

STRUCTURAL ANALYSIS AND METAMORPHISM OF PALAEOPROTEROZOIC METAPELITES IN THE SEINÄJOKI- ILMAJOKI AREA, WESTERN FINLAND

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The Palaeoproterozoic Svecofennian bedrock of the Seinäjoki–Ilmajoki area, western Finland, is largely composed of porphyroblastic metapelites. In the area, the regional metamorphic grade increases towards the southwest. Over a distance of 15 km, andalusite mica schists gradually grade into migmatitic garnet-cordierite-sillimanite mica gneisses with a facies-series of the andalusite-sillimanite type. Five regional metamorphic zones are present: andalusite, sillimanite-muscovite, sillimanite-K-feldspar, cordierite-K-feldspar and garnet-cordierite-K-feldspar.

The primary layering (S_0) of the mica schists is deformed by an isoclinal fold phase (F_2), which is synchronous with the main metamorphic phase and the growth of micas. S_1 is very weak and subject to interpretation. The S_2 schistosity is deformed by intense late-metamorphic F_3 and F_{3b} folds, which have formed under slightly different metamorphic conditions: practically no metamorphic micas have grown parallel to axial planes while within F_{3b} folds there are a few granitic veins parallel to these planes. The F_3 and F_{3b} folds probably belong to one phase. S_2 dominates in the mica schists while S_3 and S_{3b} dominate in the mica gneisses. The metapelites are also deformed by younger minor fold phases (F_4 and F_5). A composite schistosity ($S_0 \pm S_1 \pm S_2 \pm S_3$ or S_{3b}) commonly occurs in the metapelites.

The peak of regional metamorphism has been associated with the intrusion of 1.89–1.88 Ga old tonalite plutons. Geothermometric estimates for regional metamorphism are c. 730 °C at an assumed pressure of 5 kbar. Neosomes in the high-grade mica gneisses occur as patches rather than as elongated, narrow veins. Garnet coexists with cordierite, but the minerals are rarely in equilibrium. Muscovitization and the formation of retrogressive andalusite did not occur in the high-grade mica gneisses, but there is minor kyanite indicating that the crust probably underwent near-isobaric cooling. The area of highest-grade regional metamorphic conditions contains a post-kinematic mangeritic quartz monzonite (1.87 Ga), which has a narrow granulite-grade contact aureole. The chemical composition of biotites in the metapelites varies as a function of metamorphic zoning, but the chemical composition of metapelites remains mostly unchanged.

Key words: metapelite, structural analysis, metamorphism, zoning, chemical composition, electron probe data, P-T conditions, Paleoproterozoic, Svecofennian, Seinäjoki, Ilmajoki, Finland

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INTRODUCTION

The acceptance of the concept of a dynamic tectonic environment for regional metamorphism has led to the understanding that metamorphic rocks follow complex paths in P-T space, reflecting burial, heating and exhumation (e.g. Brown 1993). The tectonic setting for regional metamorphism is usually collision between continental elements and/or arcs that has resulted in substantial crustal thickening. The metamorphic style, cooling paths and relative age of deformation can vary within an orogenic belt. Therefore, in the research of ancient orogenic belts, regional studies of the structural succession and metamorphism of their exhumed crustal portions are necessary.

Metamorphically, the Palaeoproterozoic Svecofennian (1.9–1.8 Ga) crust of southern Finland is divided into two parts (Korja et al. 1994): (1) a northern part characterised by tonalite migmatites, in which the metasedimentary rocks are often psammitic, and (2) a southern part characterised by potassium granite migmatites, in which the metasedimentary rocks are usually metapelitic with excess aluminium in relation to alkalies and calcium. Both zones underwent intense metamorphism ~1885 Ma ago, but the southern part is also overprinted by a strong thermal pulse 1.86–1.81 Ga in age (Korsman et al. 1984, Ehlers et al. 1993). There is an E–W-trending tectonometamorphic discordance between these parts (Vaasjoki & Sakko 1988). Several studies of deformation in relation to metamorphism in southern Finland have been published (e.g. Kilpeläinen 1988, 1998, Väisänen et al. 1994, Koistinen et al. 1996).

