 7352424, easting 571849; d) the onset of melting, exposure PSH$-2013-61, northing 6847140, easting 616069. The edge of the tag in each figure is 7.5 cm and coordinates are given using the EUREF-FIN (UTM35) system.

10–20 vol.% neosome in metatexites. The observed associations are:

bt-ms-pl-qtz±grt
grt-st-crd-ky-bt-ch-pl-qtz
and-st-crd-bt-chl-pl-qtz
and-ky-crd-bt-qtz±grt±pl
and-crd-bt-ms-pl-qtz
st-crd-bt-chl-pl-qtz
and-grt-bt-pl-qtz±crd±chl±ms
and-sil-grt-crd-spl-bt-pl-qtz

Mineral reactions indicate decompression from the kyanite to andalusite field. For example, garnet, staurolite, andalusite and kyanite are altered to cordierite (Fig. 24c–e). Andalusite is found as elongated prisms, as if forming pseudomorphs after kyanite (Fig. 24d). In some samples, kyanite is always altered from rims into cordierite, and staurolite inclusions in cordierite and andalusite are common (Fig. 24f). Obviously, the early assemblage has been grt-st±ky, which reacted during decompression producing and-crd assemblages. If kyanite crystallized with melt in migmatitic rocks, the pressure must have been high, >7 kbar, in temperatures above 650 °C (Figs. 1–2). As in the Tuntsa suite, the problem is the existence of staurolite in these migmatites, because staurolite is not normally stable with melt. It is possible that the st-grt-ky assemblage preceded melting, or that melting was an earlier event and staurolite crystallized during cooling and decompression.

Sillimanite is rare, and when present it overgrows andalusite (Figs. 25a–c). In one locality in the northeastern part of the zone, there are numerous small garnet grains that overgrow andalusite and biotite (Fig. 25d). These features may indicate that after decompression there was still one more prograde metamorphic event with a temperature and pressure increase. The metamorphic history of this zone

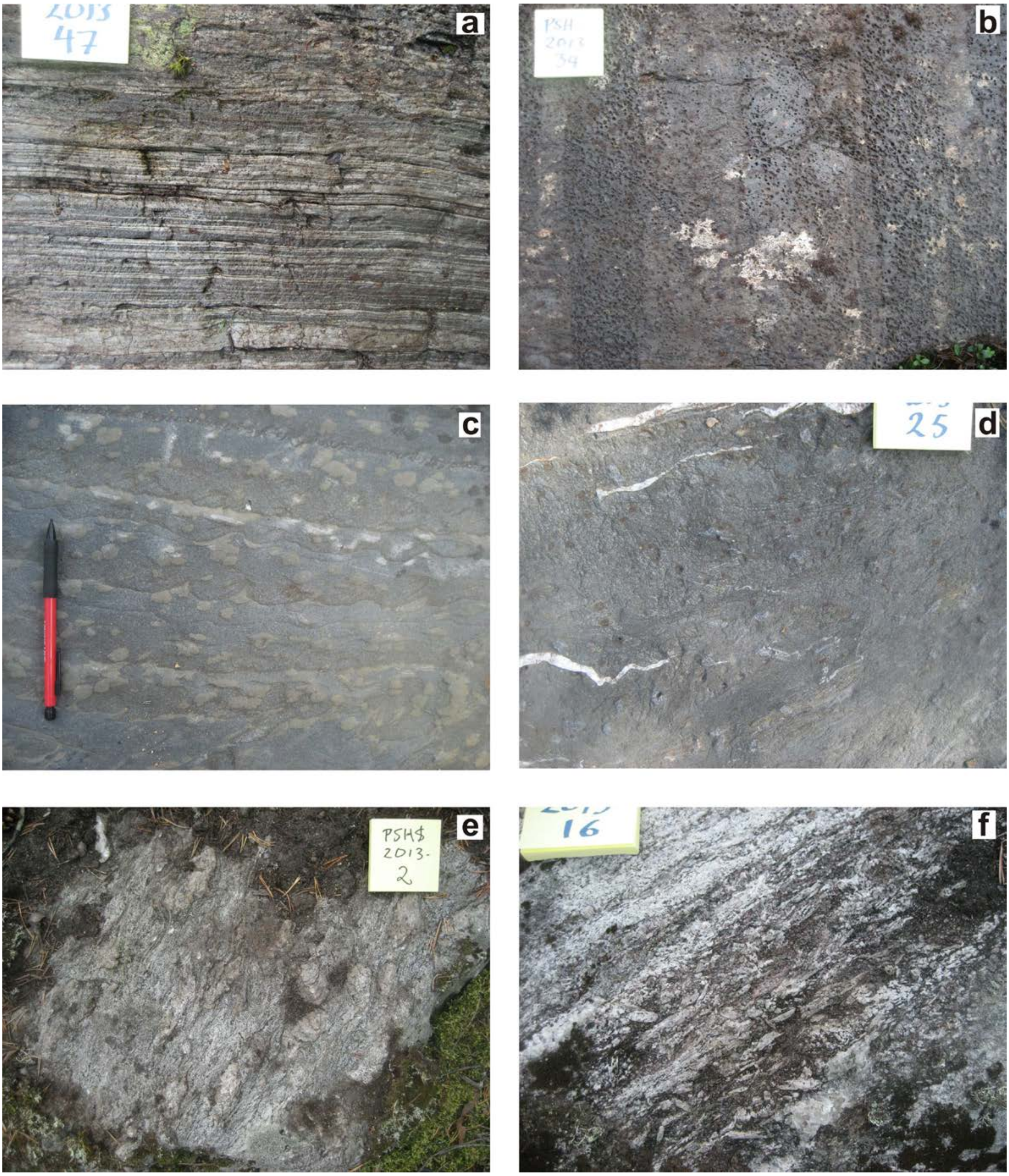

Fig. 23. Increase in metamorphic grade in the schists and gneisses of the Peräpohja belt: a) greenschist facies metapelitic schist in the southern part of the belt, exposure PSH$-2013-47, northing 7305406, easting 395843; b) cordierite-bearing schist in the western part of the belt, exposure PSH$-2013-34, northing 7323559, easting 367373; c) cordierite porphyroblasts in load-structured metasedimentary rock, exposure PSH$-2013-27, northing 7365759, easting 400149; d) andalusite porphyroblasts in a schist, exposure PSH$-2013-25, northing 7364154, easting 407026; e) andalusite porphyroblasts in a gneiss, exposure PSH$-2013-2, northing 7371306, easting 427644; f) kyanite-rich gneiss, Rovaniemi area, exposure PSH$-2013-16, northing 7379324, easting 455294. The edge of the tag in each figure is 7.5 cm and coordinates are given using the EUREF-FIN (UTM35) system.

is complicated, but it is classified as HP 5.1, overprinted by LP3.1 and LP4.1 (Figs. 8 and 10).

Central Lapland granitoid complex

The observations in the southern part of the Central Lapland granitoid complex (CLGC) area during the course of this study were not numerous, and because of the scarcity of supracrustal rocks, the metamorphic classification is difficult. Metasedimentary rocks within and at the borders of the complex (Fig. 10) are migmatitic, even diatexitic (Väänänen 1998, 2003). Garnet is rare, but bt-crd-sil-pl-qtz±grt assemblages are locally found. However, even in the highly migmatitic rocks, both in the eastern and western part of the complex, muscovite is a common mineral in the association bt-ms-kfs-qtz±sil±pl, indicating strong retrogression. The southern part of the CLGC (area 132, Fig. 9) is classified as LP7.1 with an LP4.1 overprint.

Within the granitoids of the northern part of the CLGC (area 143, Fig. 9), there are more interlayers of gneissic metasedimentary rocks. Common associations are:

bt-ms-sil-pl-qtz
and-bt-ms-grt-sil-st-pl-qtz±chl±grt
bt-ms-chl-grt-pl-qtz±sil±st
chl-ms-ep-grt-pl-qtz

Chlorite and muscovite are mostly retrograde phases. Rocks are often slightly migmatized, and the zone is therefore classified as MP4.1 (Fig. 8) with MP3.1b and MP3.1c overprints (Fig. 11). Hölttä et al. (2007) calculated pressures of 6–8 kbar for this area using the Thermocalc average PT geobarometry. At the northern boundary of the CLGC, sillimanite and garnet disappear (area 144, Fig. 9) and the observed associations in metapelitic rocks are:

and-bt-ms-pl-qtz±chl,
bt-ms-crd-chl-qtz.

This zone is classified as LP3.1. The northeastern boundary of the CLGC (area 145, Fig. 9) is charaterized by the presence of kyanite, and the following associations are found:

st-grt-bt-ms-pl-qtz
st-bt-chl-ms-pl-qtz
ky-bt-ms-pl-qtz±sil
and-crd-grt-st-bt-chl-ms-qtz
and-ky-sil-crd-bt-ms-chl-qtz
ky-sil-crd-bt-ms-qtz
crd-bt-ms-qtz±sil

This zone shows decompressional mineral reactions. Cordierite together with muscovite was formed in a reaction between kyanite/andalusite and biotite (Figs. 26a–c). Some cordierite grains also have garnet inclusions, indicating that cordierite was produced by the decomposition of garnet. All three Al_2SiO_5 polymorphs can be found in the same thin section (Figs. 26a, d) from an exposure in the western part of the zone, which is classified as MP3.1a. It is overprinted by low-pressure events LP3.1 and LP4.1, producing sillimanite-, cordierite- and andalusite-bearing assemblages (Figs. 8 and 10).

