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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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)

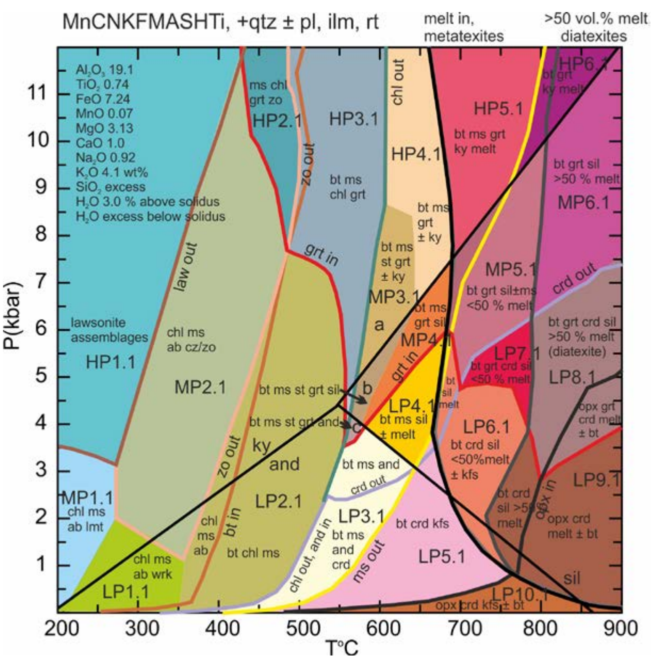


Fig. 1. A generalized PT pseudosection for an Al-rich pelitic rock.

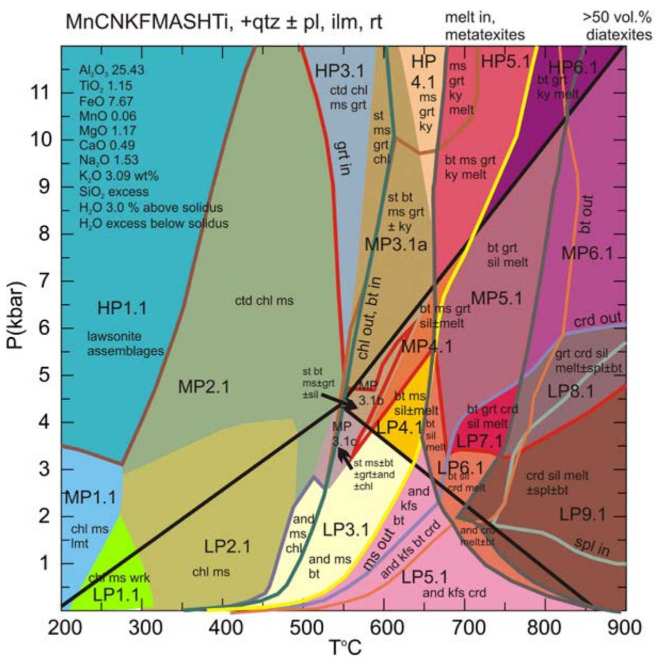


Fig. 2. A generalized PT pseudosection for a low-Ca, Fe- and Al-rich pelitic rock.

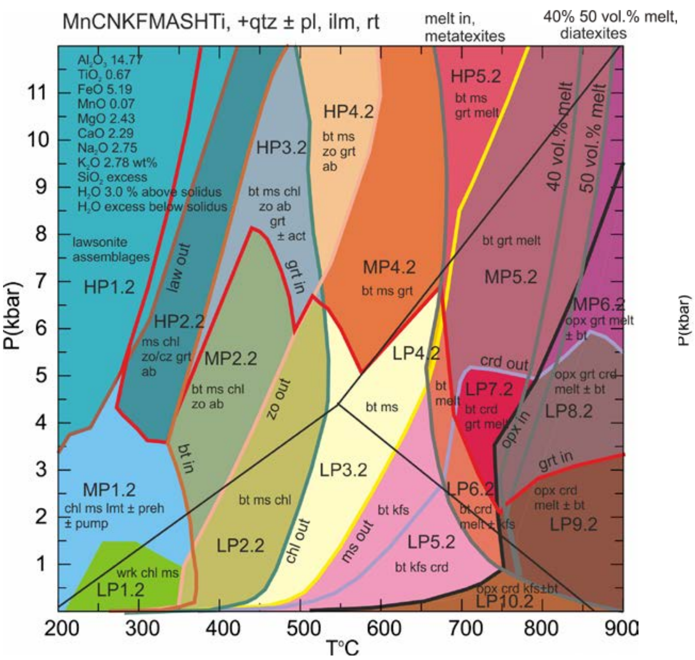


Fig. 3. A generalized PT pseudosection for an average Svecofennian metasedimetary rock.

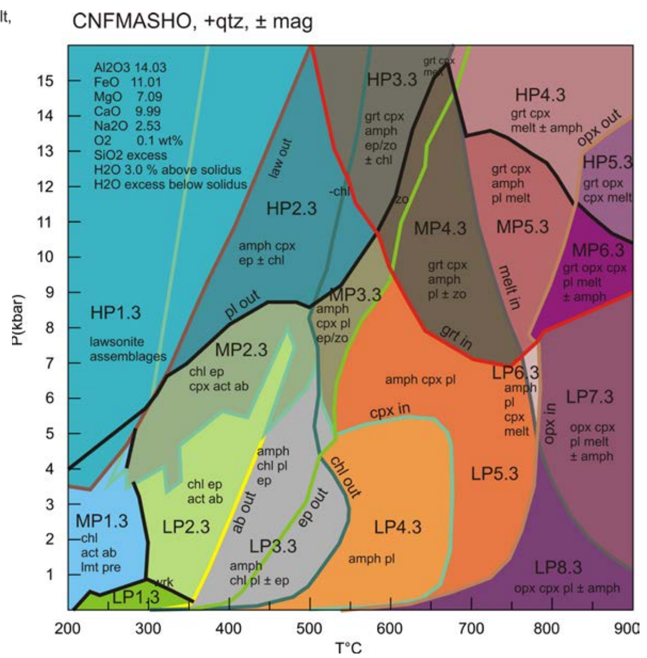


Fig. 4. A generalized PT pseudosection for an average Archaean amphibolite.

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.

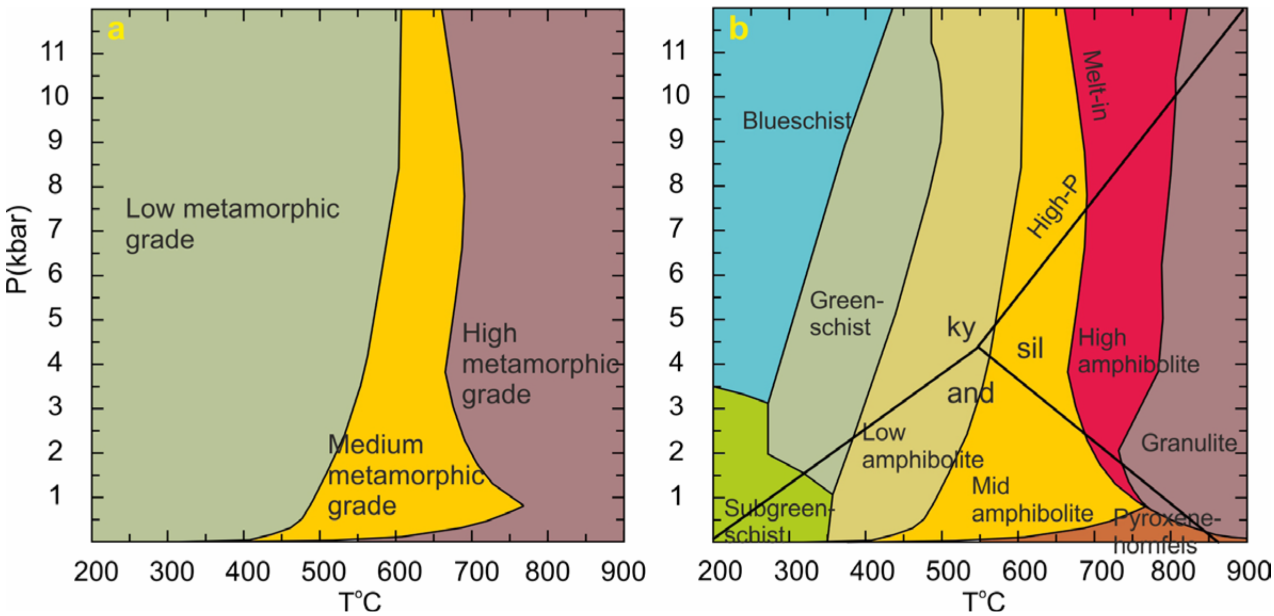


Fig. 5. a) PT fields of low, medium and high metamorphic grade, based on Fig. 1. b) PT fields of metamorphic facies, based on Fig. 1.

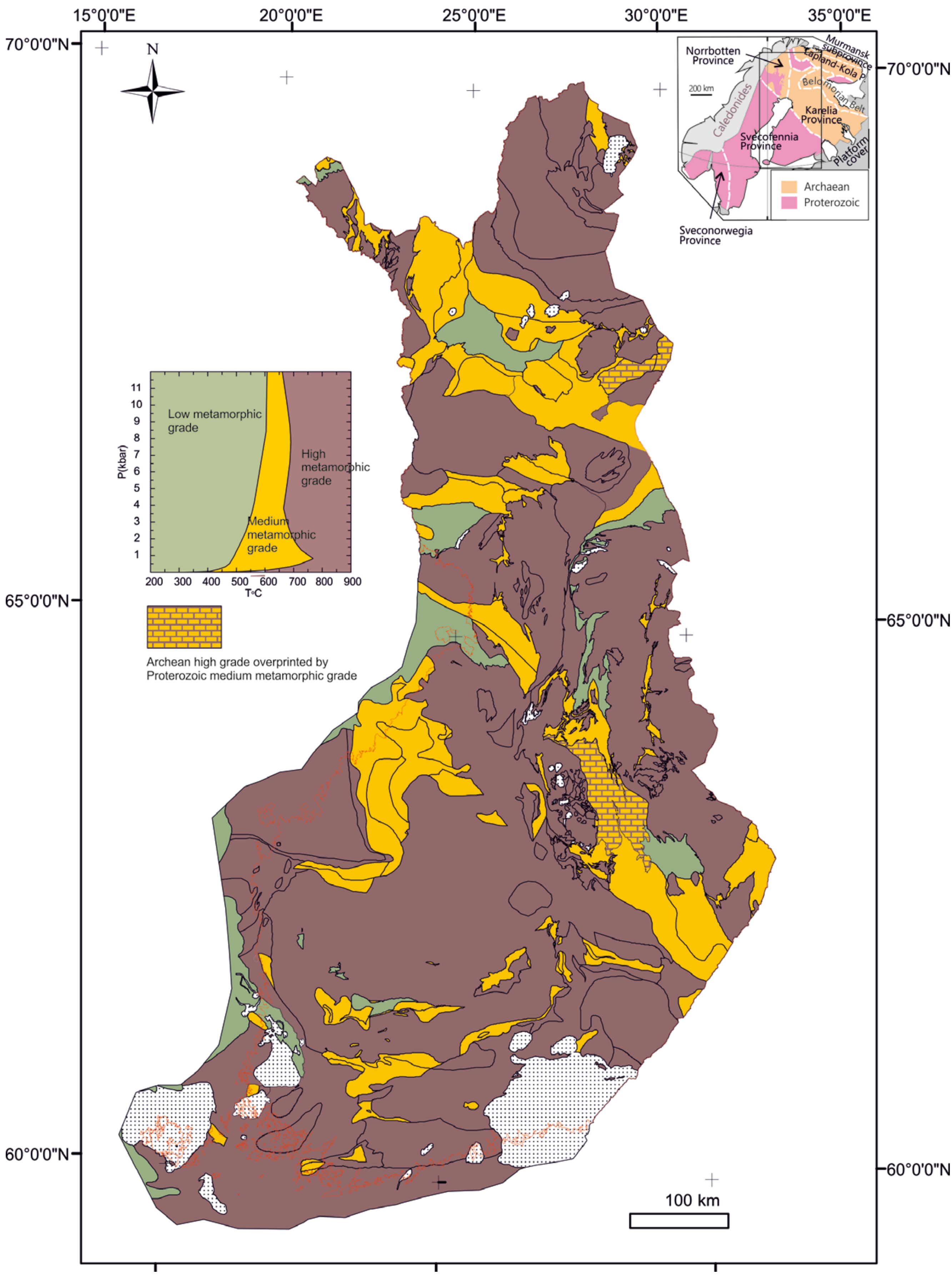


Fig. 6. Low-, medium- and high-grade areas. Stippled areas indicate undefined plutonic rocks. Updated 4.4.2022.

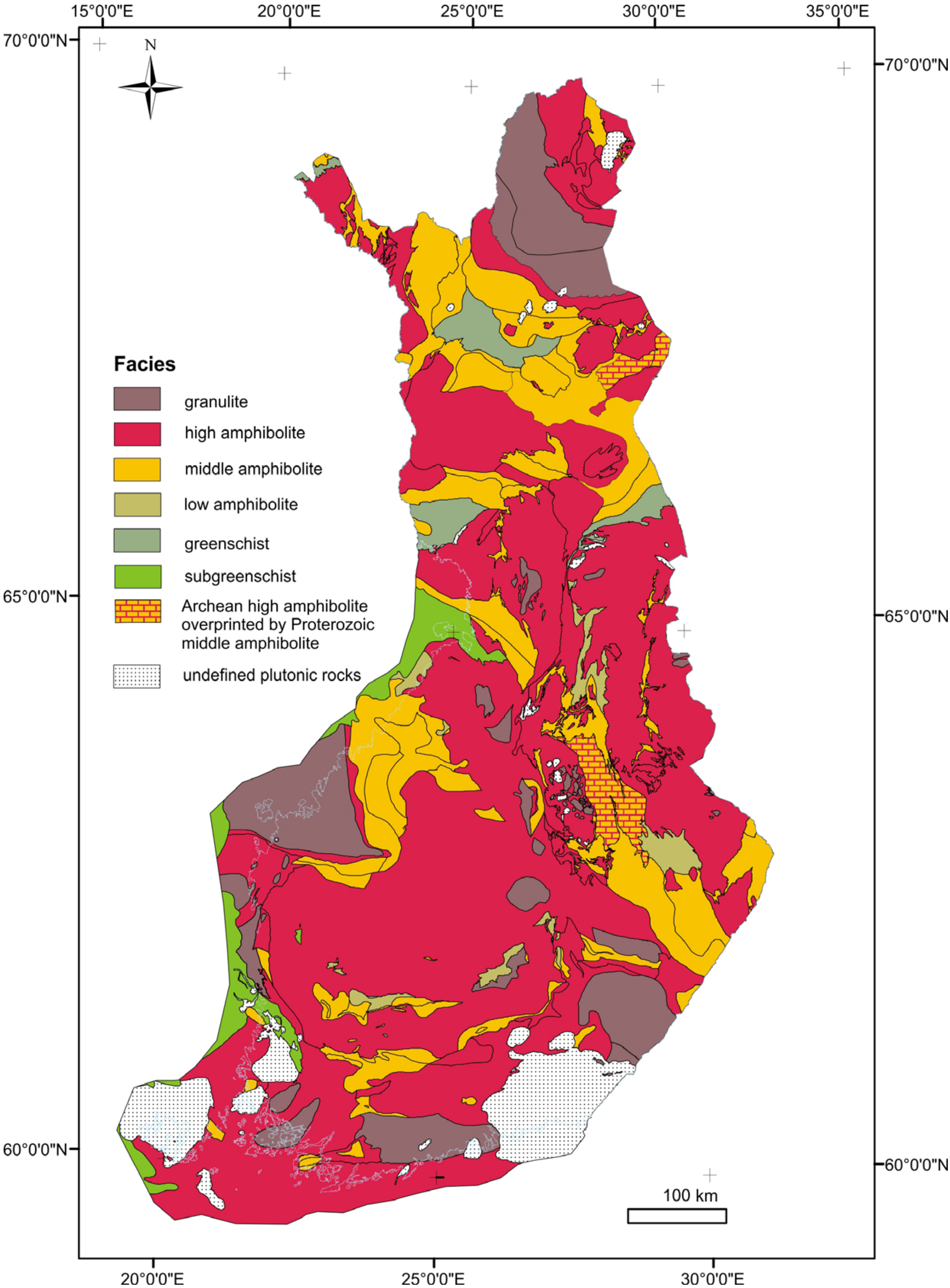


Fig. 7. Metamorphic map based on facies division. Updated 4.4.2022.