The Seinäjoki–Ilmajoki area, in western Finland, is situated north of the discordance, and mostly comprises high-temperature/low-pressure porphyroblastic metapelites (Neuvonen 1961, Mäkitie & Lahti 1991). These rocks exhibit poly-phase deformation and increase in regional metamorphic grade towards the mangeritic quartz monzonite stock of Luopa in the southwest (Fig. 1). The tectonometamorphic evolution of the Seinäjoki–Ilmajoki area is interesting because the area also contains various granitoids, rare-element pegmatites and Sb-, Sn- and Au-mineralizations

(e.g. Mäkitie & Lahti 1991).

The purpose of this paper is to give an overview of the deformation and metamorphism of the area, which is based on a study of the metapelites.

GEOLOGICAL SETTING

The Seinäjoki–Ilmajoki area belongs to the Palaeoproterozoic accretionary arc complex of central and western Finland (1.90–1.87 Ga), which is a part of the Svecofennian domain (Korsman et al. 1997). The major part of the study area lies in the Svecofennian Pohjanmaa schist belt (also known as the Ostrobothnian schist belt), which includes orogenic granitoids (Fig. 1, see also Laitakari 1942). The main rock types of the study area are pelitic schists and gneisses (Mäkitie et al. 1991). In the northeast, the metapelites are fine-grained andalusite mica schists, in the central part they are sillimanite-bearing mica gneisses, and the southwestern parts comprise migmatitic garnet-cordierite-sillimanite mica gneisses. Mica schists and mica gneisses commonly have psammitic intercalations that in places dominate over the metapelites. Metavolcanic rocks are present in minor amounts.

In the northeast, near the town of Seinäjoki, pegmatite granites, rare-element pegmatites and Sb-mineralizations are common (Pääkkönen 1966, Borodaev et al. 1983, Oivanen 1983, Alviola 1989) (Fig. 1). Foliated tonalites (1882±9 Ma) and granodiorites, which are associated with regional metamorphism, and which belong to the large Central Finland Granitoid Complex, occur in the southern part of the study area (Mäkitie & Lahti 1991). In the south there are also granites and the post-kinematic, almost undeformed, porphyritic olivine-pyroxene quartz monzonite stock of Luopa (1871±1 Ma) (Mäkitie & Lahti 1991).

The regional metamorphic grade of the rocks increases to the southwest, from conditions of low-temperature amphibolite facies to lower granulite facies with a facies-series of low-pressure intermediate type (Fig. 1). The highest-grade mineral assemblages are found in the overprinting contact aureole of the quartz monzonite of Luopa. The

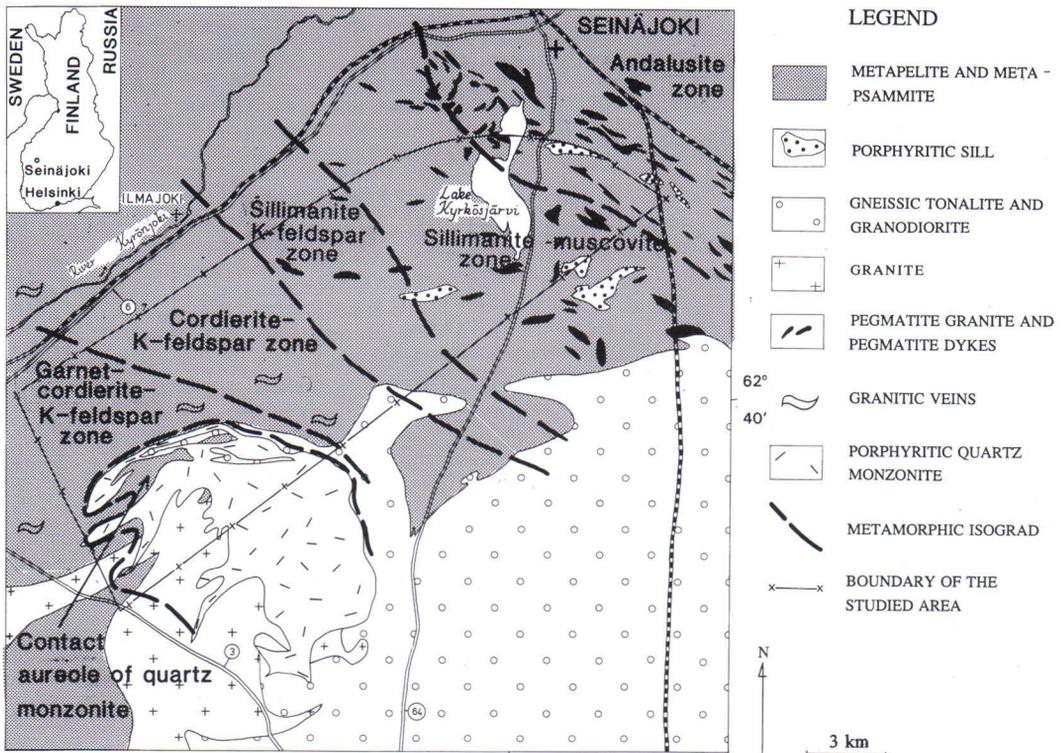


Fig. 1. Geological map of the Seinäjoki–Ilmajoki area with metamorphic zones. Simplified after Lahti and Mäkitie (1990) and Mäkitie et al. (1991).