Central Lapland area

A description of metamorphic zones, their mineral assemblages and PT estimates in the Central Lapland area north of the CLGC was provided by Hölttä et al. (2007). The Kittilä belt (area 150, Fig. 9) was metamorphosed in upper greenschist facies at temperatures of ca. 350–400 °C at ca. 2–4 kbar (Hölttä et al. 2007), and is classified as LP2.3. To the east, the metamorphic grade increases to low amphibolite facies (area 147, Fig. 9), where chloritoid can be found as a relic in Al-rich, Ca- and Na-poor metasedimentary rocks (Figs. 27a, c, d). These commonly have the and-st-ms-chl-cld-pl-qtz association overgrown by randomly oriented kyanite (early metamorphism in MP2.1, followed by LP3.1, overprinted by MP3.1a). Further to the east, the metamorphic grade increases to mid-amphibolite facies, where gneisses (area 148, Figs. 9 and 27b, e, f) have ky-and-st-ms-pl-qtz and ky-st-bt-ms-pl-qtz-grt assemblages (MP3.1a) and finally to grt-sil-bt bearing gneisses (MP4.1) at the boundary of the Archaean bedrock (area 149, Fig. 9). North of the Kittilä belt, the schists have grt-st-and-ms assemblages overgrown by late, randomly oriented kyanite (area 160). For this zone, Hölttä et al. (2007) estimated metamorphic temperatures of 560–615 °C and highly variable pressures of 3–8 kbar, which evidently reflect the complex thickening and uplift evolution of the area. Still further north, there are kyanite-bearing gneisses (area 165, Fig. 9) with the grt-ky-bt-ms±st assemblage, metamorphosed at 7.5–10 kbar (Hölttä et al. 2007), and the zone is therefore classified as HP4.1 (Fig. 9). In the western part of this zone, Haapala et al. (1971) described kornerupine-bearing rocks.

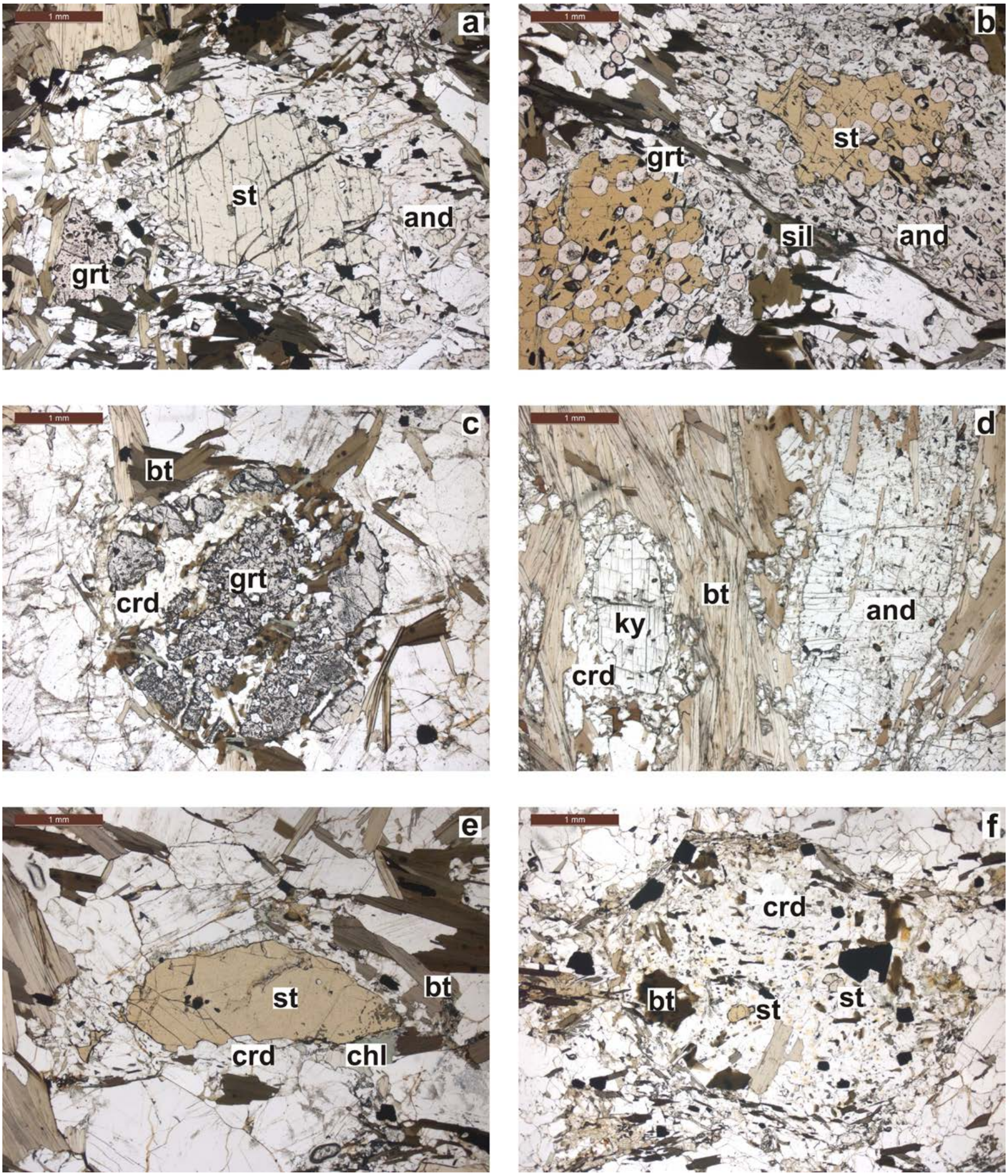

Fig. 24. Textures in metapelitic gneisses of the Rovaniemi area: a) staurolite altered from rims into andalusite, exposure PSH$-2013-8, northing 7368491, easting 450674; b) staurolite altered from rims into andalusite, both minerals overgrown by euhedral garnet grains, exposure PSH$-2013-5, northing 7372358, easting 444098; c) garnet altered from fractures into cordierite, exposure PSH$-2013-12, northing 7372830, easting 459578; d) kyanite and andalusite altered from rims into cordierite, andalusite on the right is obviously a kyanite pseudomorph, exposure PSH$-2013-12; d) spinel forming symplectites with cordierite between sillimanite and garnet; e) staurolite altered from rims into cordierite, exposure PSH$-2013-12; f) cordierite pseudomorphing staurolite, only small relics of staurolite are left inside of cordierite, exposure PSH$-2013-12. All coordinates are given using the EUREF-FIN (UTM35) system.

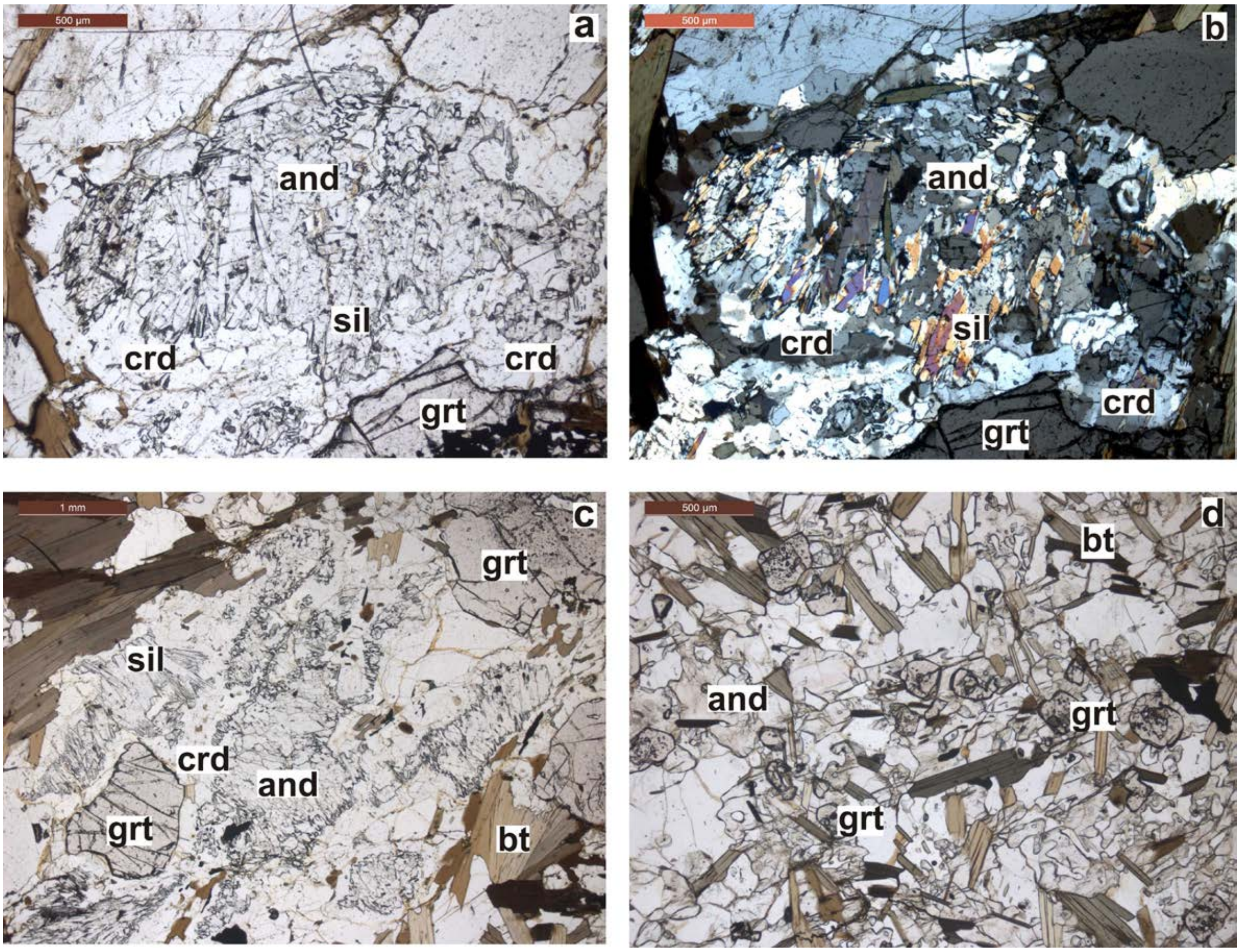

Fig. 25. Textures in metapelitic gneisses of the Rovaniemi area: a, b) a cordierite rim around andalusite overgrown by sillimanite, exposure PSH$-2013-16, northing 7379324, easting 455294; c) garnet and andalusite altered from rims into cordierite, andalusite on the right side of the figure is overgrown by sillimanite, exposure PSH$-2013-16; d) small idiomorphic garnet overgrowing andalusite and biotite, exposure PSH$-2013-14, northing 7382948, easting 464277. All coordinates are given using the EUREF-FIN (UTM35) system.