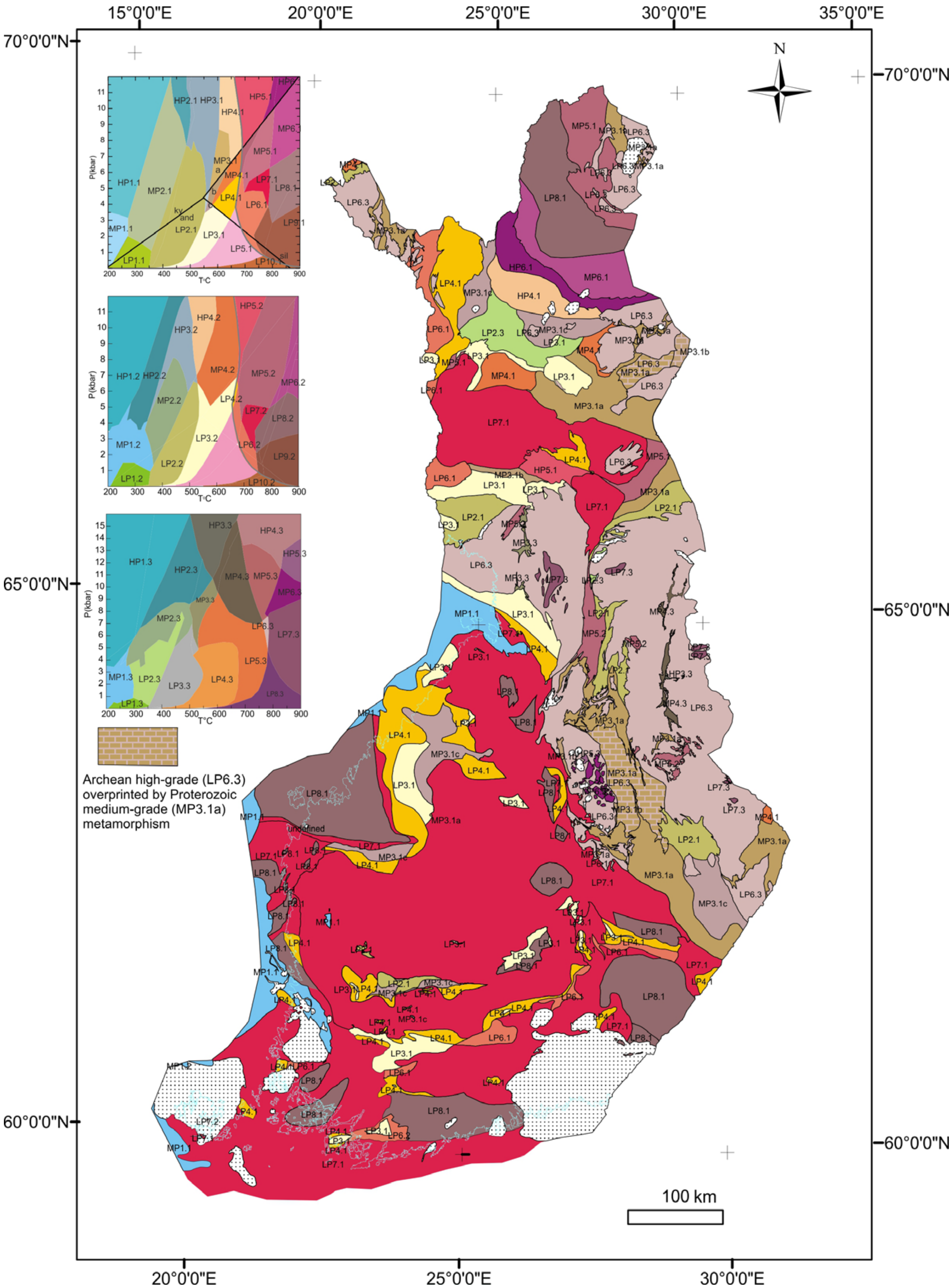


Fig. 8. Metamorphic map based on the fields of stable assemblages in generalized PT pseudosections (insets). Stippled areas indicate unclassified plutonic rocks. Updated 4.4.2022.

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 meta morphism: 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

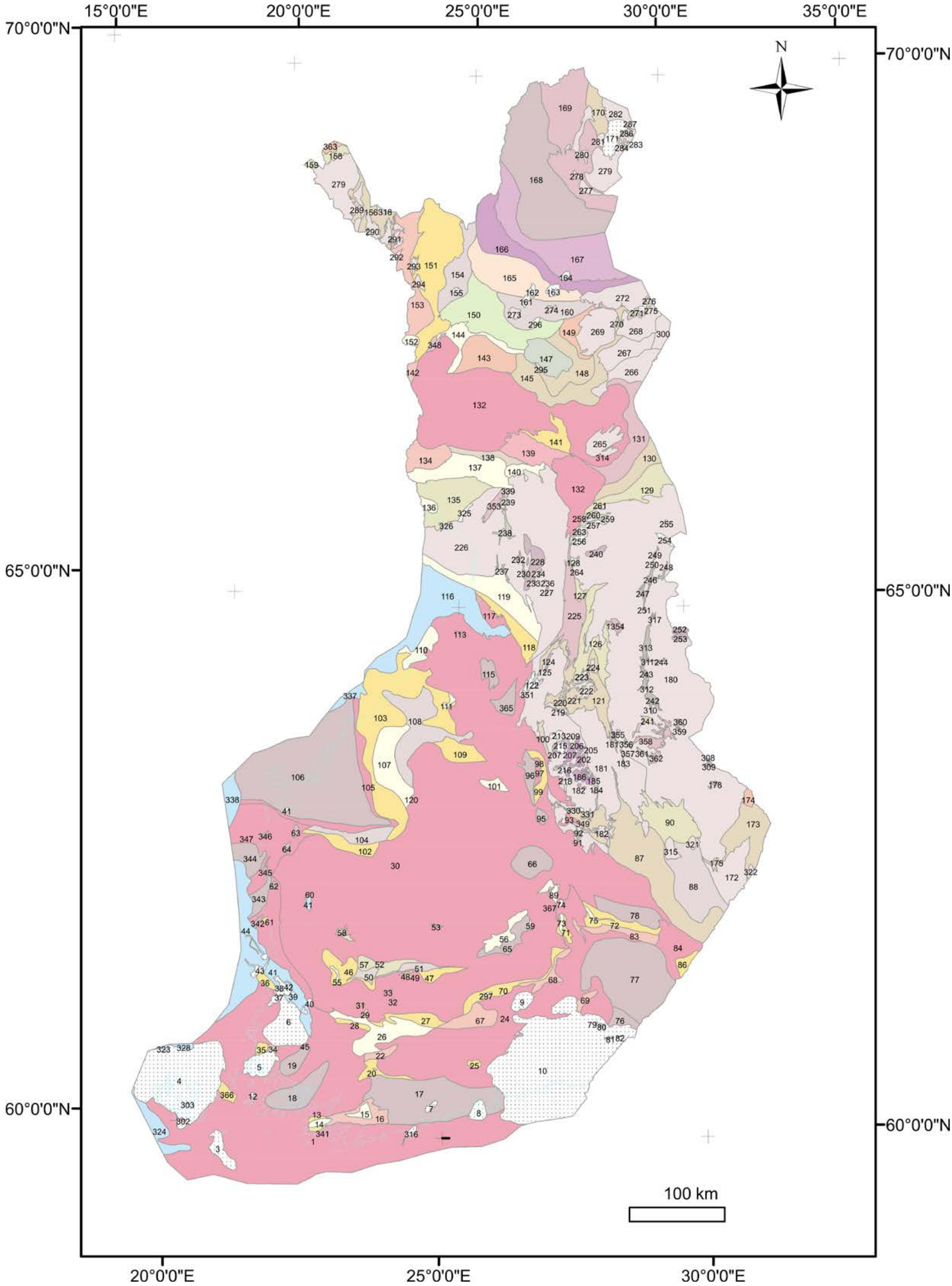


Fig. 9. The areal codes of the metamorphic zones presented in Fig. 8.

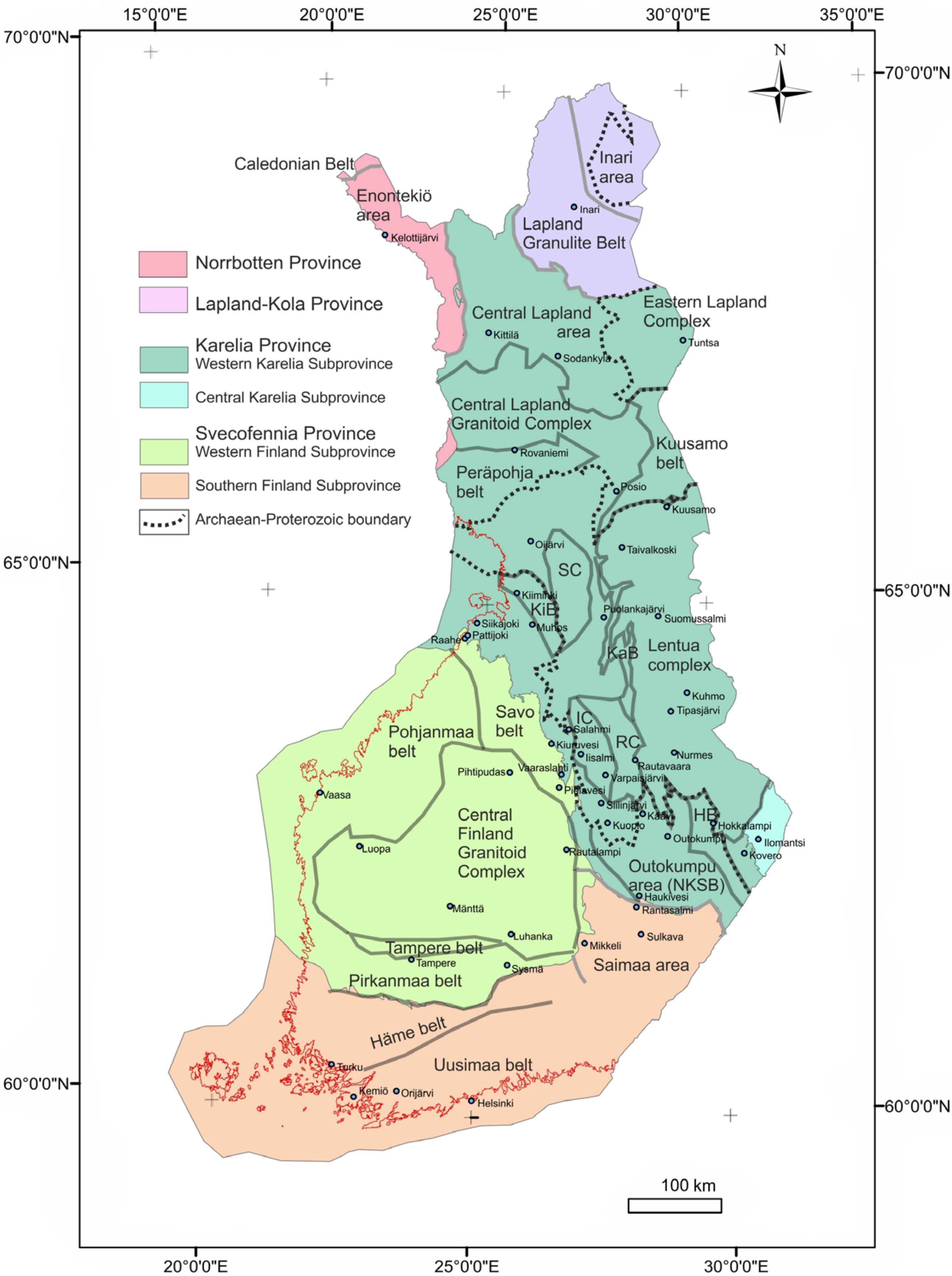


Fig. 10. Map showing the province division by Nironen et al. (2016) and the lithological-geographical areas defined by Nironen et al. (2002), cited in this paper. The Archaean complexes are from Hölttä et al. (2012). KiB = Kiiminki belt, KaB = Kainuu belt, SC = Siurua complex, IC = Iisalmi complex, RC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