metapelites show polyphase folding. This high-grade metamorphic terrain and the quartz monzonite lie in an area that has a weak positive Bouger anomaly compared to the areas of mica schist (see Kiviniemi 1980).

RESEARCH METHODS

Polyphase fold-analysis followed principles set out in Hopgood and Bowes (1972), Koistinen (1981) and Kilpeläinen (1988). The relation of mineral growth to deformation phases was studied using precepts established by Zwart (1962) and Powell (1979). Temperature conditions were estimated with the geothermometers of Holdaway and Lee (1977) and Perchuk (1989).

Mineral analyses were made from polished thin sections using electron microprobes (JEOL-JCXA 733) at the University of Oulu and at the Geolog-

ical Survey of Finland (GTK). The main elements as well as Rb, Sr, Ba, Zn, Zr, Cr, V, Th, U, Cs and La in whole rock analyses were determined by XRF (Y with OES) in the Chemistry Laboratories of the Rautaruukki Company and GTK.

The mineral abbreviations used are after Kretz (1983).

STRUCTURAL SUCCESSION

A structural map of the study area is shown in Fig. 2a. The northern part of the area represents the southern limb of a regional east – west-trending antiform described by Pääkkönen (1966). A schematic, 3D-sketch of the foliations and the folded planar rock units of the northern and central study area is given in Fig. 2b. The primary layering (S_0) is best seen in the north, being increasingly obliterated towards the southwest because of the ris-

ing metamorphic grade (Mäkitie 1990). Note that in the north, and near the hinge of the regional antiform, S_0 , S_1 , S_2 and S_3 have subparallel trends (Fig. 2b).

The dominant tight to isoclinal late-metamorphic folds (F_3 and F_{3b}) of the central and southern study area are disharmonic and in certain areas show uniformly dextral or uniformly sinistral features. The fold axes of F_3 and F_{3b} have similar trends (E-W) and are usually subparallel to the schistosity of the metapelites (Fig. 2a). The foliations usually dip steeply southwards. The central part contains a few individual folds with SE – NW-trending axial planes that, in relation to metamorphism, are similar in style to the F_3 and F_{3b} folds. The foliated tonalites in the south also display a SE – NW-trending lineation. Younger deformation phases (F_4 and F_5) are mostly seen in the mica schists. In the south, the Luopa quartz monzonite stock, which is post-kinematic in relation to the main deformation within the study area, deforms the surrounding mica gneisses and brecciates the granites.

Primary layering and D_1 deformation

The oldest planar structure is rare well-preserved primary layering (S_0), which occurs in andalusite-staurolite mica schists a few kilometres south of the town of Seinäjoki. This layering is composed of alternating thin beds of pelite (0.2–10 cm) and graded psammite (1–50 cm) (Fig. 3a). The S_0 layering is best preserved, when it is approximately perpendicular to the dominant schistosity (S_2) of the area. In places S_0 occurs as an indistinct trace discordant to S_2 . Elsewhere, it has been transposed parallel to the dominant schistosity.

The S_0 layering contains some intrafolial folds interpreted as F_1 . There is no mica growth parallel to S_0 or S_1 , but elongated post- D_1 andalusite is parallel to S_0 and S_1 (Fig. 3a).

D_2 deformation

The S_0 and S_1 planes are deformed by a tight to isoclinal F_2 fold phase, which has a well-developed synkinematic, metamorphic axial plane fo-

liation with associated biotite and muscovite growth (Fig. 3b). The S_2 schistosity forms the dominant foliation in the mica schists near the town of Seinäjoki. S_0 and S_1 are usually parallel to S_2 having been transposed on the limbs of isoclinal F_2 folds. These folds often have thickened hinges. Intersecting relations between S_0 and S_2 are seen in only a few outcrops (Fig. 3a). The S_2 schistosity is refracted where it intersects the pelitic and psammitic layers of S_0 . Where 20–50 cm thick psammitic beds occur the angle of refraction can be as much as 40°. However, the outcrops clearly exhibiting S_2 are mostly composed of thick units of homogeneous mica schists (see Fig. 4c). In places there are quartz veins parallel to S_2 . Only right-handed F_2 folds are found.