The boundary between the Central Lapland area and the Lapland granulite complex, called the Tanaelv belt or Vuotso complex (Luukas et al., this Volume) (area 166, Fig. 9), was metamorphosed at high pressures at around 10–12 kbar. The estimated temperatures for the eastern part of the belt are 650–720 °C (Tuisku & Makkonen 1999, Tuisku et al. 2006) and for the western part 770–890 °C (Hölttä et al. 2007). The latter values are probably unrealistically high, although migmatitic amphibolites are common in the area.

Lapland granulite complex and the Inari complex

The Lapland granulite complex (LGC, Fig. 10), also named as the Lapland granulite belt, has been a target of metamorphic studies for decades (Eskola 1952, Meriläinen 1976, Hörmann et al. 1980, Barbey & Raith 1990, Tuisku et al. 2006, Mints et al. 2007, Cagnard et al. 2011). The peak metamorphic pressures and temperatures reported by Tuisku et al. (2006) in the Finnish Lapland have been at 7–9 kbar and ca. 850 °C, but both thermobarometry and metamorphic reactions show a PT path with a decrease in P and T even down to ca. 2 kbar and <650 °C. Mints et al. (2007) described even higher maximum pressures and temperatures in the eastern part of the LGC, 10–14 kbar and 860–960 °C, with their data also showing decompressional PT paths down to 5–6 kbar.

The petrography of the granulites was described in detail by Tuisku et al. (2006). The most common rock of the LGC is a blastomylonitic intensively banded diatexite. Meriläinen (1976) divided the LGC into two subareas, which are the central and eastern garnet gneisses and the western garnet gneisses. The former are mainly garnet-cordierite gneisses and coarse-grained garnet-quartz-feldspar

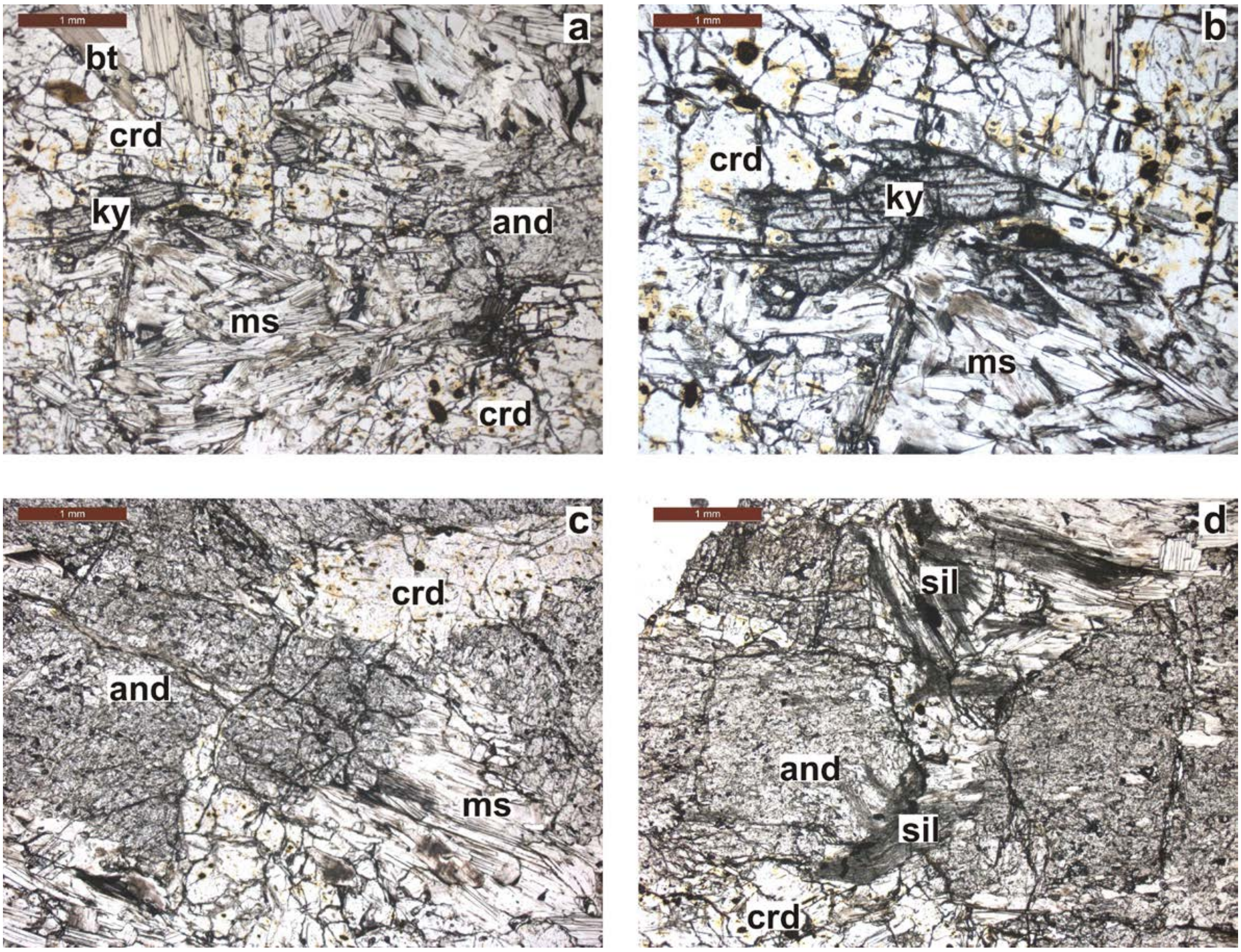

Fig. 26. Textures in the and-ky-sil rock in the northern part of the CLGC: a) Kyanite and andalusite altering into cordierite in the reaction and/ky + bt = crd + ms; b) a detail of kyanite surrounded by cordierite in Fig. 26a; c) andalusite surrounded by cordierite and muscovite; d) fibrolitic sillimanite on andalusite rims. Figs a–d are from the same thin section, exposure PSH$-1998-11, northing 7463524, easting 466836. All coordinates are given using the EUREF-FIN (UTM35) system.

gneisses, whereas the latter are largely fine- and coarse-grained garnet-quartz-feldspar gneisses and garnet-biotite gneisses without cordierite. On this basis, the northern part of the LGC (area 168, Fig. 9) is classified as LP8.1, whereas the southern part (area 167) is classified as MP6.1 (Fig. 8). The boundary between these two zones follows the one presented in Figure 1 in Barbey & Raith (1990).

The Inari complex east of the LGC mainly comprises upper amphibolite facies rocks, which are mostly migmatised. The main rock types are felsic gneisses, which seldomly contain porphyroblasts. Garnet is found locally without cordierite, and the western part of the area is therefore classified as MP5 (area 169, Fig. 9). In the eastern part (area 170), Kesola (1995) described kyanite-bearing garnet-staurolite gneisses, and it is consequently classified as MP 3.1a.

Enontekiö area

Because of the lack of informative exposures and roads, the boundaries of the metamorphic zones in western Lapland are in most cases tentative and poorly defined.

The Enontekiö area here comprises the area west of the Central Lapland area and northwest of the Central Lapland granitoid complex. Garnet-rich gneisses with sillimanite are found in a few exposures near the CLGC (area 348, Fig. 9). Sillimanite- and muscovite-bearing gneisses are common, and in the westernmost part there are local occurrences of migmatitic gneisses with the assemblage crd-bt-sil-kfs and without garnet. Therefore, western Lapland is mostly classified as LP4.1 and LP6.1 (Fig. 8). Next to the greenschist facies Kittilä belt, there is an area (154) where garnet- and staurolite-bearing gneisses are found, and the area is classified as MP3.