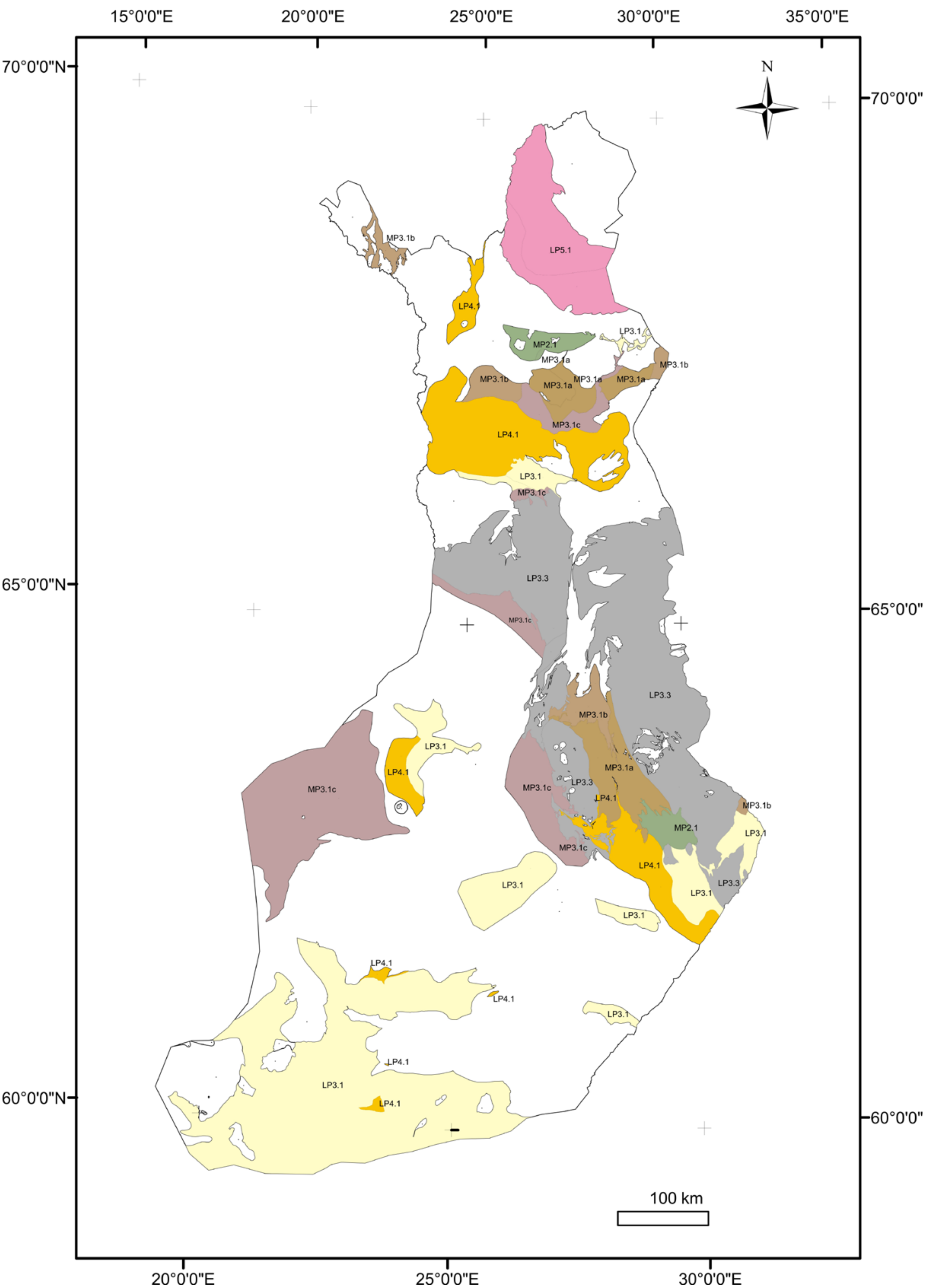


Fig. 11. A map showing the areas with a significant metamorphic overprint. The colours and symbols correspond to those in Fig. 1. White areas are either not classified or are not significantly affected by late metamorphic events.

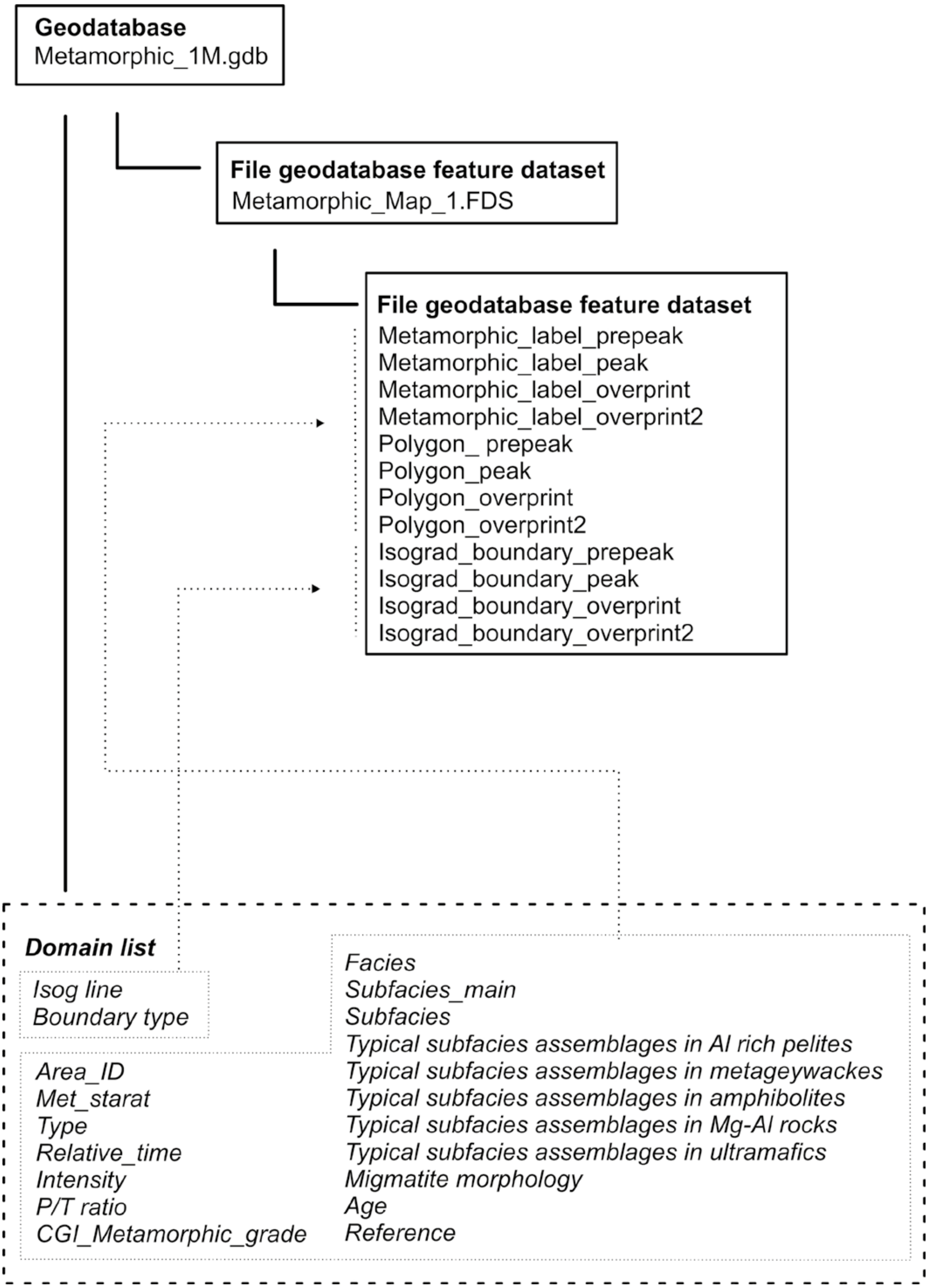


Fig. 12. The database structure.

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

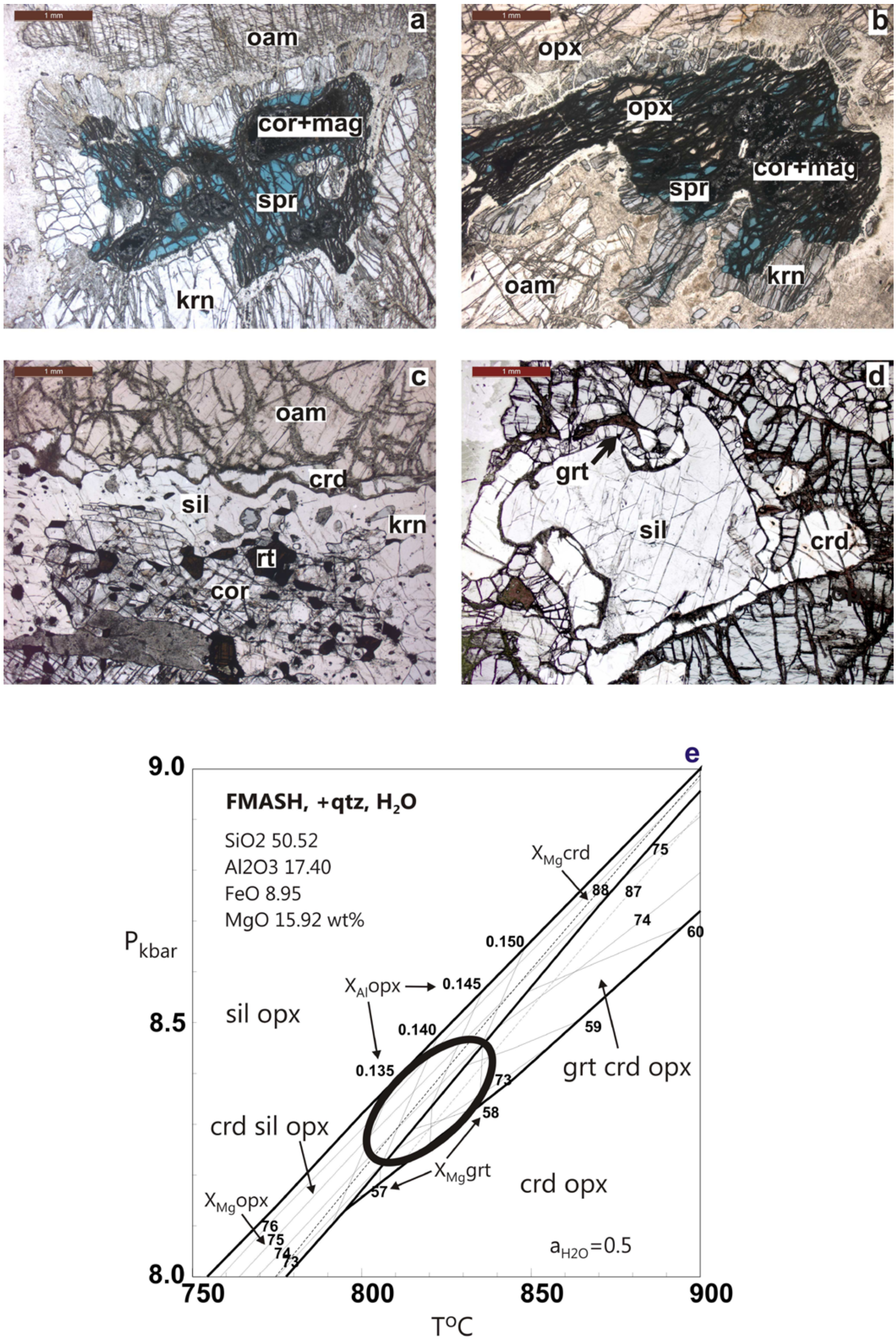


Fig. 13. Corona textures in the Mg-Al granulites in Varpaisjärvi: a, b) a sapphirine corona on an aggregate of corundum and magnetite, a kornerupine corona between orthoamphibole/orthopyroxene and sapphirine; c) a sillimanite corona on corundum, a cordierite corona between sillimanite and orthoamphibole; 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.

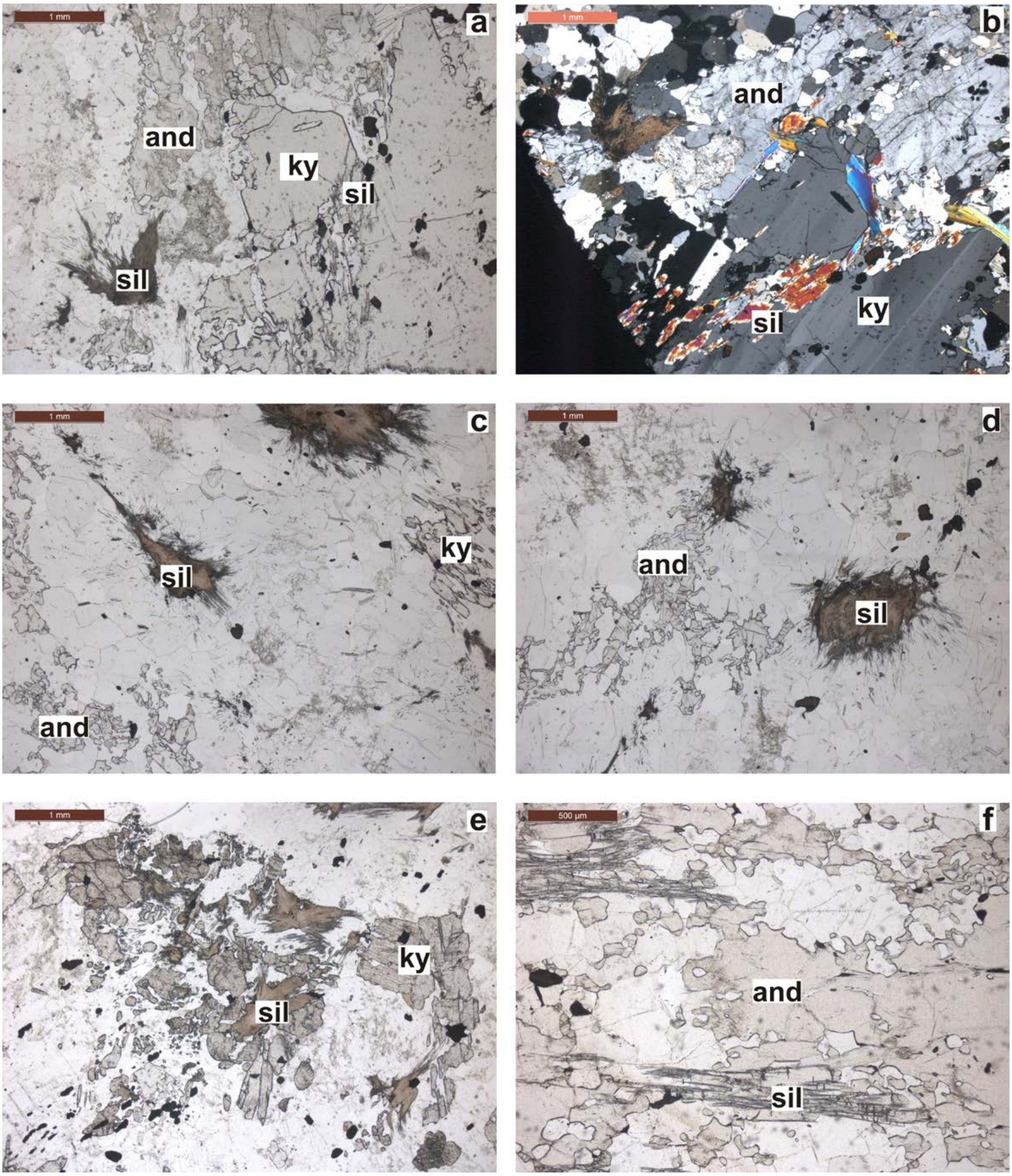


Fig. 14. Textures in the andalusite-sillimanite-kyanite rock in Rautavaara. Northing 7055574, easting 554356. Coordinates are given using the EUREF-FIN (UTM35) system.