D_3 and D_{3b} deformations

During the D_3 deformation phase S_0 , S_1 and S_2 planes and F_2 fold axes were rotated to their present subvertical position (Fig. 2b). Associated late-metamorphic tight F_3 folds tilted the S_2 schistosity seen in the metapelites. The F_3 folds (Fig. 3c) are common in the sillimanite-muscovite-biotite gneisses 1–5 km to the south of the andalusite mica schists. The F_3 folds vary in size and plunge relatively gently eastwards. The trend of the S_3 crenulation cleavage is almost parallel to S_2 (Fig. 3d). Parasitic structures are common and fold hinges are usually not thickened. Narrow pegmatitic veins in these sillimanite-muscovite-biotite gneisses are folded by F_3 (Fig. 3c). Rarely mica segments occur in the F_3 fold crest, parallel to the axial plane. Folds in certain areas are regularly either uniformly sinistral or uniformly dextral.

Further southwest (15–25 km) of the town of Seinäjoki, folds resembling F_3 folds occur in the cordierite- and garnet-bearing mica gneisses (Fig. 3e). The relation of these folds to metamorphic growth is similar to that in the aforementioned sillimanite-muscovite-biotite gneisses: biotite follows the shape of the fold hinges (Fig. 3f). There is no growth of garnet or cordierite in the axial plane of the folded palaeosomes. These late-metamorphic folds observed in the southwest are distinguished by the author as F_{3b} , even though their