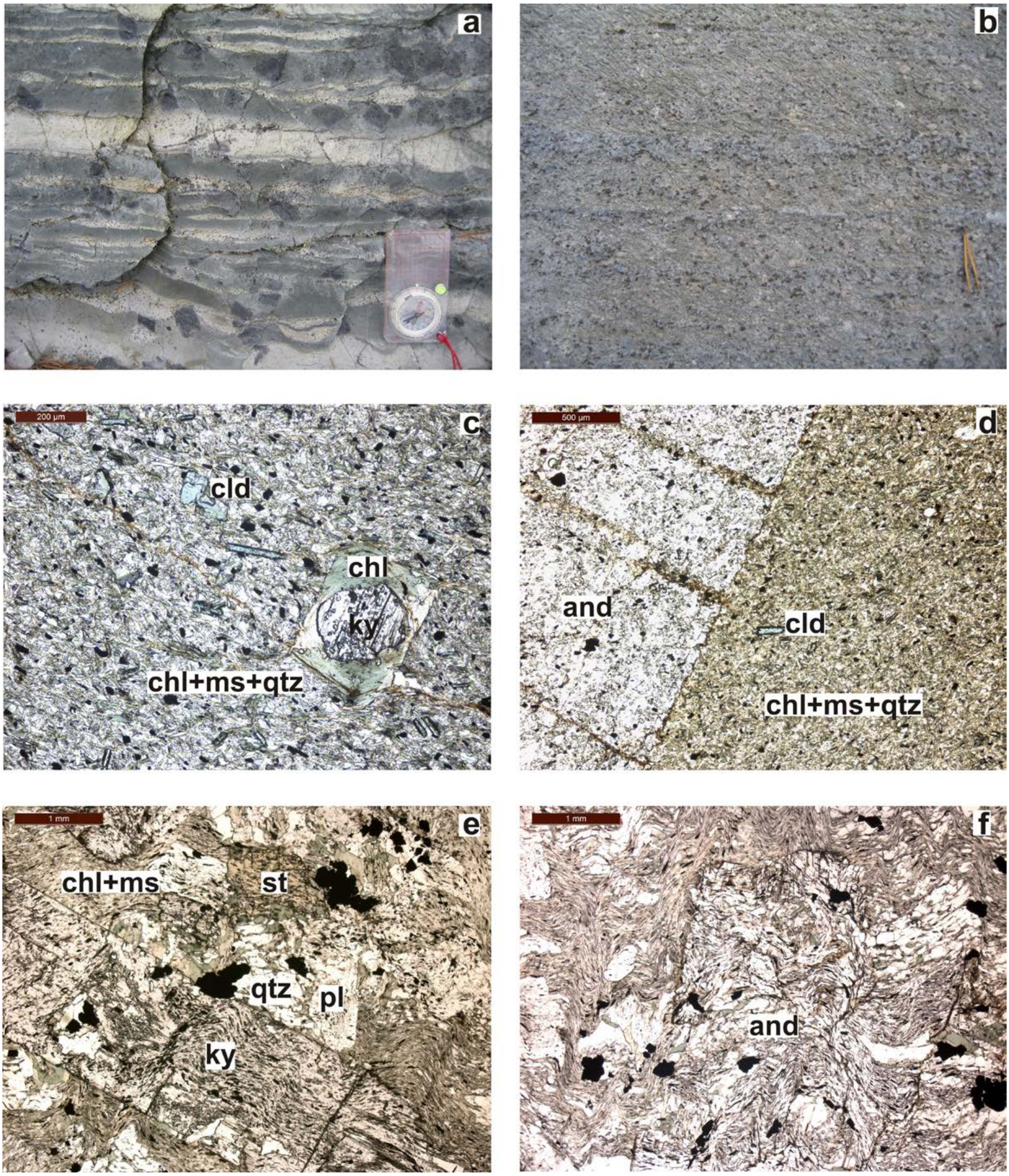

Fig. 27. Metapelites east of Sodankylä: a) andalusite schist, exposure PSH$-1998-1, northing 7480094, easting 487183; b) kyanite gneiss, PSH$-1999-72, northing 7482432, easting 511203; c) chloritoid and kyanite altered from rims into chlorite; d) andalusite in the matrix consisting of chlorite, muscovite, chloritoid and quartz, c–d are from the rock presented in Fig. a; e) kyanite and staurolite overgrowing D3 crenulation; f) andalusite overgrowing D3 crenulation in the gneiss of Fig. b. All coordinates are given using the EUREF-FIN (UTM35) system.

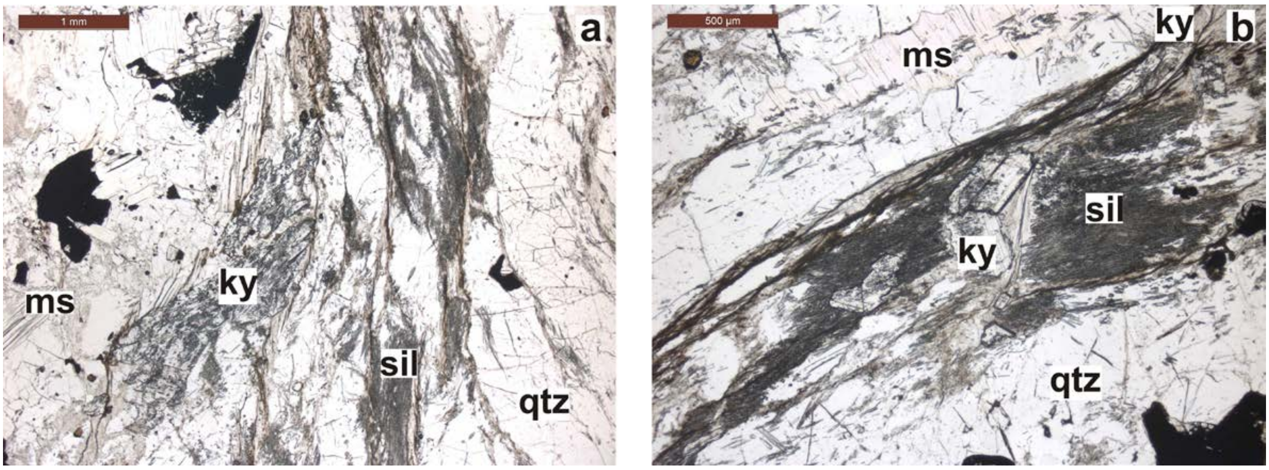

Fig. 28. a, b) Kyanite-bearing quartz rock at Kelottijärvi, exposure PSH$-2013-110, northing 7615214, easting 293529. Fibrolitic sillimanite is mostly crystallized along the cleavage planes, overgrowing the more randomly oriented kyanite. Coordinates are given using the EUREF-FIN (UTM35) system.

These gneisses also contain either andalusite or sillimanite, and sometimes both Al-silicates are found in the same thin section. Therefore, in terms of the pelite composition, this area represents MP3.1b preceded by MP3.1c, the reactions indicating increasing temperature and pressure.

In the northwest, kyanite-bearing rocks are found in a couple of exposures (area 156, Fig. 9). The association sil-ky-ms-qtz-rt was found in a quartz rock on the Swedish border northwest of Kelottijärvi. Sillimanite appears to be a younger phase than kyanite, so that sillimanite needles overgrow kyanite along the cleavage planes (Figs. 28a-b). This area is classified as MP3.1a, overprinted by MP3.1b.

SVECOFENNIA PROVINCE

Southern Finland Subprovince

The eastern part of the Southern Finland Subprovince (SFS, Fig. 10) mostly consists of metapelites and metagreywackes in which the metamorphic grade varies from andalusite schists (Figs. 29a–b) to sillimanite gneisses (Fig. 29c) to crd-bt-kfs gneisses (Fig. 29d), and finally to grt-crd-bt-sil metatexites and diatexites (Figs. 29e–f). The majority of the exposed metasedimentary rocks are metatexitic migmatites (LP7.1), but mainly diatexitic granulites (LP8.1) cover large areas (areas 17–19, 77, Fig. 9).

Most of the andalusite schists and sillimanite gneisses are found at the northern boundary of the SFS (areas 26–29, 70–75, Fig. 9). The common mineral assemblages in the andalusite schists are and-ms-bt-qtz±crd and crd-bt-ms-qtz. Staurolite has not been observed, indicating low-pressure metamorphism around 2-3 kbar. Near the boundaries of the andalusite schist areas, fibrolitic sillimanite may be present together with andalusite. Adjacent to the schists there are common occurences of sillimanite gneisses with sil-bt-ms-pl-qtz±kfs assemblages. Some of the andalusite schist areas are enveloped by sillimanite gneisses (e.g. area 297, Fig. 9).

Andalusite schists are also found in the Orijärvi area (area 15, Fig. 9) in the SW part of the SFS (Eskola 1914, 1915, Pajunen et al. 2008, Sayab et al. 2015, Skyttä et al. 2006, Väisänen & Skyttä 2007). The volcanic rocks in this area often show a strong, premetamorphic chemical alteration, which has produced protoliths for cordierite-orthoamphibole rocks, whose petrography was described by Eskola (1914). Sillimanite is found with andalusite in the Orijärvi schists (Pajunen et al. 2008, Skyttä et al. 2006). Another low amphibolite facies (LP3.1, Fig. 8) area is located west of Orijärvi in the Kemiö island (area 14, Fig. 9), where Dietvorst (1982) described andalusite schists surrounded by sil-kfs-gneisses and crd-kfs-gneisses. Around the Orijärvi and Kemiö andalusite grade rocks there is an area (16, Fig. 9) that is classified as LP6.1, because the