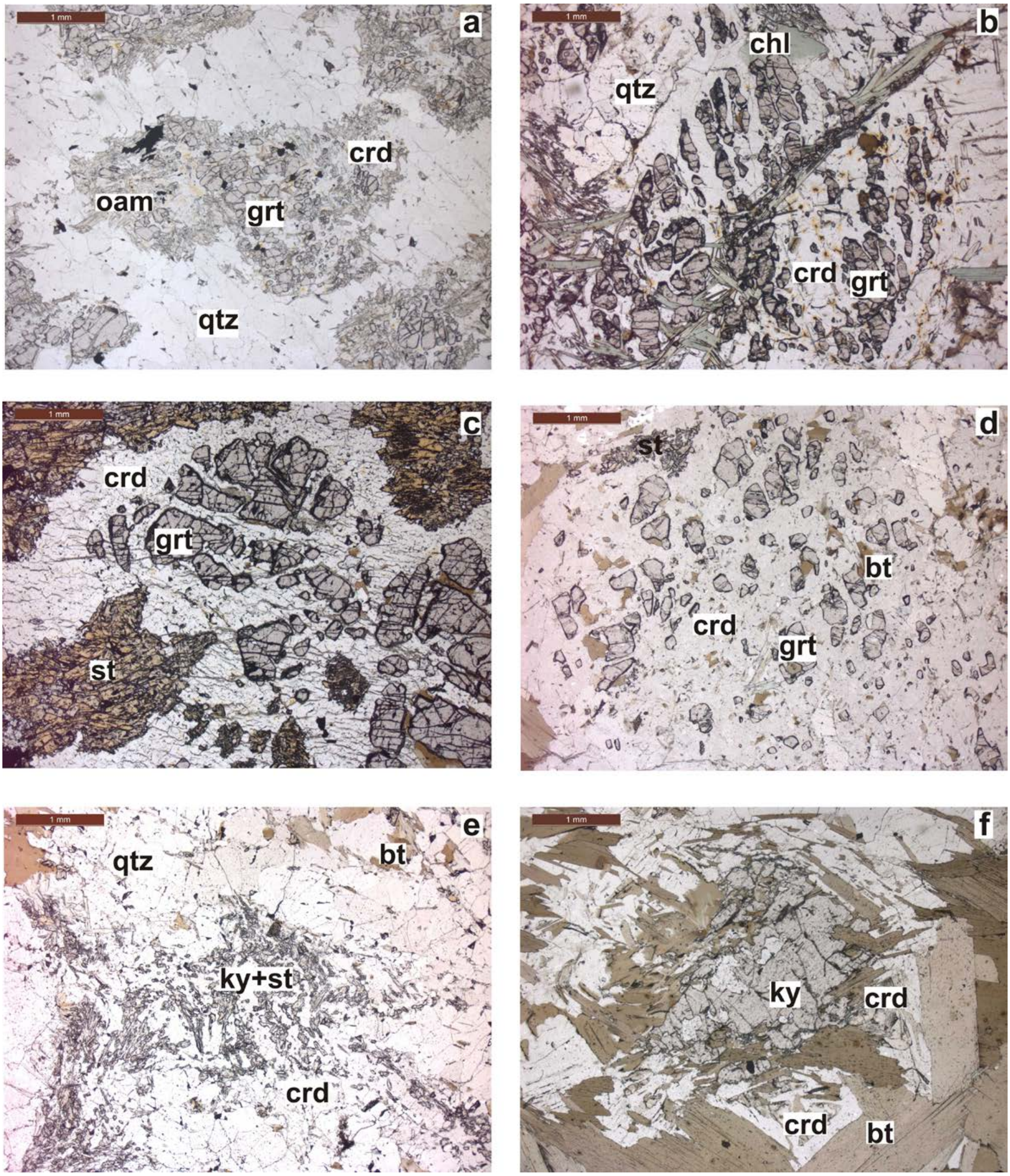


Fig. 15. Retrograde textures in the Rautavaara area: a) garnet altering into cordierite and orthoamphibole in the reaction grt + qtz = oam + crd; b) garnet altering to cordierite and chlorite in the reaction grt = crd + chl + qtz; c) garnet altering to cordierite and staurolite, possibly in the reaction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

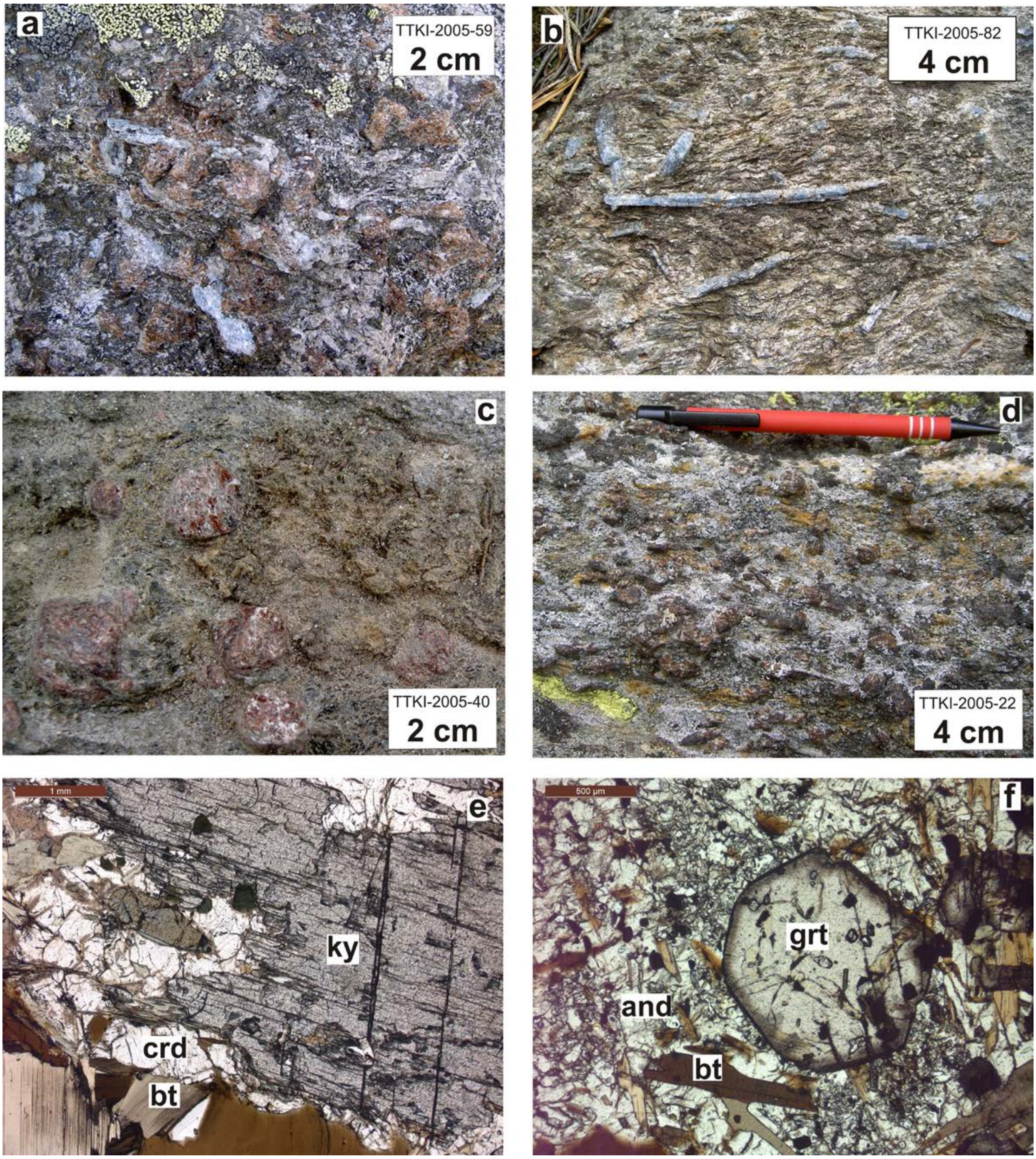


Fig. 16. Porphyroblastic rocks in Tuntsa: a) kyanite–staurolite gneiss; b) long kyanite crystals in biotite-rich gneiss; c) garnet crystals; d) staurolite crystals; e) reaction ky + bt = crd (+K^+) in the rock in Fig. 16b; f) euhedral garnet surrounded by andalusite.

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

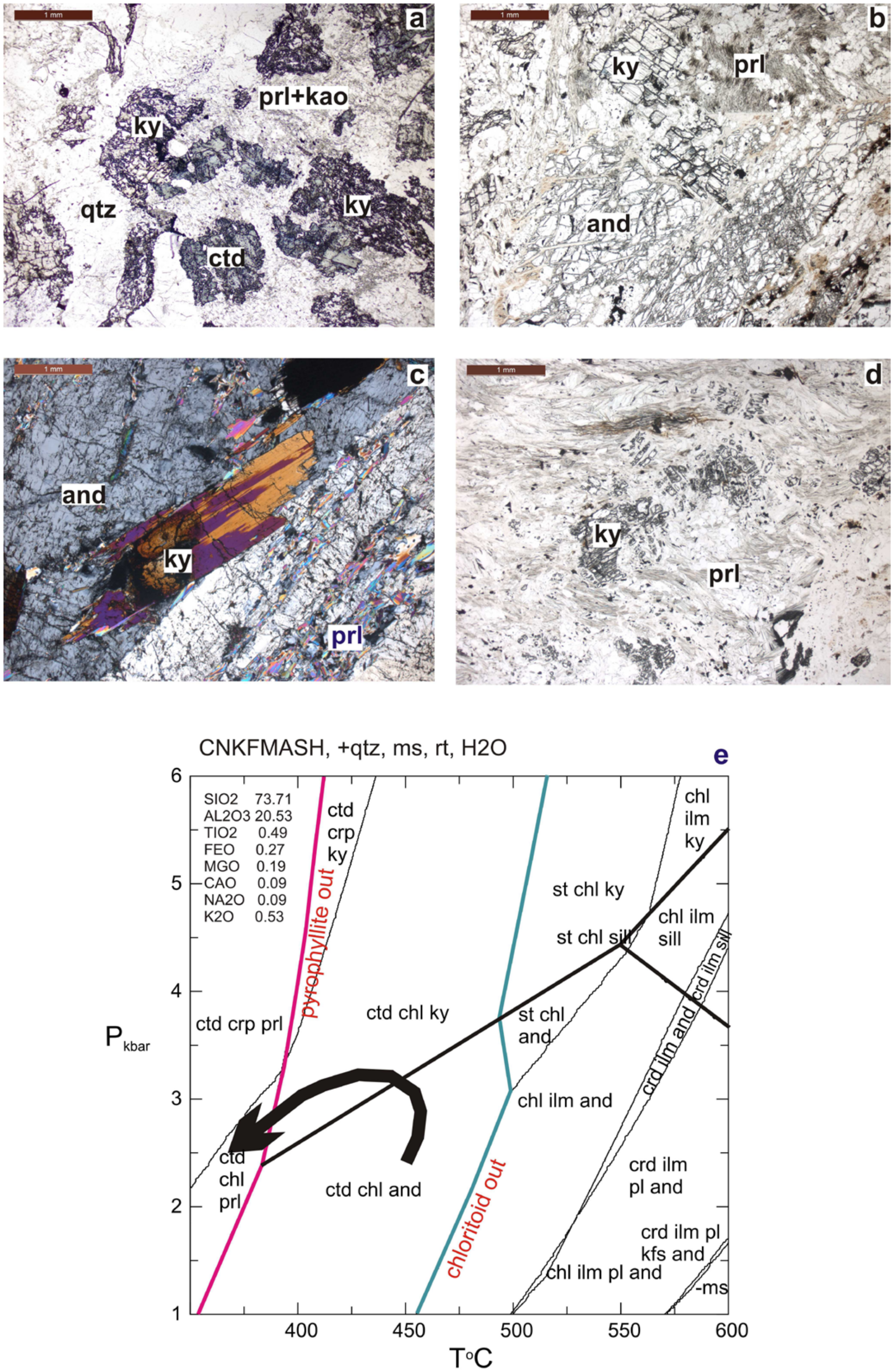


Fig. 17. Textures in the Hokkalampi kyanite quartzite in the North Karelia schist belt, northing 6973008, easting 650051: a) coexisting chloritoid and kyanite; b) andalusite and kyanite in textural equilibrium; c) kyanite overgrowing andalusite, d) kyanite altering into pyrophyllite; e) a PT pseudosection 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.

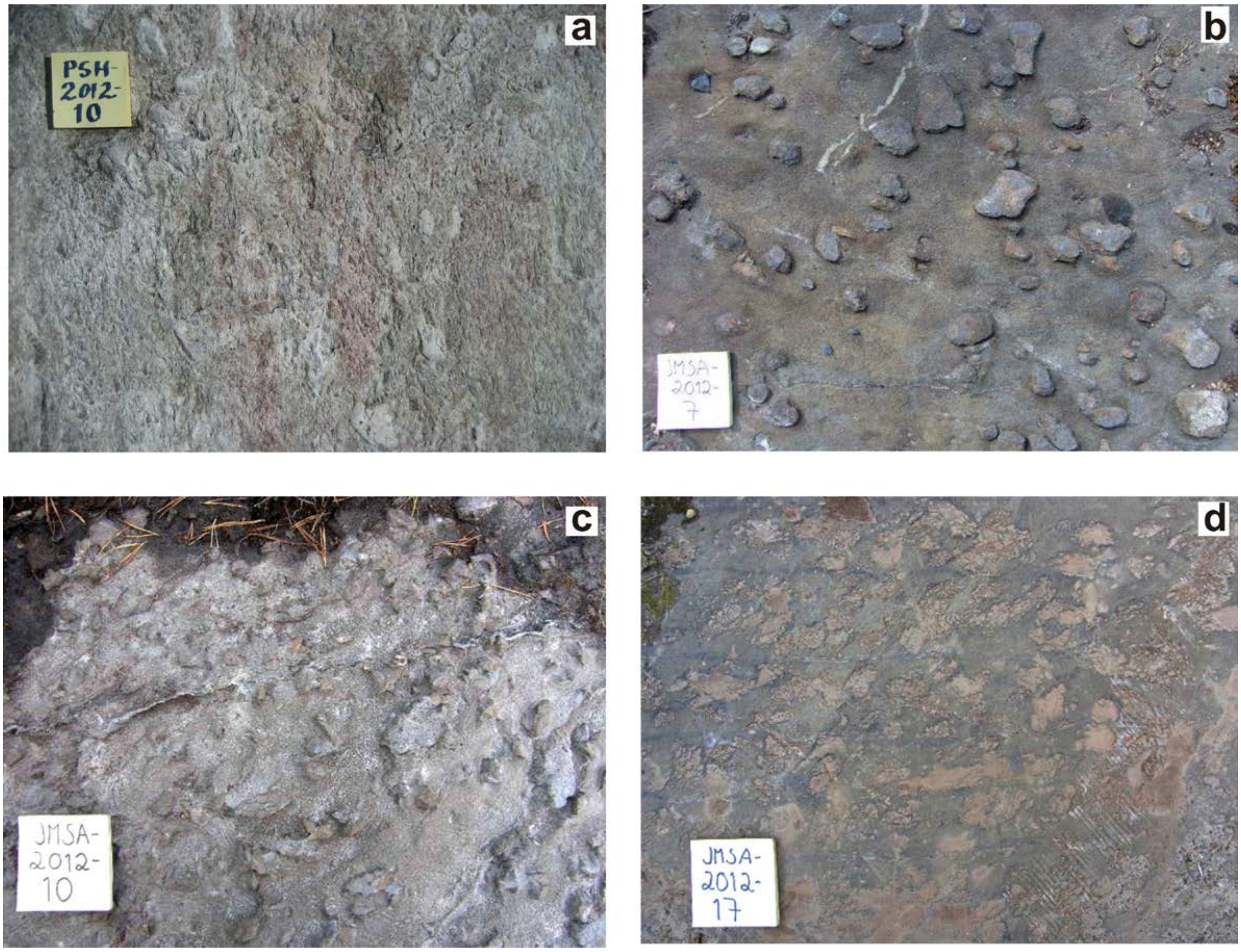


Fig. 18. Schists of the North Karelia schist belt: a) kyanite and andalusite (pink) bearing quartzite, Hokkalampi quarry, northing 6973008, easting 650051; b) andalusite porphyroblasts, exposure JMSA-2012-4, northing 6908080, easting 673135; c) andalusite and staurolite porphyroblasts, exposure JMSA-2012-10, 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