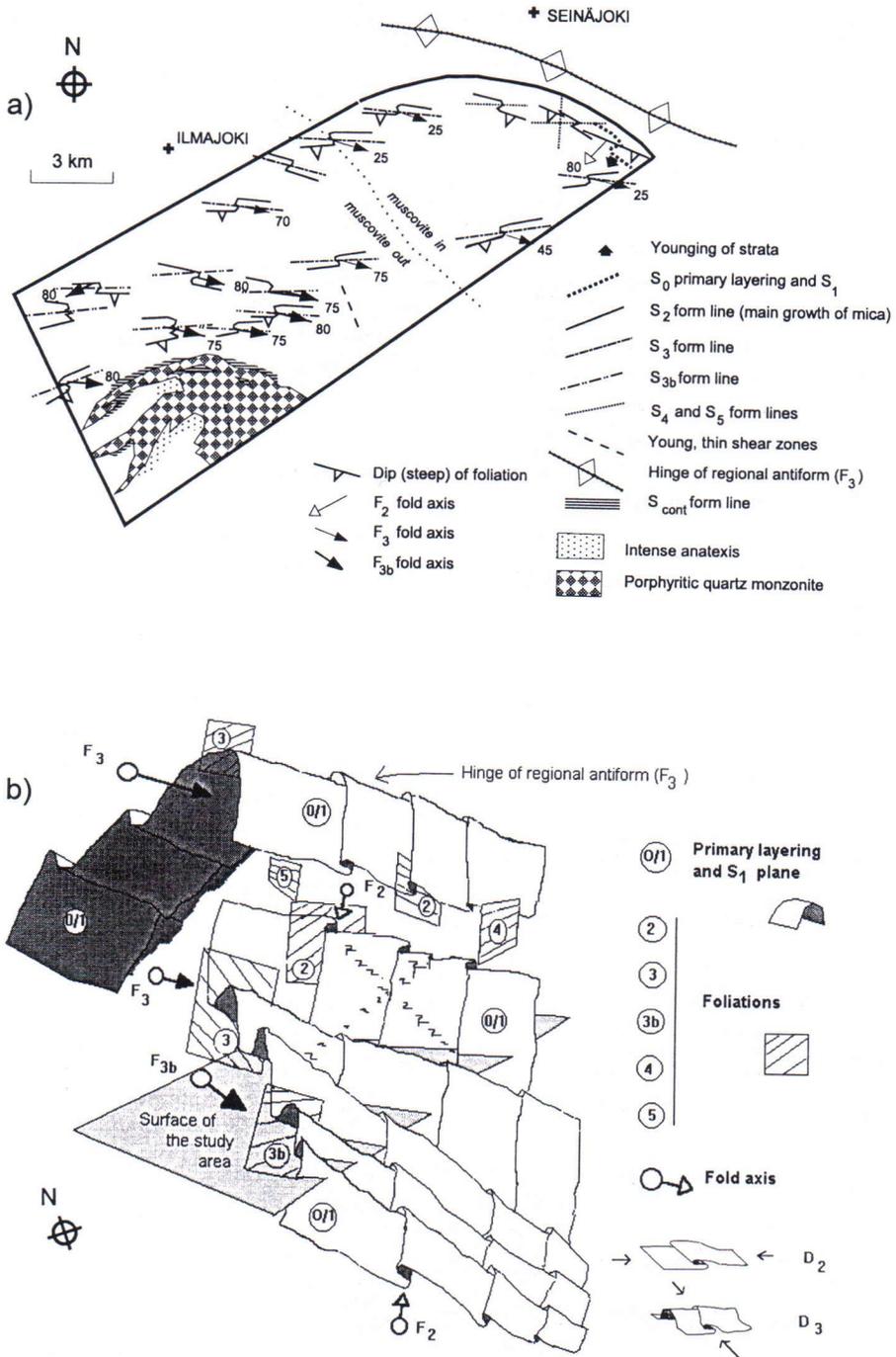


Fig. 2. a) Structural map of the Seinäjoki–Ilmajoki area with muscovite-out isograd. Note that the study area is bordered as in Fig. 1. b) 3D – sketch of the folded planar rock units in the northern and central part of the study area. Foliations are shown schematically by ruled planes.