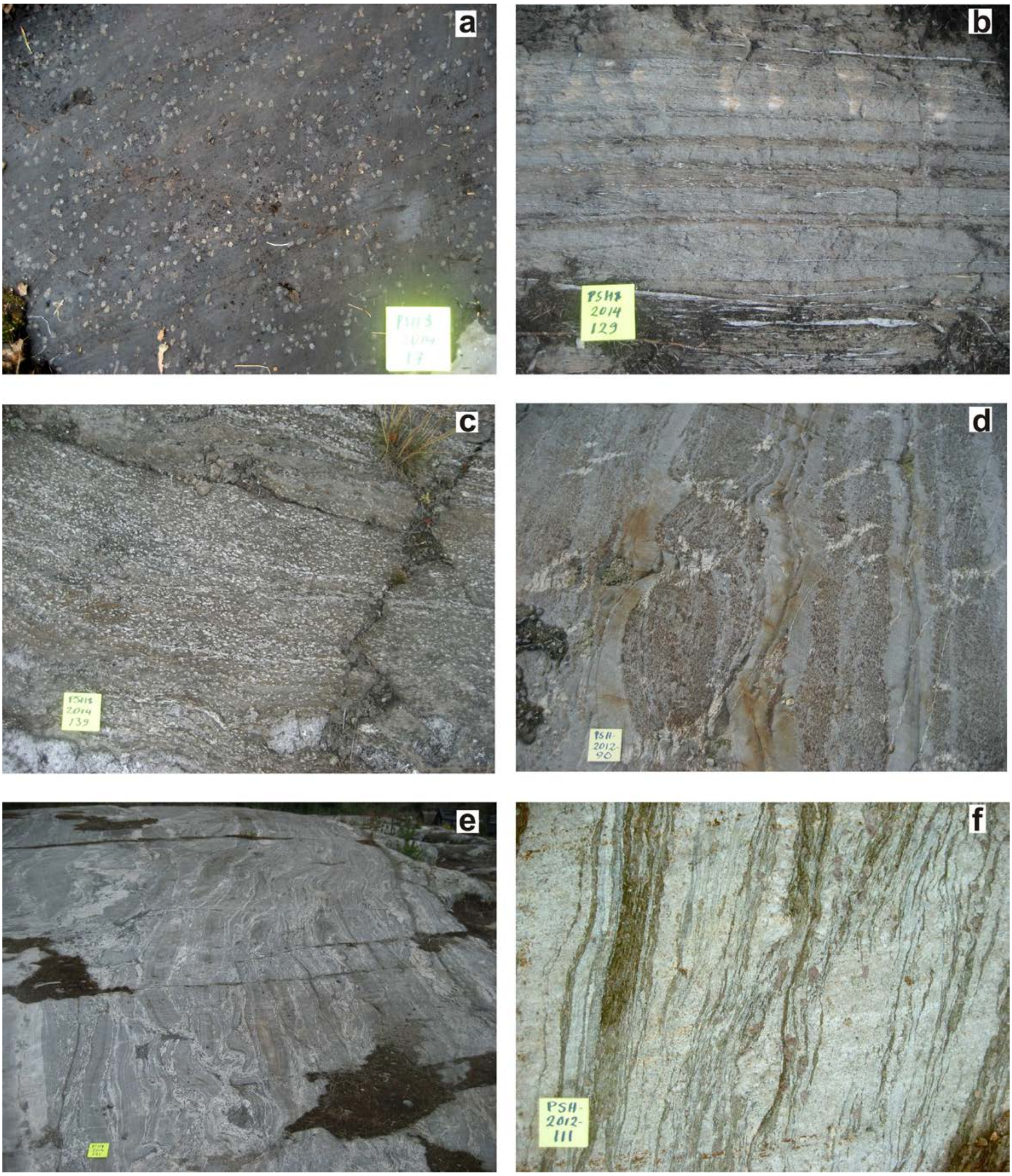

Fig. 29. Field photos showing the increase in metamorphic grade from andalusite schists to diatexitic migmatites in the Southern Finland Subprovince: a) andalusite schist in the Häme belt, area 26, exposure PSH$-2014-17, northing 6779224, easting 287484; b) andalusite schist south of Sysmä, area 297, exposure PSH$-2014-129, northing 6804439, easting 432985; c) sillimanite gneiss south of Sysmä, area 70, exposure PSH$-2014-139, northing 6807209, easting 438840; d) cordierite-K-feldspar gneiss south of Mikkeli, area 68, exposure PSH$-2012-90, northing 6818409, easting 512615; e) metatexitic migmatite, Uusimaa belt, area 24, exposure PSH$-2014-121, northing 6764067, easting 428510; f) diatexitic migmatite, Uusimaa belt, area 17, exposure PSH$-2012-111, northing 6687917, easting 413364. All coordinates are given using the EUREF-FIN (UTM35) system.

metapelitic rocks are mostly crd-bt-kfs-gneisses without garnet (Dietvorst 1982, Bleeker & Westra 1987, Veenhof & Stel 1991). For the andalusite zone in Kemiö, Dietvorst (1982) estimated metamorphic conditions of ca. 560 °C at 3 kbar and for the crd-kfs-zone ca. 670 °C at 4 kbar. In both the Orijärvi and Kemiö shear zones, the andalusite grade rocks are separated from surrounding crd-bt-kfs-gneisses, indicating that the present juxtaposition is caused by tectonic faulting.

In the eastern part of the SFS, Korsman (1977) and Korsman et al. (1984, 1988) described the change from andalusite schists to granulite facies migmatites (Gupta & Johannes 1986) as a result of progressive metamorphism that took place under low pressure at ca. 4 kbar, with temperature increasing from ca. 600 °C in the andalusite schists (LP3.1, area 75) to ca. 750 °C in pelitic diatexites (LP8.1, area 77, Figs. 8–9). The progressive metamorphism was associated with regional D2 deformation (Kilpeläinen 1988). Because of its rounded shape, the diatexitic granulite facies area was called the Sulkava thermal dome by Korsman et al. (1984, 1988), the metamorphic grade increasing towards the core of the dome from all directions.

In the SFS, other large granulite facies terrains include the West Uusimaa complex (area 17, Fig. 9) and the Turku area (areas 18-19, Fig. 9), where migmatites are mostly diatexitic and mafic and intermediate rocks locally contain orthopyroxene. The West Uusimaa granulites were first described by Parras (1958). Geothermobarometry indicates that the granulites were metamorphosed at ca. 750-800 °C at 4-5 kbar (Mouri et al. 2005, Schreurs 1985, Schreurs & Westra 1986, Schreurs 1984). Geographically, the granulite facies rocks are not restricted to west Uusimaa, but continue to east Uusimaa, where they are crosscut by rapakivi granite. Within the granulites there is a small area (25, Fig. 9) that has well-preserved bedding structures (Fig. 30a) and no signs of partial melting. The Al-rich layers often have muscovite-filled pseudomorphs, obviously after sillimanite. These schists are surrounded all over by metatexitic and diatexitic migmatites (Fig. 30b).

In the Turku area, in the southwestern SFS, diatexitic granulite domains are surrounded by metatexitic migmatites (Väisänen & Hölttä 1999, Mengel et al. 2001, Johannes et al. 2003). Temperature and pressure estimates for the diatexitic granulites are ca. 800 °C and 6 kbar. The adjacent metatexites crystallized at 100–150 °C lower temperatures and 1–2 kbar lower pressures (van Duin 1992, van Duin & Nieman 1993, Väisänen & Hölttä 1999). Granulite facies granitoids were described in the Turku archipelago (Ehlers et al. 1993), where lower grade rocks with well-preserved primary structures (area 366, Fig. 9) are also found within the migmatites (Ehlers 1976, Ehlers & Lindroos 1990). In both metatexitic and diatexitic migmatites, cordierite in both neosomes and palaeosomes of migmatites has been altered from rims and fractures to pinite, biotite and andalusite or sillimanite, indicating an LP3.1 overprint (Hölttä 1986, Väisänen & Hölttä 1999).

Western Finland Subprovince

Pirkanmaa and Tampere belts and Central Finland granitoid complex

The boundary of the SFS to the Western Finland Subprovince (WFS, Fig. 10) is tectonic. For example, in the area between the towns of Mikkeli and Sysmä, it is manifested by a deformation zone consisting of several shear zones, whose width is from hundreds of metres to 1-2 kilometres. The boundary is marked by an increase in metamorphic grade from the andalusite and sillimanite-muscovite±K-feldspar grade rocks in the SFS to metatexitic migmatites (Fig. 31a) of the Pirkanmaa belt, which forms the southern part of the WFS (Fig. 10). The protoliths of the migmatites in the Pirkanmaa belt are mostly turbiditic greywackes (Lahtinen et al. 2009), and the leucosomes are tonalitic and trondhjemitic (Kilpeläinen 1998). Campbell (1980) and Mouri et al. (1999) estimated metamorphic temperatures and pressures of ca. 700-750 °C at 5 kbar for the central parts of the Pirkanmaa belt. During cooling, retrograde andalusite crystallized locally (Mouri et al. 1999), and the belt is therefore classified as LP7.1 (Fig. 8), overprinted by LP3.1 (Fig. 11).

In the Tampere belt between the Pirkanmaa belt and the Central Finland granitoid complex (CFGC; Fig. 10), the metasedimentary rocks are andalusite grade schists (MP3.1c and LP2.1, areas 50–52, 55, 57; Figs. 30b–c), surrounded by sil-bt-ms gneisses (areas 46–47, Fig. 9). The metamorphic and tectonic structure of the western part of the Tampere belt and adjacent Pirkanmaa belt were described by Kilpeläinen (1998), who explained the complicated metamorphic pattern as a result of postmetamorphic isotherm folding. With a few exceptions, porphyroblasts are not found in the schists in the

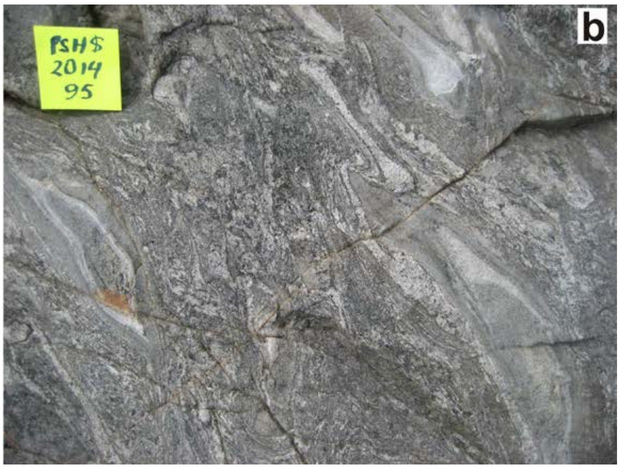

Fig. 30. Well-preserved schist within migmatites in the eastern part of the Uusimaa belt: a) bedding and sillimanite pseudomorphs in a schist, area 25, exposure PSH$-2014-93, northing 6729723, easting 422866; b) migmatite, area 24, exposure PSH$-2014-95, northing 6734225, easting 418934. The distance between these two exposures is 2 km. Coordinates are given using the EUREF-FIN (UTM35) system.

central and northern parts of the Tampere belt, and they are therefore classified as LP2.1 (area 57, Fig. 9). Staurolite and garnet are locally found with andalusite in the southern part of the belt, which is classified as MP3c. In the western part of the Tampere belt, andalusite is locally overgrown by sillimanite (Figs. 30d–f) (Nyyssönen 2012). Andalusite grade schists are also found in the Luhanka area (56, Fig. 9), west of the Tampere belt.