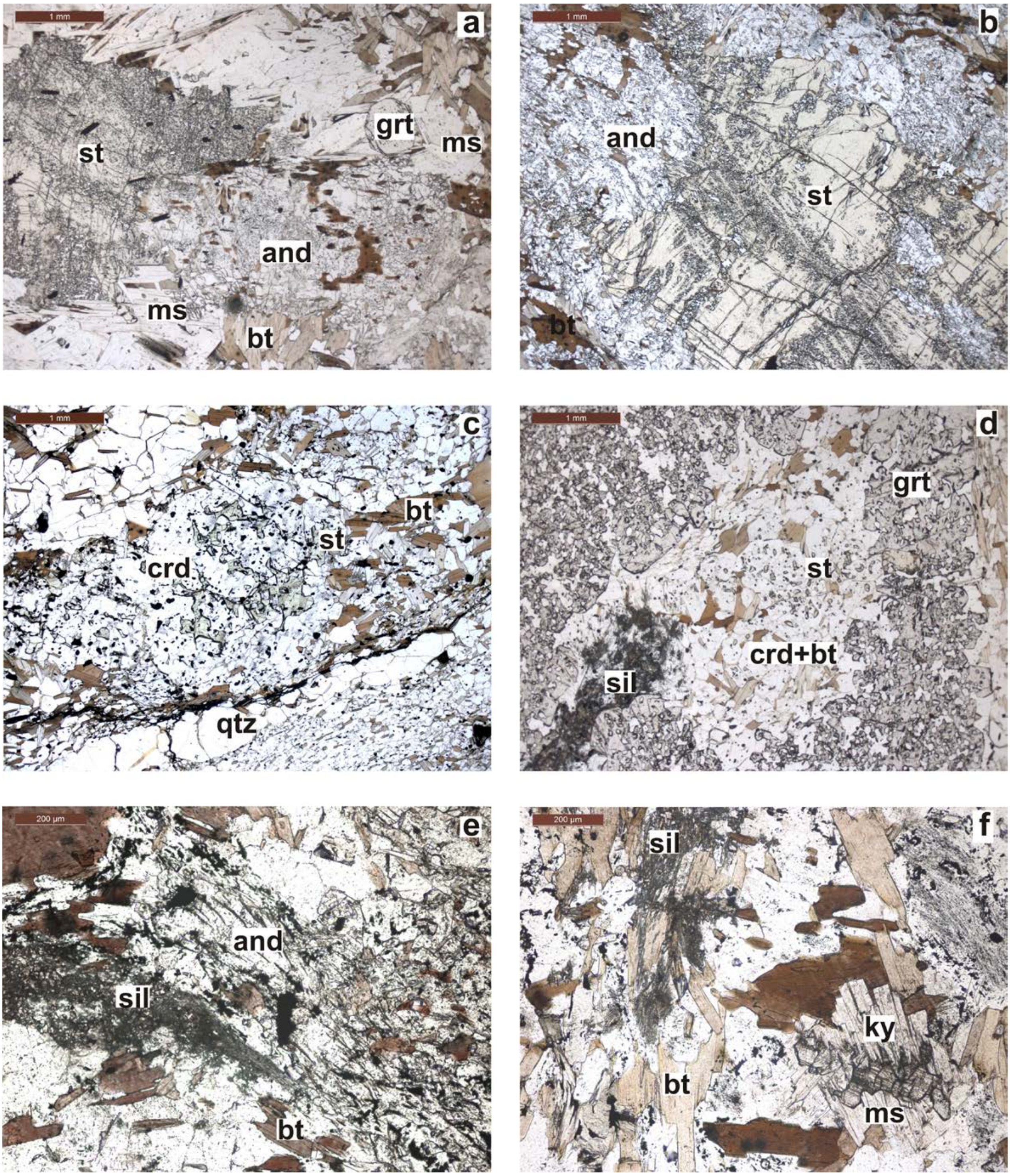


Fig. 19. a) Coexisting staurolite and andalusite, euhedral garnet overgrowing micas, in the southern part of the North Karelia schist belt, exposure JMSA-2012-4, northing 6908080, easting 673135; b) an andalusite corona on staurolite, exposure JMSA-2012-10, northing 6894074, easting 677559; c) staurolite 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.

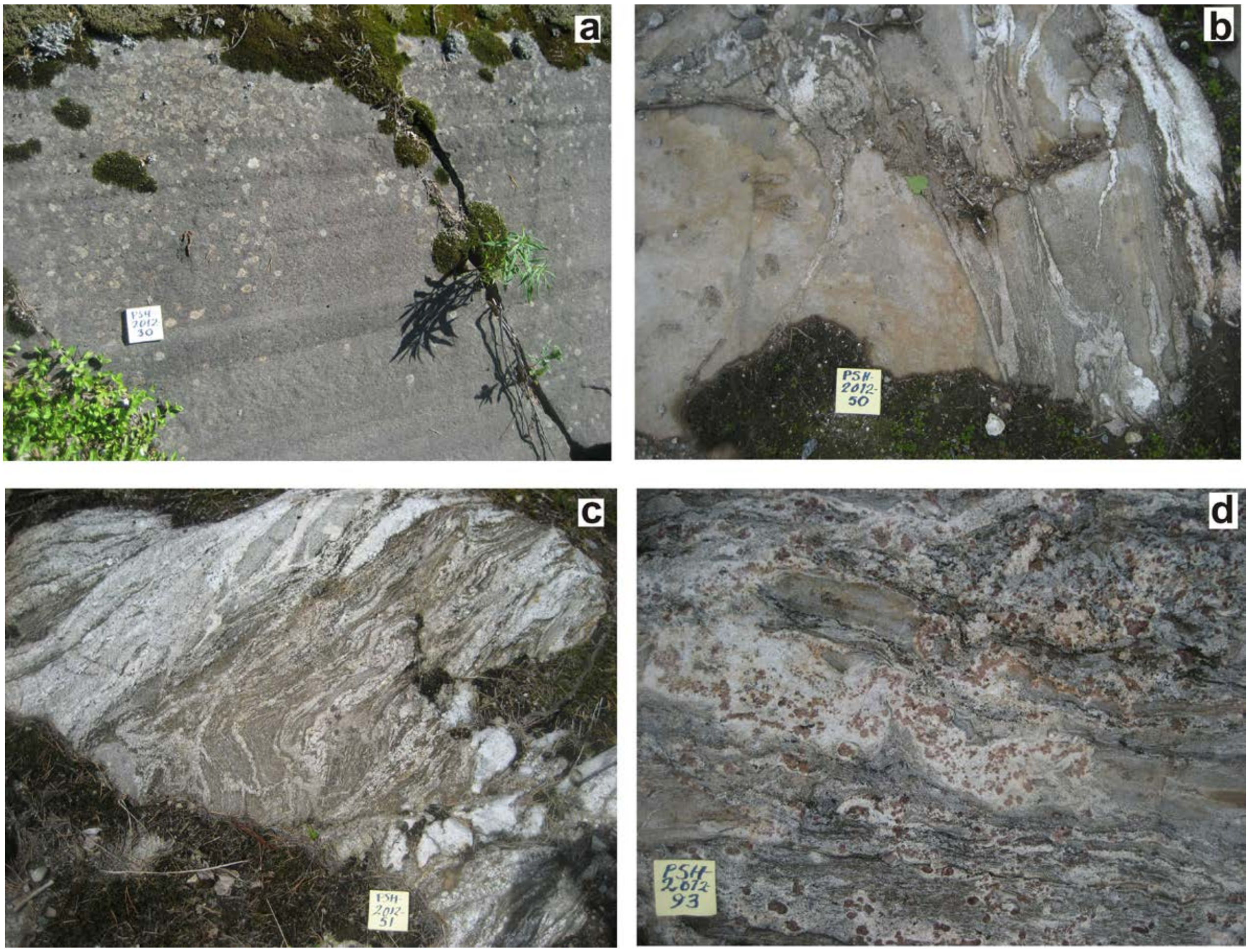


Fig. 20. The gradual increase in metamorphic grade in the Outokumpu area from a) a bedded monotonous metagreywacke, exposure PSH$-2012-30, northing 7064405, easting 350570 to b) the onset of melting in a metagreywacke, exposure PSH$-2012-50, northing 6919095, easting 579808, to c) diatexitic migmatite, 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,

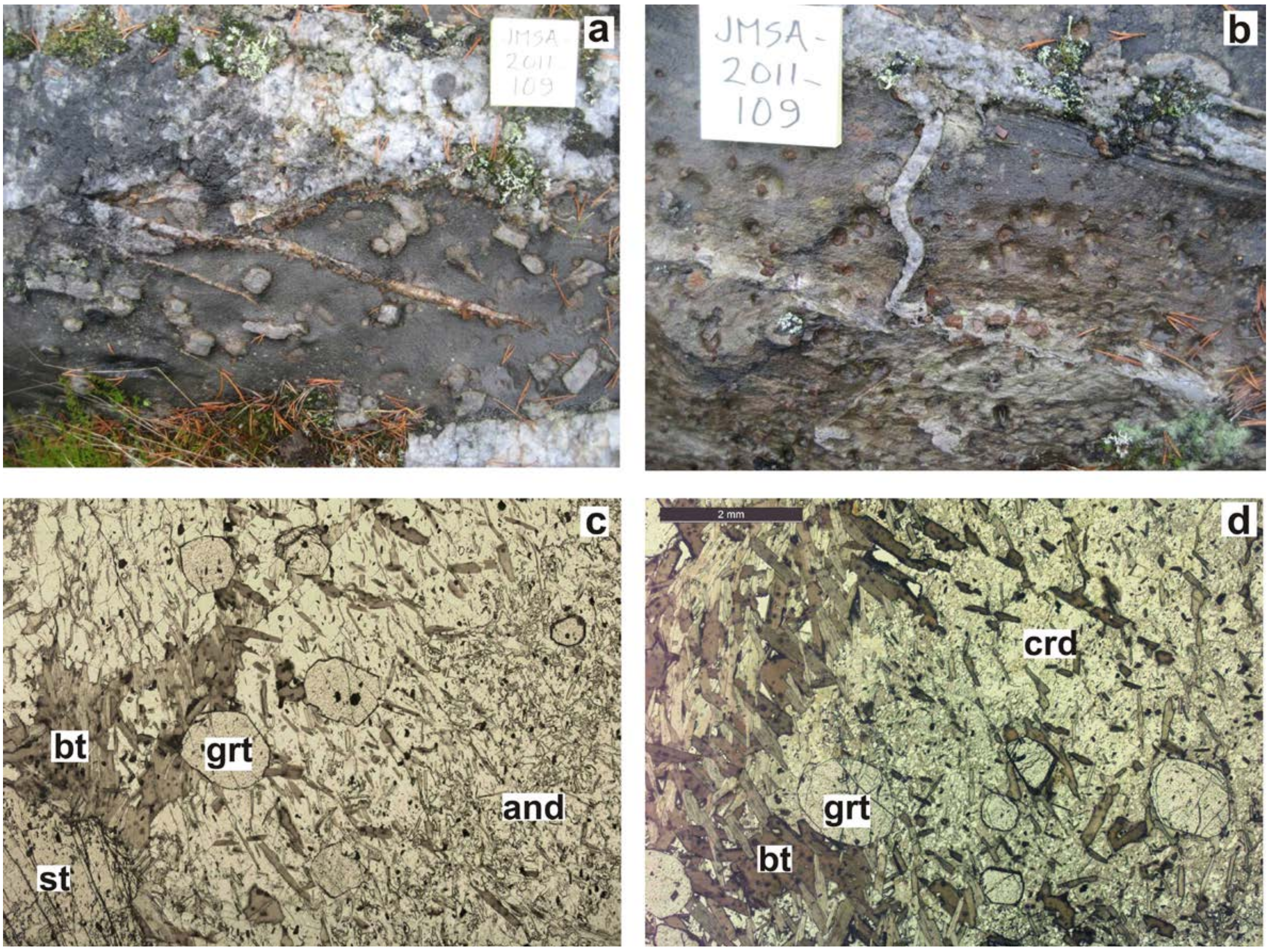


Fig. 21. Porphyroblastic schist in the Kiiminki belt: a) andalusite porphyroblasts; b) andalusite, staurolite and cordierite porphyroblasts; c) garnet overgrowing andalusite and biotite; d) garnet overgrowing cordierite and biotite. Exposure JMSA-2011-109, northing 7211739, easting 477829. The edge of 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