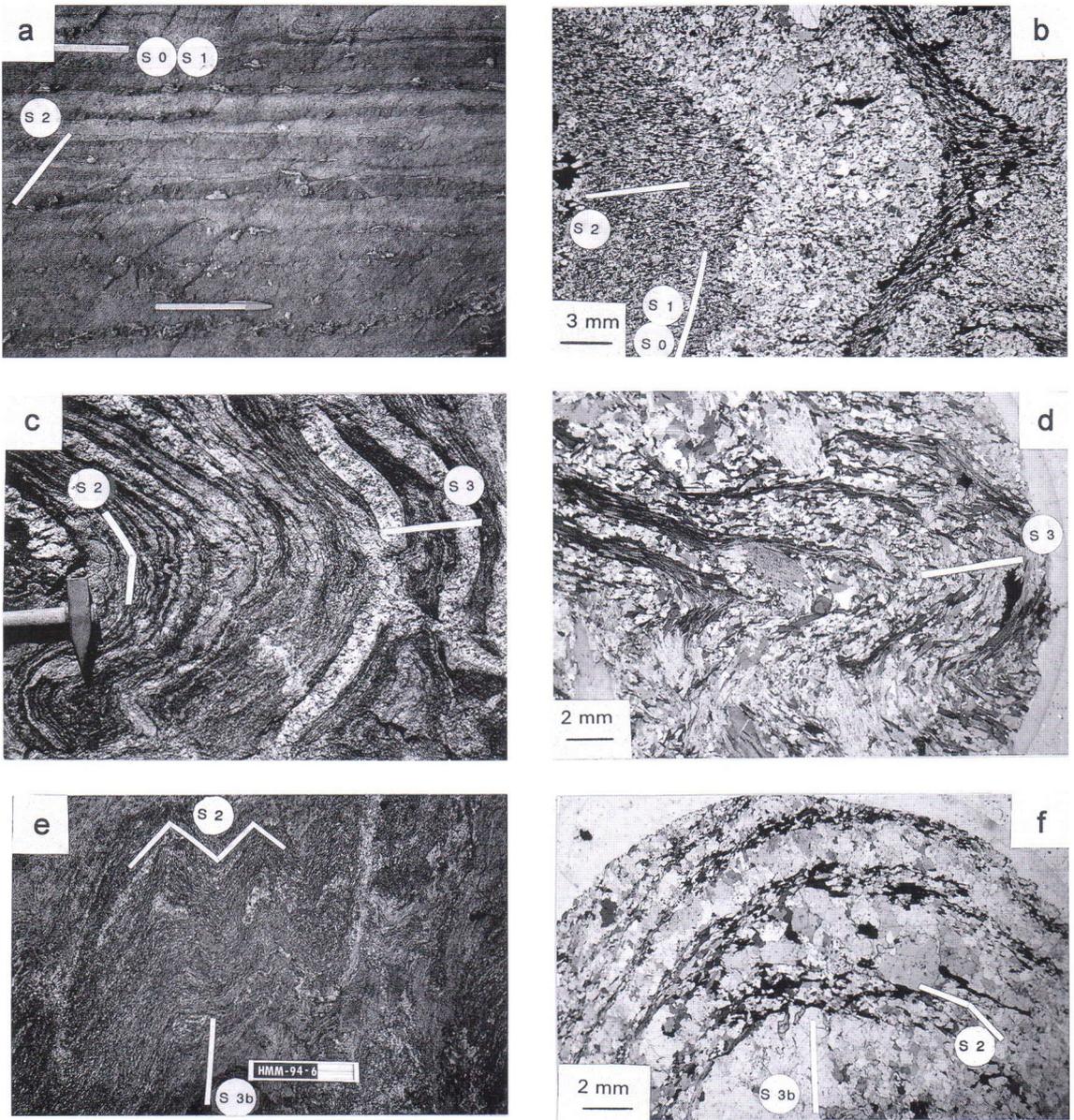


Fig. 3. Structures in metapelites of the Seinäjoki–Ilmajoki area. Coordinates are given as in the base coordination of Finnish maps. a) Andalusite-staurolite mica schist containing primary sedimentary layering (S_0) and parallel weak S_1 . The S_2 schistosity intersects S_0 and S_1 . Elongated light-coloured knots are andalusite porphyroblasts mostly parallel to S_0 and S_1 . Andalusite zone. Length of the pen is 15 cm. $x = 6960480$, $y = 2443960$. b) Photomicrograph of F_2 fold crest, which includes synkinematic metamorphic axial plane foliation (S_2) with growth of biotite and muscovite. Mica schist from the andalusite zone. $x = 6960480$, $y = 2443950$. c) Late-metamorphic fold (F_3) in muscovite-sillimanite (fibr.)-biotite gneiss. S_2 schistosity and narrow pegmatite veins are folded. Length of the blade of the hammer is 12 cm. Sillimanite-muscovite zone. $x = 6958680$, $y = 2443670$. d) Photomicrograph of F_3 fold crest in muscovite-sillimanite (fibr.)-biotite gneiss. There is no mineral growth parallel to S_3 . Sillimanite-muscovite zone. $x = 6958690$, $y = 2443680$. e) Folded (F_{3b}) K-feldspar-garnet-cordierite-sillimanite mica gneiss containing granitic neosomes in the axial plane. Cordierite-K-feldspar zone. Length of code bar is