The CFGC, north of the Tampere belt, forms a large part of the WFS and the granitoids were not studied in this project. However, with a few exceptions, supracrustal rocks within the complex are migmatitic and many granitoids are deformed and consequently metamorphosed. Therefore, most of the complex is classified as LP7. Within the CFGC, there are small areas where andalusite grade schists without staurolite are found, being classified as LP3.1 (Fig. 8). These are found at Mänttä (area 53, Fig. 9) (Sjöblom 1990) and at Pihtipudas (area 101, Fig. 9) (Hölttä 1988).

Pohjanmaa belt

The prominent feature in the Pohjanmaa belt, northwest of the Central Finland granitoid complex, is metamorphic zoning with a prograde increase in metamorphic grade towards the Vaasa complex from andalusite grade schists (LP3.1, areas 104, 107–108, Fig. 9) to diatexitic migmatites (LP8.1, area 106, Fig. 9) (Mäkitie 1999, Mäkitie et al. 2001, Lehtonen et al. 2003). Similar metamorphic zoning can be found both on the southern and on the eastern-northeastern side of the complex (Lind 2013). The lowest grade rocks are schists with well-preserved bedding structures and Al-rich layers with and-bt-ms-qtz±st±chl associations (Figs. 32a–b). On the eastern side of the Vaasa complex, the schist area is divided into two parts. In the western part, staurolite was not observed and sillimanite needles were locally found in andalusite schists (area 107, Fig. 9, LP3.1 overprinted by LP4.1, Figs. 8 and 10). In the eastern part (area 108, Fig. 9), staurolite is common in mica schists, locally in textural equilibrium with andalusite (MP3.1c, Fig. 8). Garnet is also found in staurolite schists (Savunen 2015). In some staurolite-bearing schists, cordierite is the breakdown product of staurolite (Fig. 33a), indicating a decrease in pressure or increase in temperature.

On the southern side of the Vaasa complex, the metamorphic grade increases almost directly from andalusite schists (area 104, Fig. 9) to metatexitic garnet-cordierite migmatites (area 105), but on the eastern side the change is more gradual, so that fibrolitic sillimanite is first found in the same exposures with andalusite, and then the andalusite schists change into sil-bt-ms-kfs gneisses, whose grain size increases but may still have well-preserved bedding structures (Fig. 32c). Small amounts of leucosome (<5 vol.%) are often found in mica-rich layers. These gneisses first change into metatexitic grt-crd-sil-bt gneisses (Fig. 32d) and then into diatexitic migmatites (Figs. 32e–f) at the contact of the granitoids of the Vaasa complex. According to the data presented by Savunen (2015) and Mäkitie (1999), this change took place almost isobarically at around 4–5 kbar. Garnet-cordierite migmatites often show retrograde alteration of cordierite into

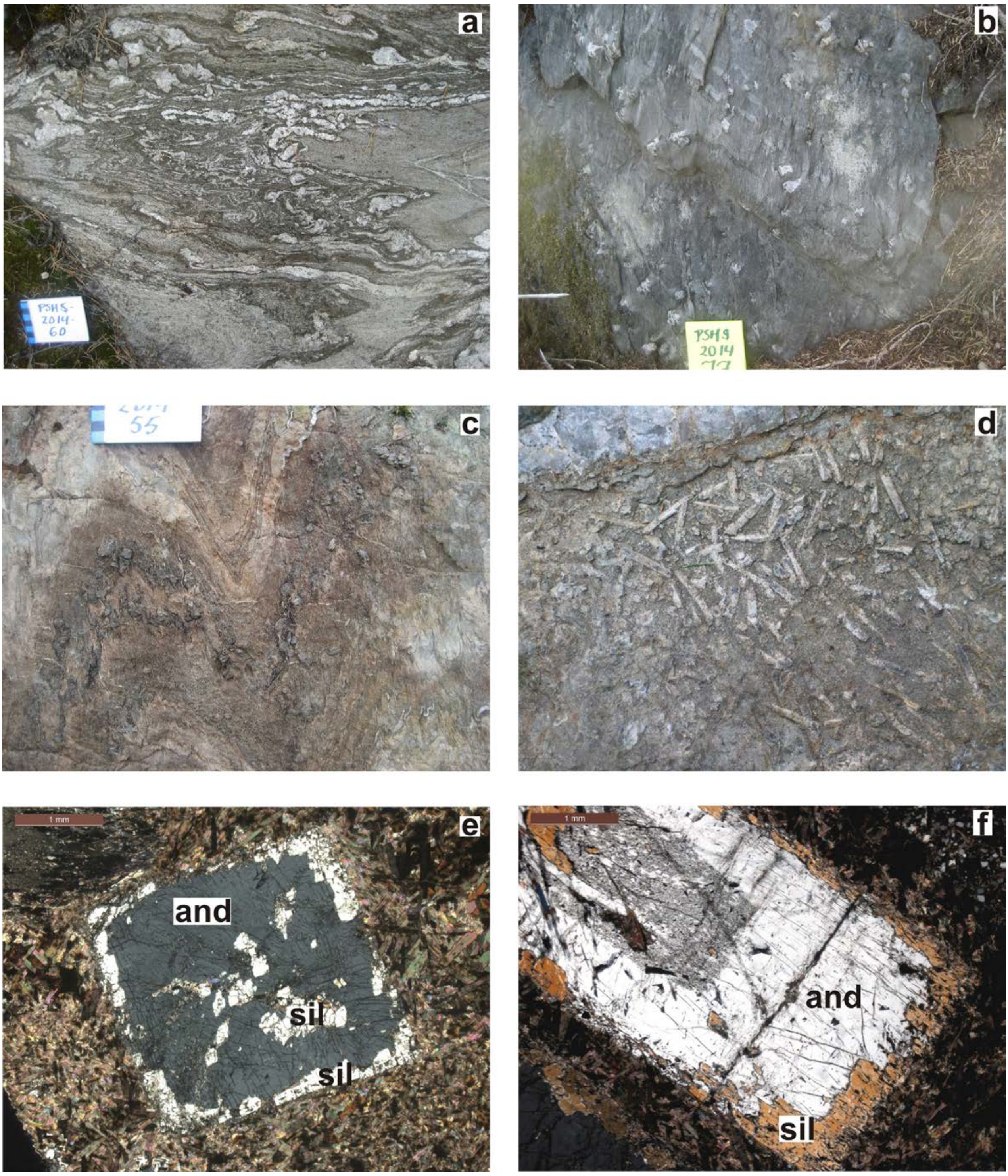

Fig. 31. Migmatites and schists of the Pirkanmaa and Tampere belts: a) a typical metatexitic folded migmatite of the Pirkanmaa belt, area 30, exposure PSH$-2014-60, northing 6782358, easting 302659; b) andalusite grains growing along the S2 axial plane, which is at a high angle with the S0 bedding; area 50, exposure PSH$-2014-77, northing 6822898, easting 297341; c) folded andalusite-rich layer in a schist, area 55, exposure PSH$-2014-55, northing 6816226, easting 277371; d) randomly oriented andalusite grains in a schist, area 50, northing 6828992, easting 315564; e, f) microphotographs from samples from d, andalusite prisms altered from rims and fractures into sillimanite. All coordinates are given using the EUREF-FIN (UTM35) system.

andalusite and biotite (Fig. 33b), and sometimes even into kyanite (Mäkitie 1999), indicating only moderate uplift during cooling.

The boundary of the andalusite–staurolite grade schists (areas 107, 108, Fig. 9) and Central Finland granitoid complex is tectonic, related with the N–S-striking shear zone system at the western boundary of the CFGC (Nironen et al. 2016). According to observations made from drill cores at Raahe in the Pattijoki formation, the contact between andalusite schists (area 110, Fig. 9) and migmatites is a shear zone showing alternation of schists with migmatitic gneisses (Nikander 2000). Low amphibolite facies schist is also found at Siikajoki in northern Pohjanmaa as a narrow tectonic sliver in partly diatexitic migmatite, classified as LP3.1 (area 113, Fig. 9).

Near the southeastern boundary of area 107, there is a small area (120, Fig. 9) where prograde kyanite is found (MP3a, Fig. 8). This is the only observation on prograde kyanite in the Svecofennia Province so far. Kyanite was found in one exposure, the host rock being a medium-grained felsic gneiss (Fig. 34a) whose extent is obviously less than 1 km^2, because the surrounding rocks are fine-grained schists and well-preserved volcanic rocks. The mineral association is ky-st-bt-pl-qtz±ms±chl, and in the same exposure there are garnet-bearing layers with grt-bt-chl-pl-qtz, plagioclase being anorthitic and forming haloes around garnet (Fig. 33b). Kyanite forms prisms of several mm in length (Figs. 34c–d). The P/T ratio of this rock appears to differ completely from the rest of the Svecofennia Province, which represents the andalusite-sillimanite type low P/T ratio.

In the northeastern part of the Pohjanmaa belt, the andalusite–staurolite schists change into sillimanite-biotite-muscovite gneisses and garnet-cordierite migmatites, which are mostly metatexitic, but diatexites are also found. The southwestern part of the Pohjanmaa belt mostly consists of diatexitic and metatexitic migmatites. In some small areas, orthopyroxene-bearing diatexites are found (Lehtonen et al. 2003).