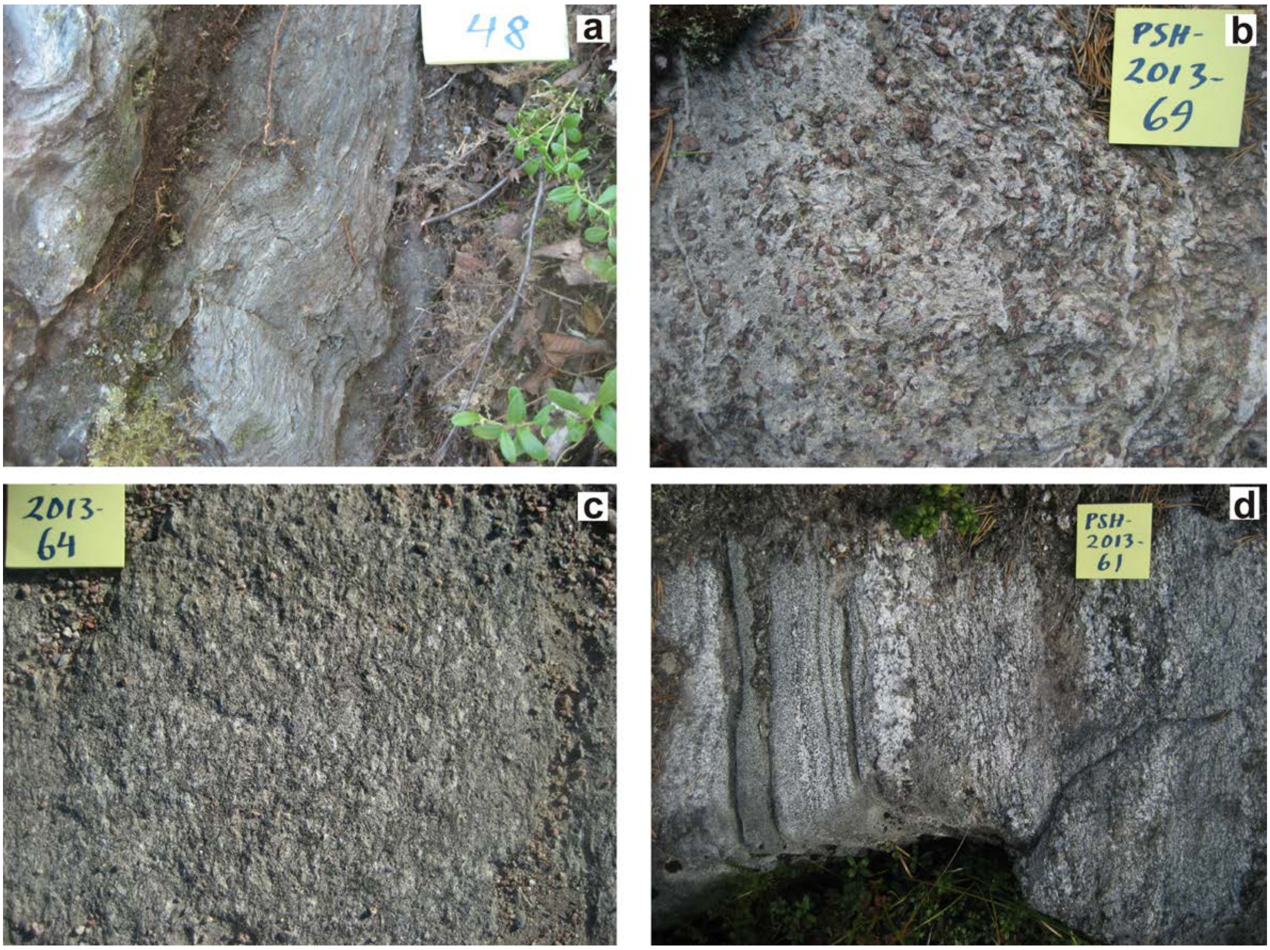


Fig. 22. Increase in metamorphic grade in the schists and gneisses of the Kuusamo belt: a) fine-grained green-schist facies schist, exposure PSH$-2013-48, northing 7328316, easting 602221; b) garnet-staurolite gneiss, exposure PSH$-2013-69, northing 7335733, easting 556385; c) sillimanite gneiss, exposure 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 north-eastern 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

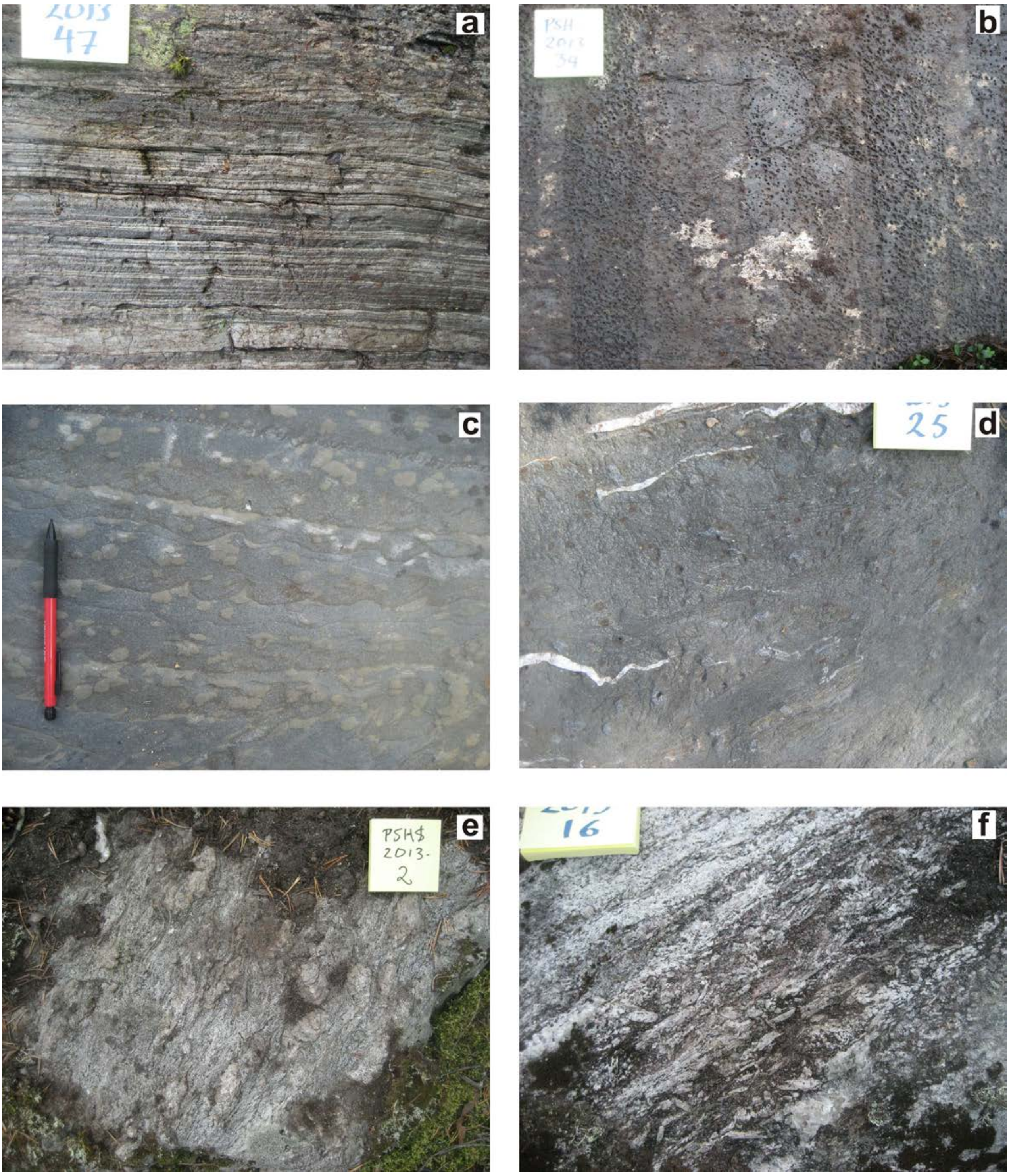


Fig. 23. Increase in metamorphic grade in the schists and gneisses of the Peräpohja belt: a) greenschist facies metapelitic schist in the southern part of the belt, exposure PSH$-2013-47, northing 7305406, easting 395843; b) cordierite-bearing schist in the western part of the belt, exposure PSH$-2013-34, 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.

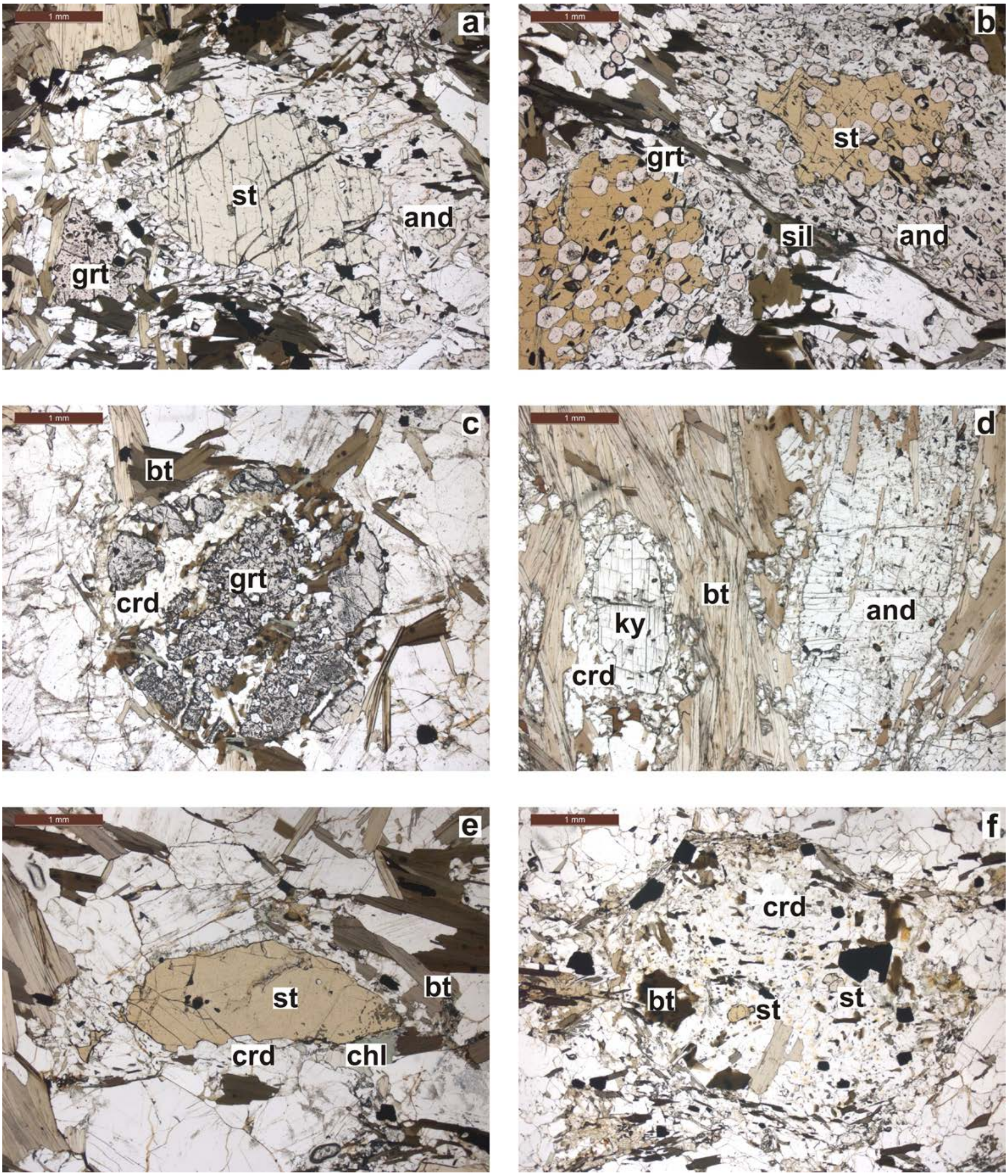


Fig. 24. Textures in metapelitic gneisses of the Rovaniemi area: a) staurolite altered from rims into andalusite, exposure PSH$-2013-8, northing 7368491, easting 450674; b) staurolite altered from rims into andalusite, both minerals overgrown by euhedral garnet grains, exposure PSH$-2013-5, northing 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.

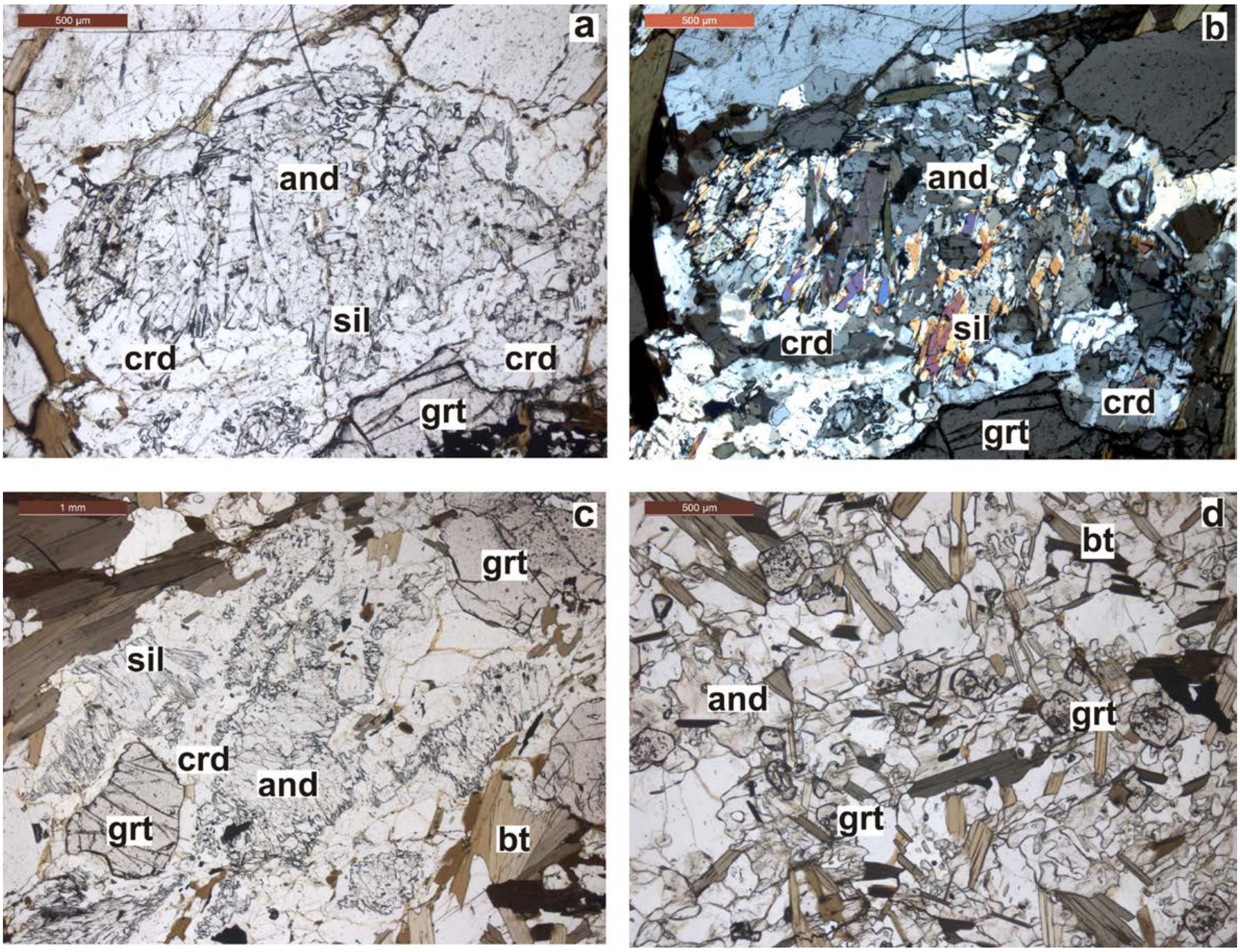


Fig. 25. Textures in metapelitic gneisses of the Rovaniemi area: a, b) a cordierite rim around andalusite overgrown by sillimanite, exposure PSH$-2013-16, northing 7379324, easting 455294; c) garnet and andalusite altered from rims into cordierite, andalusite on the right side of the figure is overgrown by sillimanite, exposure PSH$-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