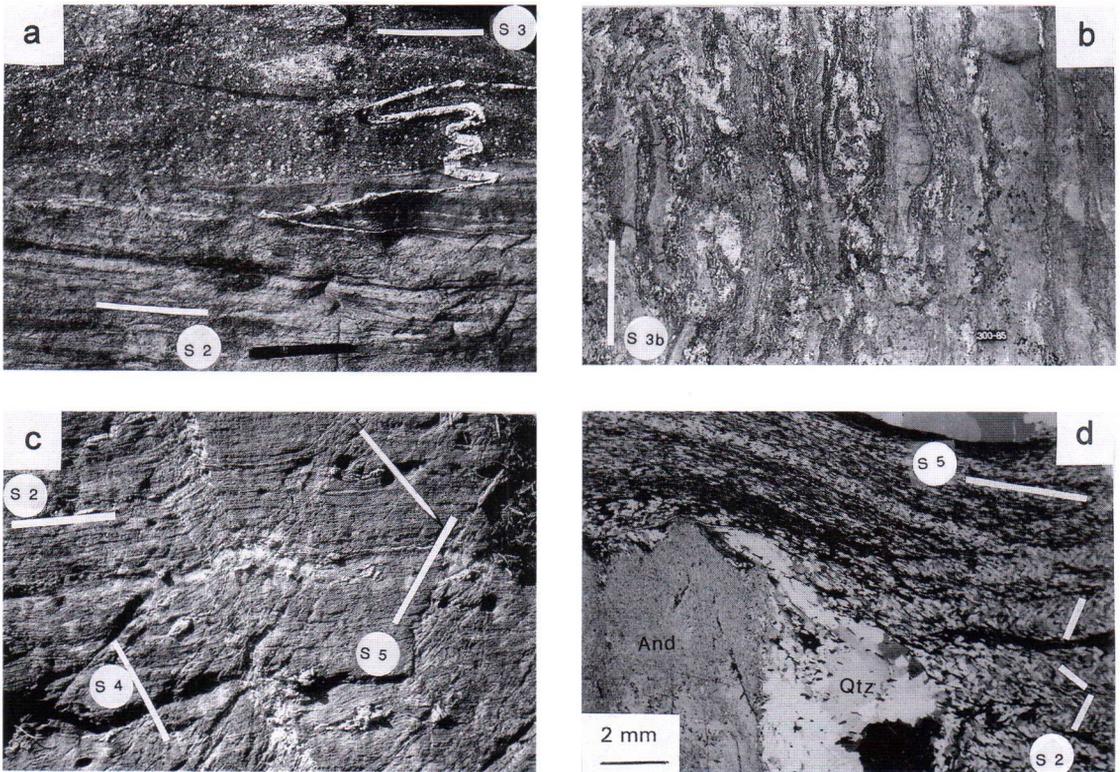


Fig. 4. Structures in metapelites of the Seinäjoki–Ilmajoki area. Coordinates are given as in the base coordination of the Finnish maps. a) Contact between plagioclase porphyrite sill (upper part of the figure) and mica schist shows a small angle with S_2 . Both rocks and a narrow pegmatite are foliated (S_3). The strikes of S_2 and S_3 are subparallel. Andalusite zone. Length of the black pen is 14 cm. $x = 6960780$, $y = 2443720$. b) Typical garnet-cordierite-sillimanite mica gneiss, in which S_0 , S_1 , S_2 and S_{3b} form a composite schistosity. Neosomes occur as patches rather than as elongated, narrow veins. Garnet-cordierite-K-feldspar zone. Length of code bar is 8 cm. $x = 6951390$, $y = 2424410$. c) Typical andalusite mica schist of the Seinäjoki area. D_4 and D_5 have deformed S_2 , which is parallel to S_0 and S_1 . Knots are andalusite porphyroblasts. Length of the pen is 13 cm. Andalusite zone. $x = 6960780$, $y = 2443750$. d) Photomicrograph of strongly crenulated (S_5) mica schist, which contains a pre- D_5 andalusite (And) porphyroblast. Note the quartz (Qtz) in pressure shadow of andalusite porphyroblast and that S_2 schistosity is folded. Andalusite zone. $x = 6960470$, $y = 2433940$.

fold axes are usually subparallel with those of F_3 folds (see Fig. 2a).

Intersections of S_2 and S_3 are rare in the mica schists, which deform plastically. This is a reflection

of the regional structure: the limb of a large antiform in which S_2 and S_3 are subparallel (Fig. 2b). However, one example of the relationship between S_2 and S_3 is shown in Fig. 4a, where S_2 in isoclinally folded (F_2) mica schist has a small angle with a plagioclase porphyrite sill, c. 1.89 Ga old (Mäkitie & Lahti 1991). Here, both rocks have been later deformed by D_3 forming S_3 foliation that is, in practice, parallel to S_2 . A narrow pegmatite was intruded after D_2 and was folded by F_3 (Figs. 3c and 4a). There are also pegmatite boudins parallel to the dominant foliation in mica

15 cm. $x = 6951760$, $y = 2427250$. f) Photomicrograph of F_{3b} fold crest of K-feldspar-garnet-cordierite-sillimanite mica gneiss. Note that metamorphic differentiation has formed microscopic layers and that the S_2 schistosity is folded. Cordierite-K-feldspar zone. $x = 6951780$, $y = 2427240$.

schist. These pegmatites have a similar tectonic position to the pegmatite in Fig. 4a; they are deformed by D_3 and due to the parallelism of S_3 and S_2 the pegmatites are nearly conformable with the schists. However, some pegmatite dykes also cut the trend of the S_3 schistosity. Usually pegmatites are subconformable with the schists in the Seinäjoki area (Nurmela 1985).

No intersections between the F_3 and F_{3b} folds are found. Due to the subparallel trend of their fold axes (see Fig. 2a) and their relation to metamorphism (see Figs. 3c – 3f), the F_3 and F_{3b} folds probably belong to one regional-scale deformation phase. There are two main differences between F_3 and F_{3b} . Firstly, garnet- and cordierite-bearing granitic neosomes are more common in the axial planes of F_{3b} , indicating that there was a higher metamorphic temperature during folding in the southern part of study area. Secondly, the axes of F_{3b} are steeper than the axes of F_3 folds (Fig. 2a). The F_{3b} folds often have large (0.2–2.0 m) wavelengths and parasitic features. They are usually tight to isoclinal and disharmonic with, regionally, either a right-handed or a left-handed geometry; large parasitic fold structures can thus be determined. The psammitic beds in the area containptygmatic, narrow granitic veins. As a result of the formation of isoclinal F_3 and F_{3b} the foliation of the garnet-cordierite-sillimanite mica gneiss usually represents a composite schistosity (Fig. 4b).