Savo belt

The Savo belt forms the eastern part of the WFS on the eastern side of the Central Finland granitoid complex (Fig. 10). Unlike the boundary between the SFS and WFS, the boundary with the WFS and the Karelia Province is not marked by a metamorphic discordance, probably reflecting the highly interpretative nature of the terrane boundary.

The Savo belt was mostly metamorphosed in upper amphibolite facies and in granulite facies (LP7.1 and LP8.1, Fig. 8) at pressures of around 5–6 kbar (Hölttä 1988, Korsman et al. 1984). The granulite facies areas are found around large post-kinematic orthopyroxene granitoids (Nironen et al. 2000), obviously representing pluton-derived metamorphism. The orthopyroxene granitoids, with similar regional metamorphic effects, are found on both sides of the inferred boundary between the WFS and the Karelia Province. Granulites in their vicinity are diatexitic migmatites, commonly with grt-opx-bt-pl-qtz±crd and grt-crd-bt-sil±spl assemblages. Orthopyroxene is commonly present in various lithologies and mineral associations. Chemically altered garnet-cordierite-orthopyroxene rocks are found, for example, in the Rautalampi and Pielavesi-Kiuruvesi granulite areas (areas 66 and 96, respectively, Fig. 9) (Marttila 1976, Hölttä 1988, Pääjärvi 2000). These are normally coarse-grained rocks with garnet and orthopyroxenes up to 1.5–2.5 cm in size. Petrography, mineral compositions and metamorphic pressures and temperatures of the Pielavesi-Kiuruvesi grt-crd-opx-rocks were described by Hölttä (1988), who estimated temperatures of 800–880 °C and pressures of 5–6 kbar for their metamorphism.

When intruded into pelitic rocks, some of the orthopyroxene granitoids have contact metamorphic aureole with an inner diatexitic granulite facies having a width of a few tens of metres to a couple of hundreds of metres. A good example is the Vaaraslahti intrusion in the Pielavesi area (Hölttä 1995). This has a thermal aureole in which the metamorphic grade in the country rocks increases from the stability field of muscovite to granulite facies at the contact. The temperature of metamorphism increases almost isobarically at ca. 5 kbar, geothermometers showing an increase from ca. 600 °C in the muscovite zone to ca. 750 °C at the contact. The minimum horizontal distance through which this change takes place is two kilometres. A similar aureole was described around the post-kinematic Luopa pyroxene granitoid intrusion in the Pohjanmaa belt (Mäkitie 1999, Mäkitie & Lahti 2001).

Metapelitic rocks in the Savo belt often show prominent rehydration with replacement of cordierite by andalusite and biotite intergrowths, sometimes also with fine-grained staurolite and locally even kyanite (Hölttä 1995). This indicates moderate uplift of ca. 5–8 km during cooling from the peak upper amphibolite and granulite facies conditions down to the andalusite and kyanite field.

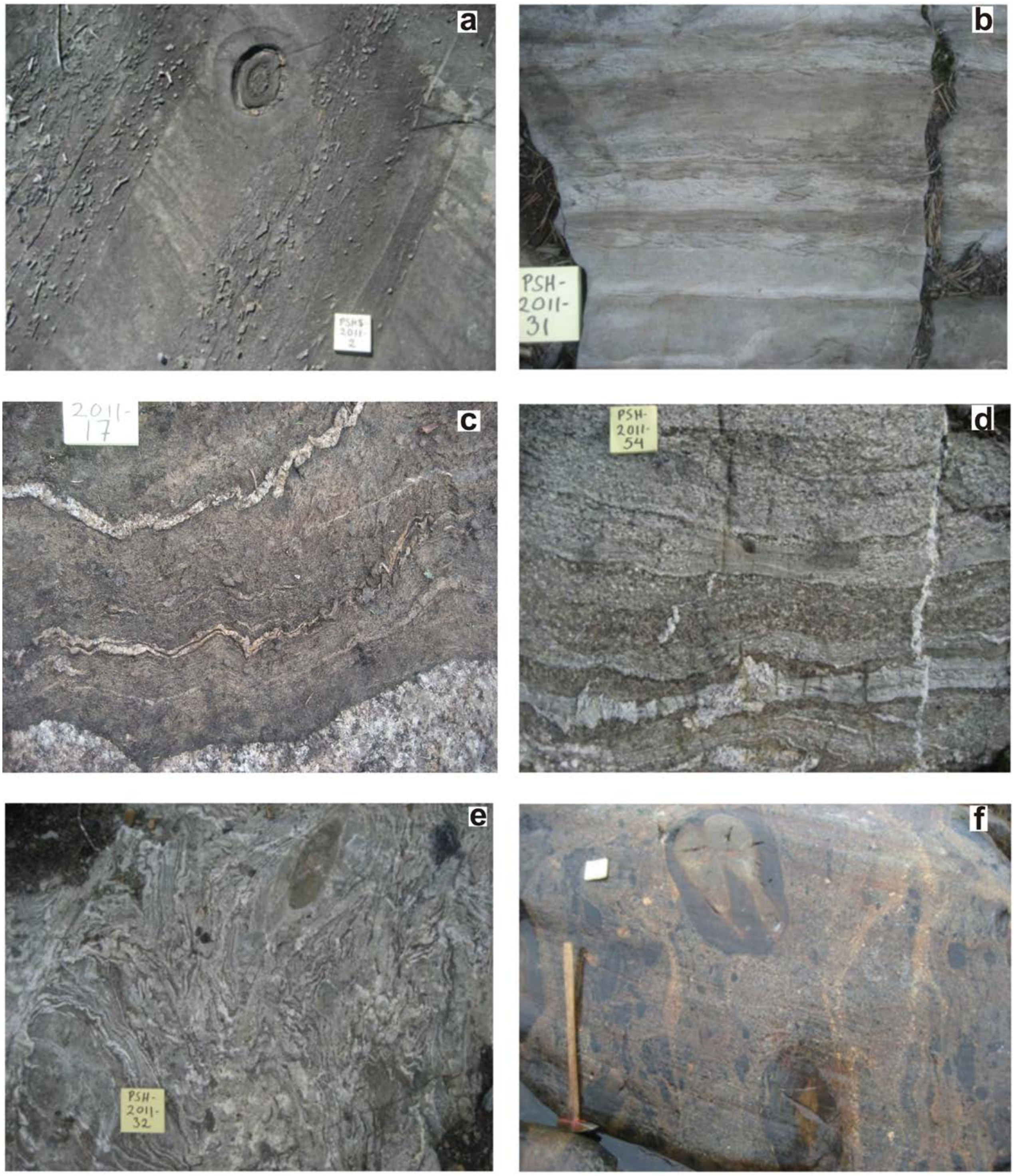

Fig. 32. Metamorphic zoning in the Pohjanmaa belt: a) andalusite porphyroblasts in a schist with a calc-silicate concretion, area 107, exposure PSH$-2011-2, northing 7032726, easting 318913; b) ripple marks in a bedded metagreywacke, area 108, exposure PSH$-2011-31, northing 7063777, easting 350616; c) quartz-veined sillimanite gneiss, area 103, exposure PSH$-2011-17, northing 7090175, easting 342685; d) garnet-cordierite-sillimanite gneiss with bedding structures showing the onset of melting, area 105, exposure PSH$-2011-54, northing 7028153, easting 309733; e) diatexitic migmatite at the eastern contact of the Vaasa complex, area 106, exposure PSH$-2011-32, northing 7054901, easting 295605; f) diatexitic migmatite at the northern contact of the Vaasa complex, area 106, exposure PSH$-2011-70, northing 7063874, easting 277901. The edge of the tag in each figure is 7.5 cm and all coordinates are given using the EUREF-FIN (UTM35) system.

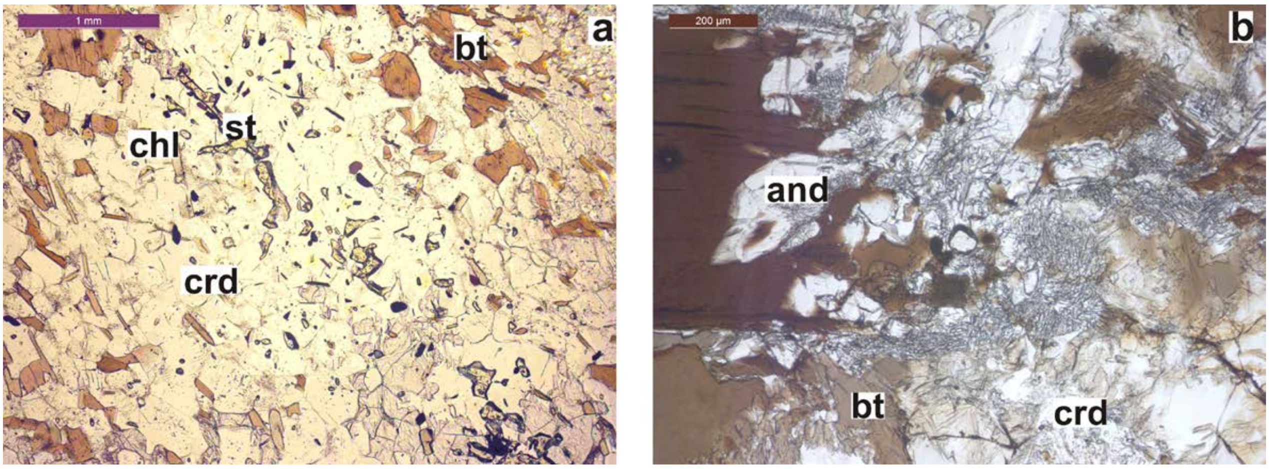

Fig. 33. Decompression and cooling reactions in schists and migmatites in Pohjanmaa: a) staurolite decomposing into cordierite, area 108, exposure JMSA-2011-100, northing 7110977, easting 340396; b) cordierite decomposing into andalusite and biotite, area 106, exposure PSH$-2011-12, northing 7031694, easting 303357. Coordinates are given using the EUREF-FIN (UTM35) system.