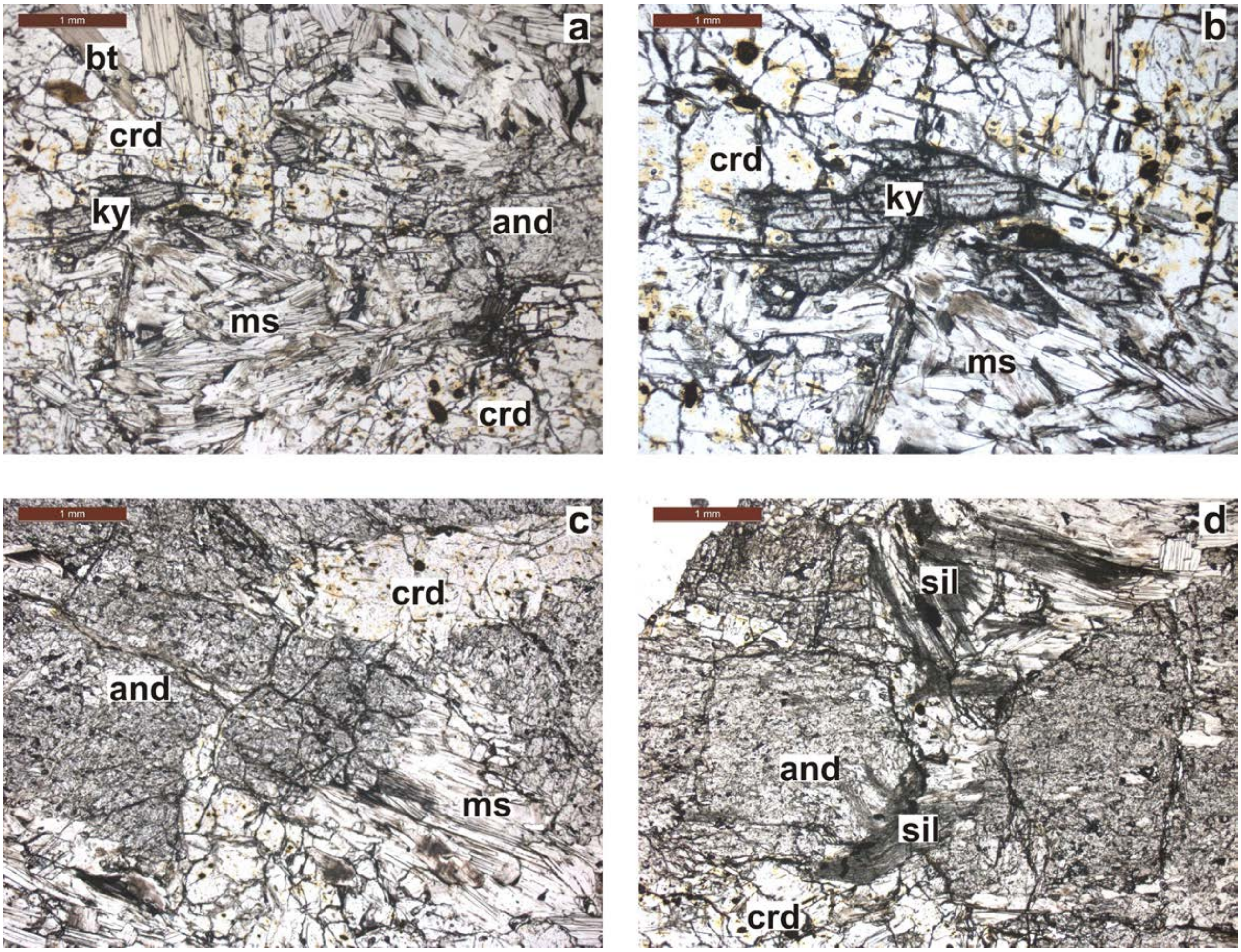


Fig. 26. Textures in the and-ky-sil rock in the northern part of the CLGC: a) Kyanite and andalusite altering into cordierite in the reaction and/ky + bt = crd + ms; b) a detail of kyanite surrounded by cordierite in Fig. 26a; c) andalusite surrounded by cordierite and muscovite; d) fibrolitic sillimanite 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.

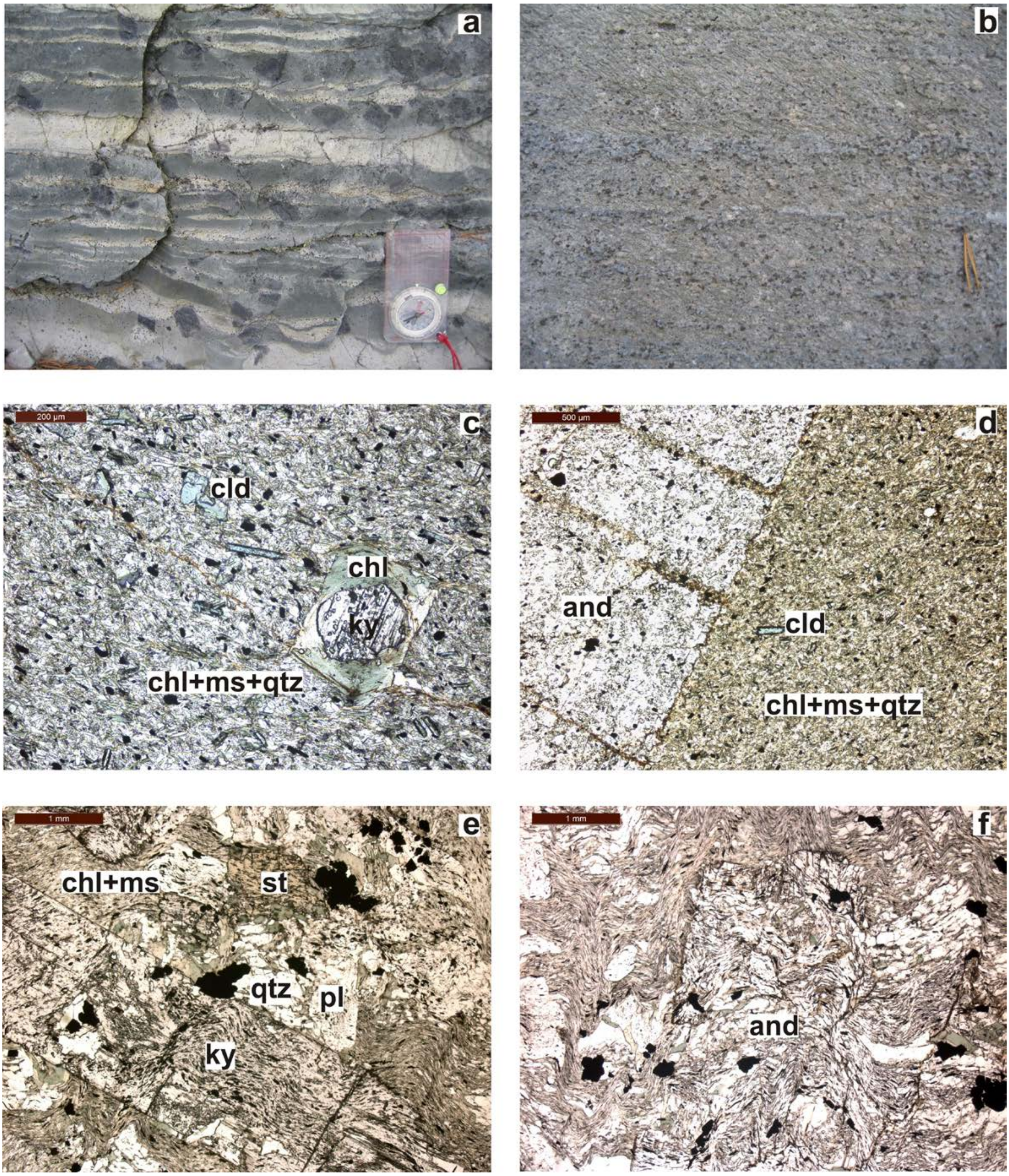
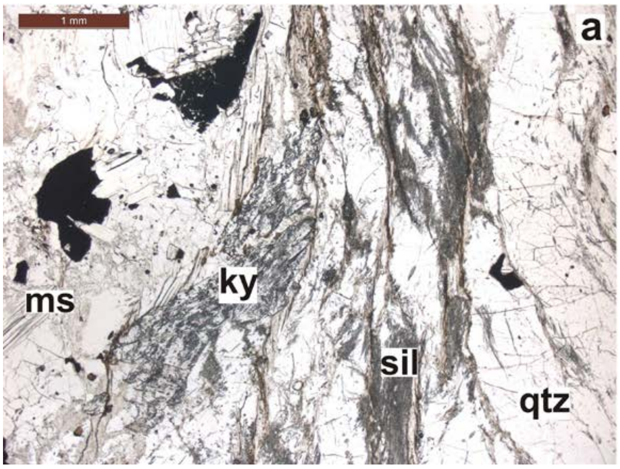


Fig. 27. Metapelites east of Sodankylä: a) andalusite schist, exposure PSH$-1998-1, northing 7480094, easting 487183; b) kyanite gneiss, PSH$-1999-72, northing 7482432, easting 511203; c) chloritoid and kyanite altered from rims into chlorite; d) andalusite in the matrix consisting of chlorite, muscovite, 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.



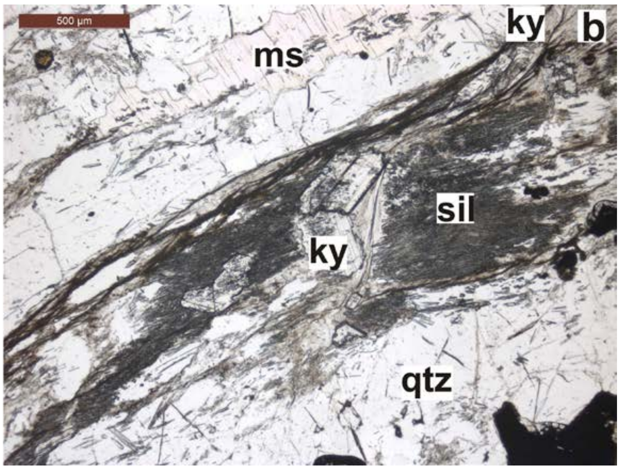


Fig. 28. a, b) Kyanite-bearing quartz rock at Kelottijärvi, exposure PSH$-2013-110, northing 7615214, easting 293529. Fibrolitic sillimanite is mostly crystallized along the cleavage planes, overgrowing the more randomly oriented kyanite. Coordinates are given using the EUREF-FIN (UTM35) system.

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

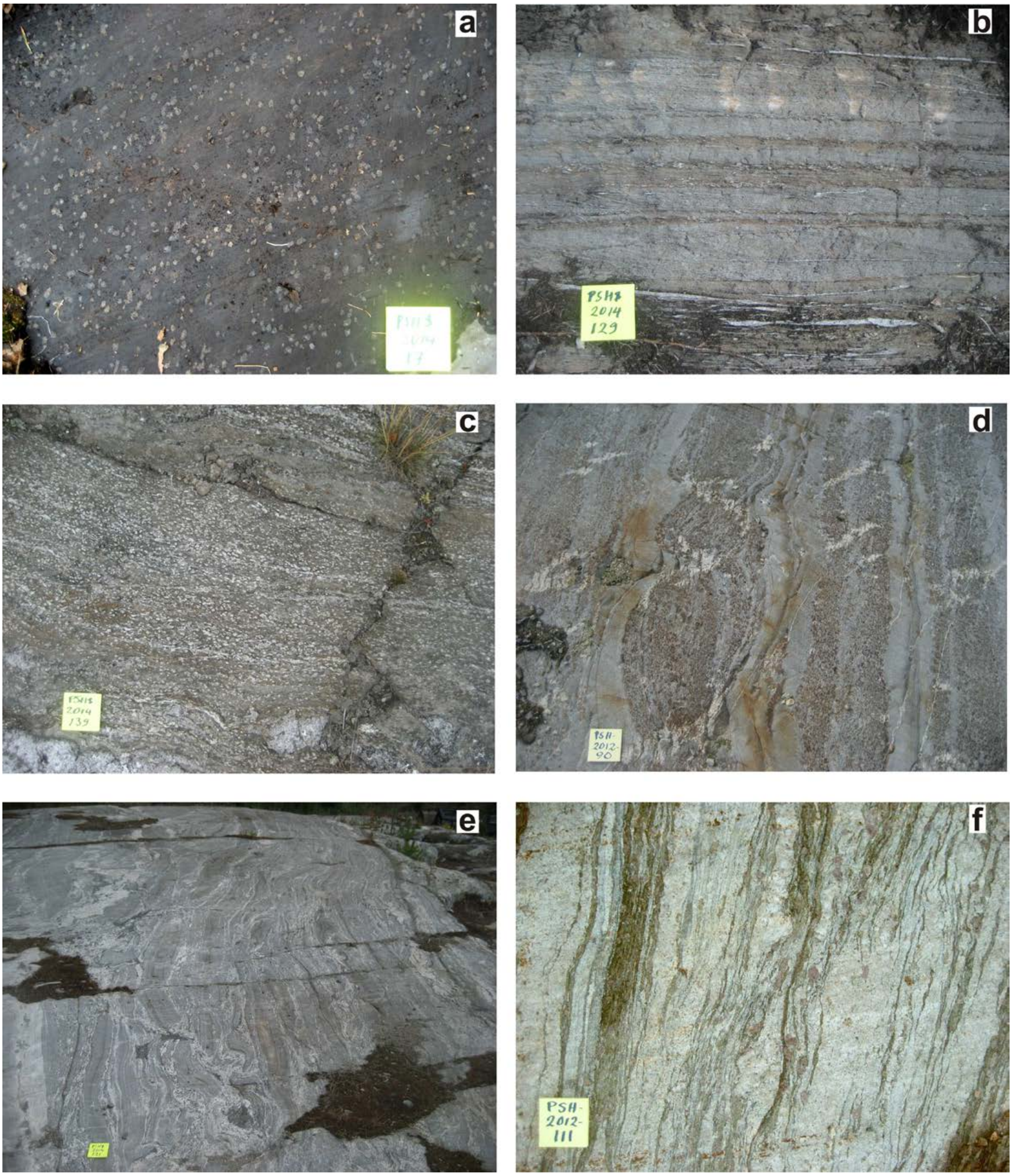


Fig. 29. Field photos showing the increase in metamorphic grade from andalusite schists to diatexitic migmatites in the Southern Finland Subprovince: a) andalusite schist in the Häme belt, area 26, exposure PSH$-2014-17, northing 6779224, easting 287484; b) andalusite schist south of Sysmä, area 297, exposure PSH$-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

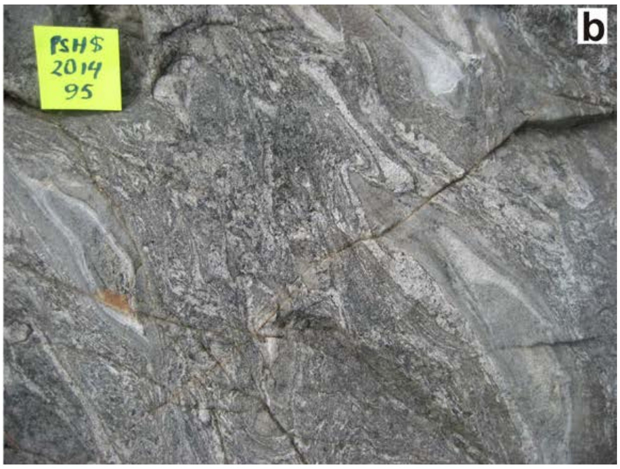


Fig. 30. Well-preserved schist within migmatites in the eastern part of the Uusimaa belt: a) bedding and sillimanite pseudomorphs in a schist, area 25, exposure PSH$-2014-93, northing 6729723, easting 422866; b) migmatite, area 24, exposure PSH$-2014-95, northing 6734225, easting 418934. The distance 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

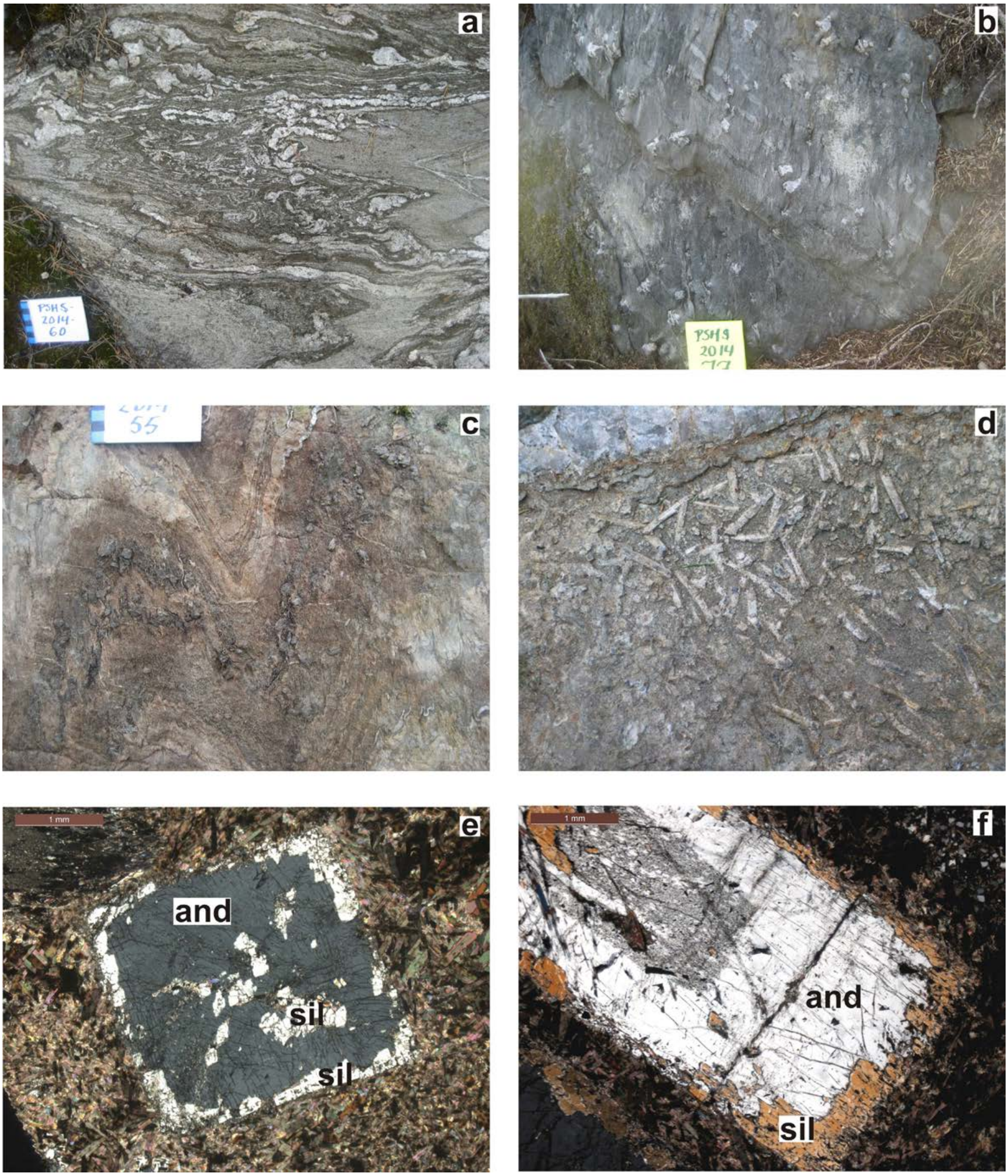


Fig. 31. Migmatites and schists of the Pirkanmaa and Tampere belts: a) a typical metatexitic folded migmatite of the Pirkanmaa belt, area 30, exposure PSH\$-2014-60, northing 6782358, easting 302659; b) andalusite grains growing along the S2 axial plane, which is at a high angle with the S0 bedding; 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.

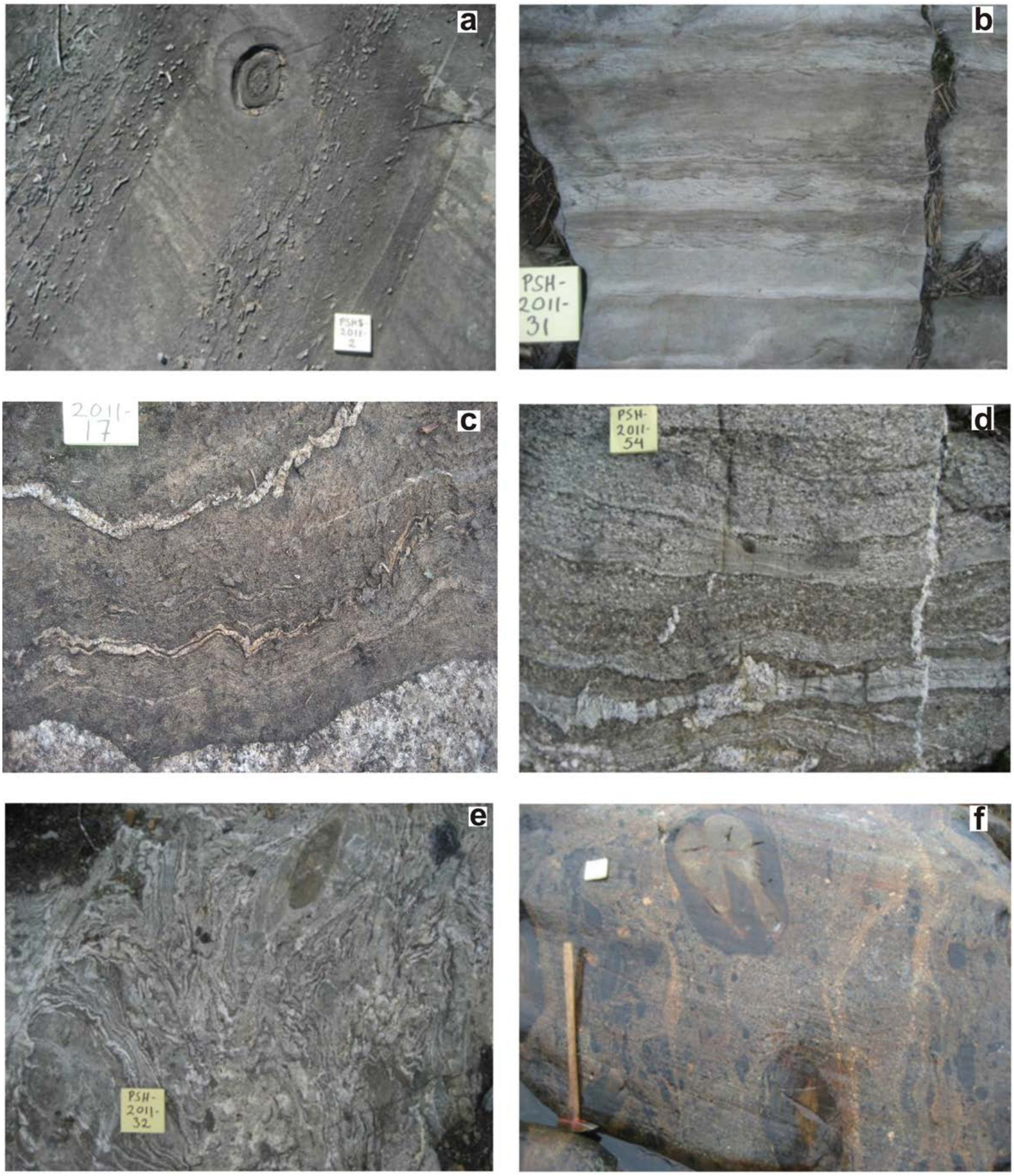


Fig. 32. Metamorphic zoning in the Pohjanmaa belt: a) andalusite porphyroblasts in a schist with a calc-silicate concretion, area 107, exposure PSH$-2011-2, northing 7032726, easting 318913; b) ripple marks in a bedded metagreywacke, area 108, exposure PSH$-2011-31, northing 7063777, easting 350616; 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.

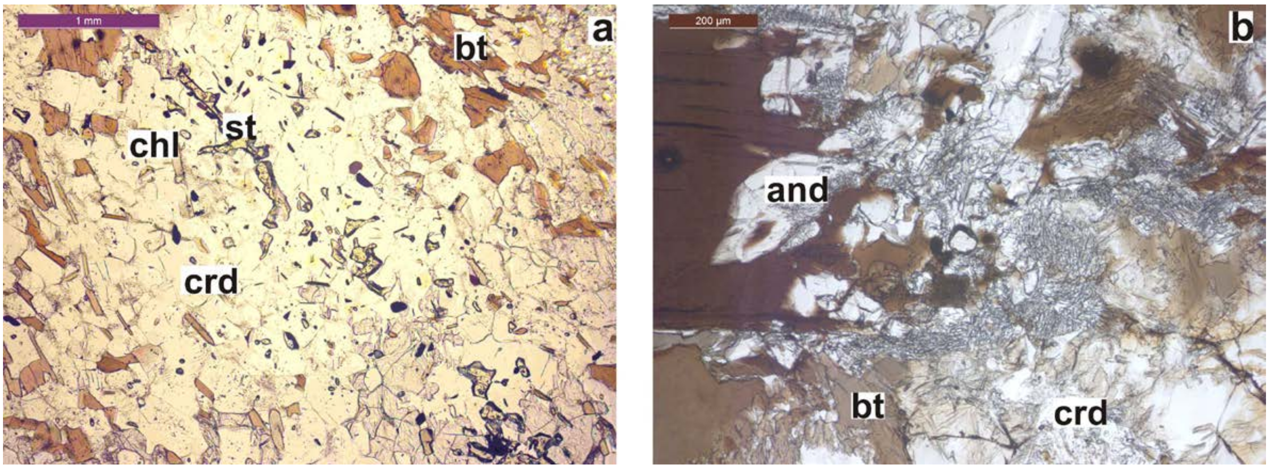


Fig. 33. Decompression and cooling reactions in schists and migmatites in Pohjanmaa: a) staurolite decomposing into cordierite, area 108, exposure JMSA-2011-100, northing 7110977, easting 340396; b) cordierite decomposing into andalusite and biotite, area 106, exposure PSH$-2011-12, northing 7031694,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

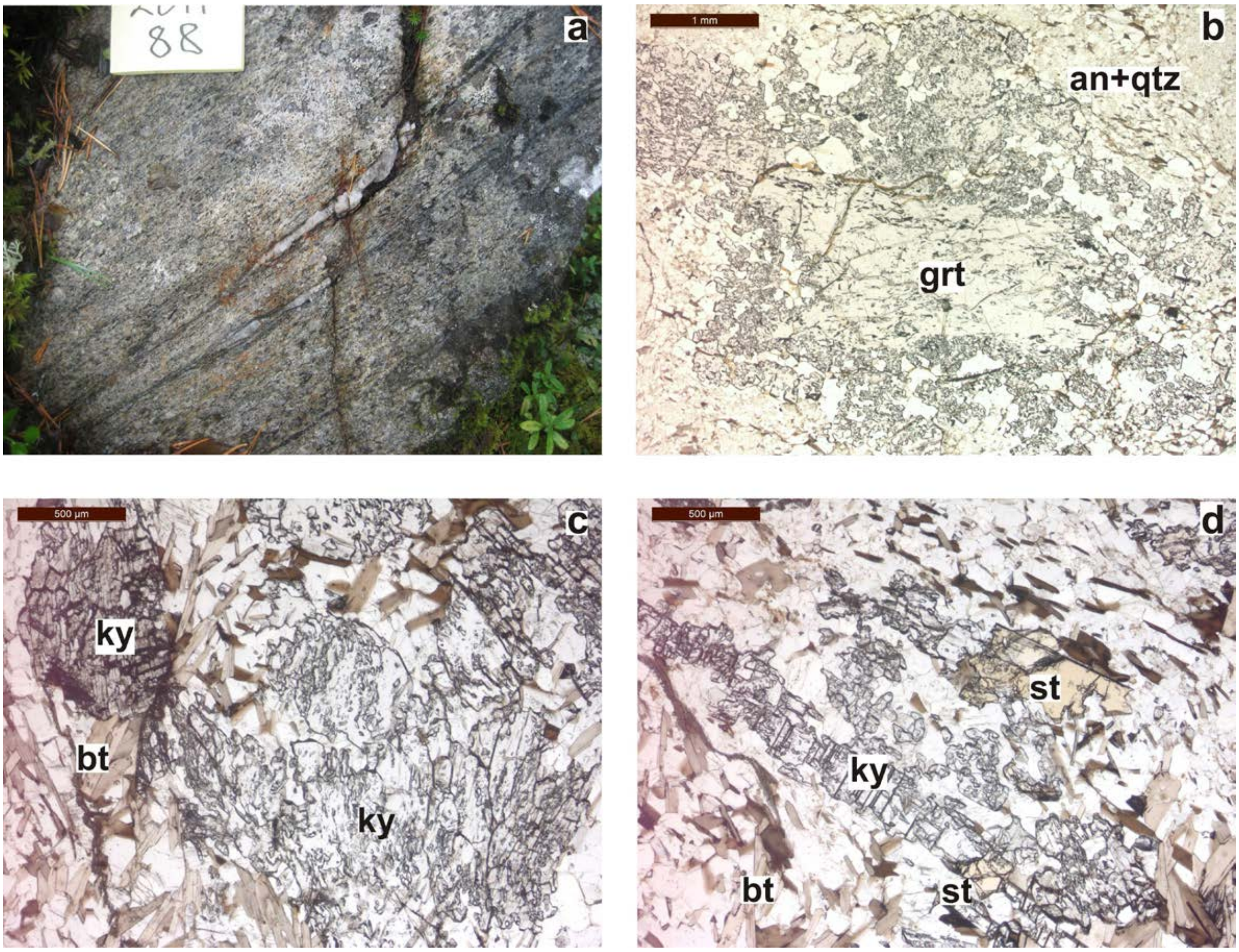


Fig. 34. a) Kyanite rock in the southern part of the Pohjanmaa belt, area 120, exposure PSH$-2011-88, northing 7010502, easting 355354; b) garnet decomposing into anorthitic plagioclase in a garnet-bearing layer without kyanite; c) kyanite grains; d) coexisting kyanite and staurolite. The edge of the 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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