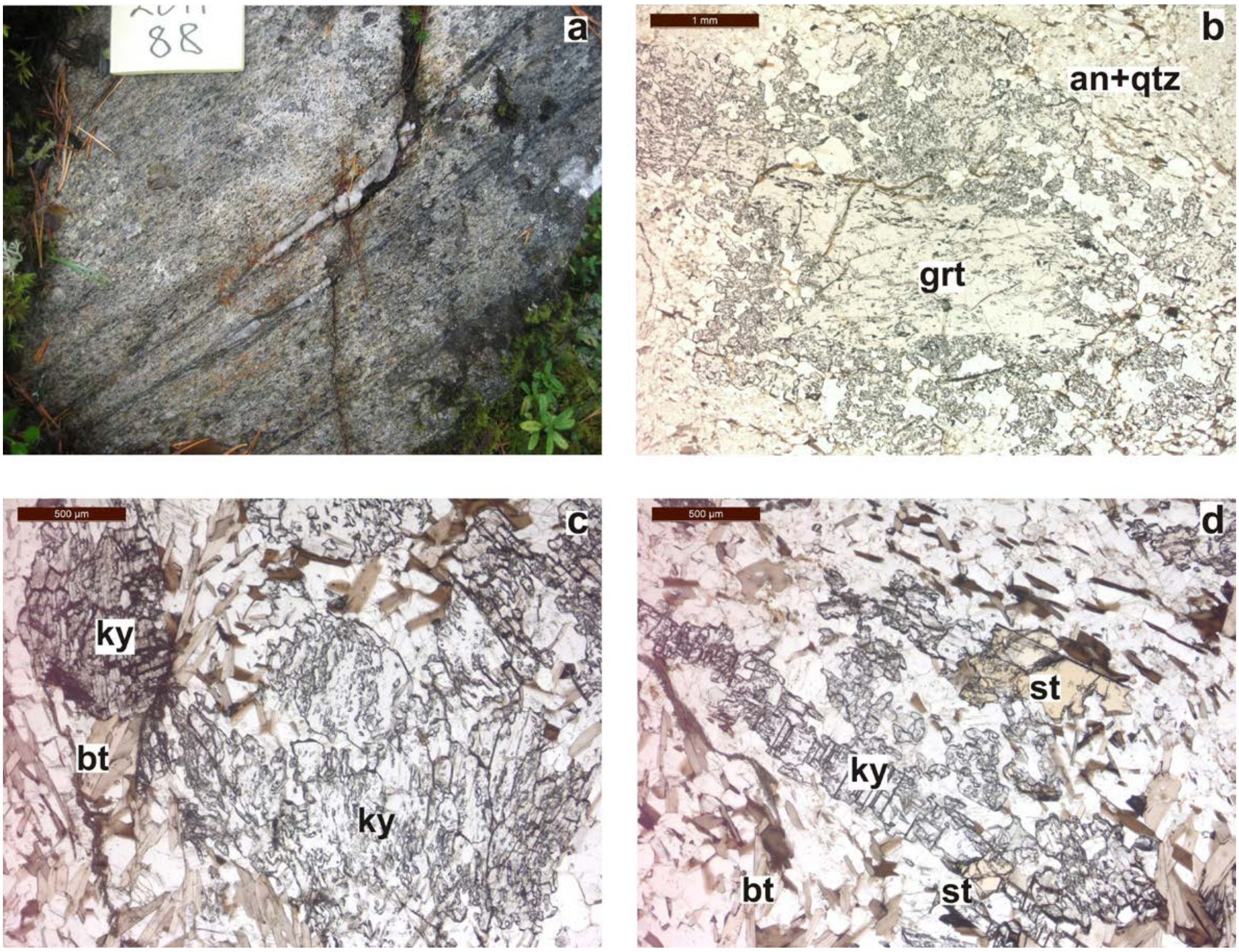

Fig. 34. a) Kyanite rock in the southern part of the Pohjanmaa belt, area 120, exposure PSH$-2011-88, northing 7010502, easting 355354; b) garnet decomposing into anorthitic plagioclase in a garnet-bearing layer without kyanite; c) kyanite grains; d) coexisting kyanite and staurolite. The edge of the tag in Fig. a is 7.5 cm and coordinates are given using the EUREF-FIN (UTM35) system.

MESOPROTEROZOIC AND YOUNGER SEQUENCES

Mesoproterozoic sedimentary rocks

On the west coast of Finland are two large Mesoproterozoic sedimentary rock formations, the Satakunta and Muhos formations. The Satakunta formation (area 41, Fig. 9) mostly consists of sandstones, whereas the Muhos formation (area 116, Fig. 9) also includes siltstones and shales (Simonen & Kouvo 1955). At least the Satakunta formation is weakly metamorphosed, because laumontite is locally found as a main mineral (Pokki et al. 2013), and is therefore classified as MP1.1. There are no descriptions of laumontite in the Muhos formation, but well-preserved varve structures in siltstones and the existence of microfossils (Tynni & Uutela 1984) indicate that the metamorphic grade was very low.

Caledonides

Palaeozoic rocks emplaced during the Caledonian orogeny are found in a small area in northwesternmost Finland (areas 158–159, 363–364, Fig. 9). The metamorphic setup is complicated and characterized by nappes (thrust sheets) of low-, medium- and high-grade metamorphic rocks and contact metamorphism around mafic and ultramafic intrusions. The autochthonous Dividal group rocks between the Archaean gneisses and the overlying Jerta and Nalganas nappes consist of low-grade schists metamorphosed in epidote-amphibolite facies (here LP2.1, areas 158–159, Figs. 8 and 9). The Nabar nappe above the Nalganas nappe represents a higher grade with garnet and muscovite-bearing gneisses (MP4.1, area 363, Fig. 9). The Vaddas nappe on the Nabar nappe comprises mafic and ultramafic intrusions, which have caused high-temperature contact metamorphism at high pressure, producing kyanite-bearing diatexites and garnet, cordierite, orthopyroxene and sillimanite bearing gneisses (Sipilä 1992, Lehtovaara 1995).

SUMMARY

Most of the Archaean bedrock was metamorphosed at high-amphibolite facies and low to medium pressures, around 6–7 kbar, although only a few geobarometric pressure estimates exits because of the scarcity of mineral assemblages suitable for geothermobarometry in the Archaean TTG complexes. Granulite facies areas are scarce, and most of them were also metamorphosed at low pressures. An exception is the Iisalmi complex, where medium pressure granulites are found, metamorphosed at 9–11 kbar. The Archaean greenstone belts were metamorphosed at mid-amphibolite facies and medium pressures, in Ilomantsi around 5–6 kbar, but in Kuhmo and Oijärvi, pressures close to 10 kbar or even higher may have been possible.

The Archaean areas were overprinted by Proterozoic metamorphism, which can be seen as local rehydration (epidotization, chloritization), especially close to shear zones. In the Rautavaara and Tuntsa areas, Proterozoic overprint was pervasive in large areas, extending from several kilometres to tens of kilometres in width. Proterozoic metamorphism is manifested by the retrogression of the Archaean upper amphibolite and granulite facies assemblages into mid-amphibolite facies medium pressure assemblages, with crystallization of staurolite and kyanite in Al-rich rocks. This retrogression was obviously related to the metamorphism of the Proterozoic cover sequences of the Karelia Province, which were metamorphosed in greenschist to mid-amphibolite facies conditions. The type of metamorphism of the cover sequences varies from low pressure (Peräpohja and Kiiminki belts) preserving andalusite and cordierite assemblages to medium pressure (North Karelia schist belt, Central Lapland) with kyanite assemblages.

Most areas of the Svecofennia Province were metamorphosed in upper amphibolite and granulite facies under low pressures at around 4–6 kbar. Within the migmatites, there are a few low- to mid-amphibolite facies zones, which commonly have tectonic boundaries. These also represent low pressure with andalusite and cordierite assemblages in peraluminous schists. In the Southern Finland Subprovince

(SFS), the majority of the lower grade rocks are at the northern boundary of the subprovince, so that the contact with the Western Finland Subprovince (WFS) is both tectonic and metamorphic, the WFS migmatites being juxtaposed with andalusite grade schists in the SFS. In the Svecofennia Province, there are several relatively large granulite facies areas with diatexitic migmatites (Sulkava, Uusimaa, Turku). In the WFS, diatexite areas are smaller and often related to emplacement of granitoids. In the Vaasa complex, there is a prograde increase in metamorphic grade from andalusite-bearing schists to diatexitic migmatites towards the contacts of the granitoid batholith.

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The three papers in this Special Paper are the outcomes of two programmes that initiated in the Geological Survey of Finland (GTK) around 2005. The aim of the first programme was to implement a digital bedrock map database, to provide a seamless vector bedrock map, and to divide the bedrock of Finland into stratigraphic units according to international standards. The first paper represents the major stratigraphic units (supergroups, supersuites and complexes), and an outline to tectonostratigraphic division.

The aim of the second programme was to present several aspects of the bedrock of Finland at 1:1 000 000 scale. The second paper is a guide to the legend of the map 'Geological Map of Finland – Bedrock 1:1 000 000', published in 2016. The guide includes principles for division of the bedrock into tectonic provinces, and a tectonic evolution model from the Neoarchaean to the Cenozoic. In the third paper, metamorphic maps of Finland at 1:1 000 000 scale are presented for peak metamorphic grade, for metamorphic facies, and for peak and post-peak p-T conditions. The metamorphic domains are demonstrated by numerous examples.

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