D_4 and D_5 deformations

The structures formed by the D_2 and D_3 were locally deformed by young, in practice post-metamorphic fold phases (F_4 and F_5), which occur as narrow bands in the andalusite mica schists and as gentle, disturbing folds in the sillimanite (fibr.)-muscovite-biotite gneisses. These folds are kinks (Fig. 4c) but usually the hinge lines, especially as seen in microscopic scale, are curved. The density of the occurrence of these folds varies, and in some outcrops D_5 is so dominant that a S_5 schistosity, composed of mica-rich and mica-poor stripes, is formed (Fig. 4d). The east-west trending S_5 schistosity is younger than the north-south trending S_4 schistosity. The pegmatites were buck-

le-folded during D_5 .

Some very narrow (< 2 mm) late shear planes found in the garnet-cordierite-sillimanite mica gneisses intersect S_3 and S_{3b} with no associated mineral growth other than minor retrogressive chlorite after biotite. There are both brittle and ductile shears that usually trend NW-SE. Similar shears occur sporadically in the quartz monzonite of Luopa. The relationship of the shear zones to D_4 and D_5 is not clear.

D_{cont} deformation

The emplacement of the post-kinematic quartz monzonite stock of Luopa deformed the surrounding mica gneisses resulting in a schistosity, here called the contact schistosity (S_{cont}). Previously folded and migmatized mica gneisses were strongly deformed and reoriented, and now they include the contact schistosity (Fig. 5a). In the mica gneisses, the S_{cont} schistosity occurs up to about 20 m from the contacts with the quartz monzonite. The trend of S_{cont} follows that of the intrusive contacts and is strongest between wide (3–25 m), parallel apophysic dykes, which are most common in the northwestern part of the stock (see Lahti & Mäkitie 1990, Mäkitie et al. 1991).

METAMORPHISM

The regional metamorphic zones of the study area are, from northeast to southwest, andalusite, sillimanite-muscovite, sillimanite-K-feldspar, cordierite-K-feldspar and garnet-cordierite-K-feldspar (Fig. 1). In addition, the overprinting granulite-grade contact aureole around the Luopa quartz monzonite occurs in the south.

The changes in mineral composition of metapelites in the metamorphic zones are shown in Table 1. The average modal compositions and the average chemical compositions of the metapelites in the metamorphic zones are shown in Tables 2 and 3. The relationships between the mineral assemblages and chemical whole rock compositions were studied using the AFM-diagrams of Thompson (1957) (Fig. 6). These diagrams also show the

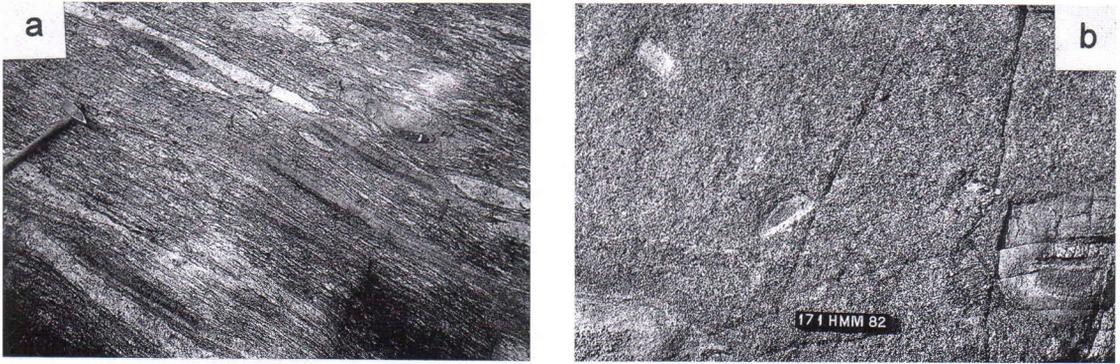


Fig. 5. Structures in metapelites of the contact aureole of the quartz monzonite stock of Luopa. Coordinates are given as in the base coordination of Finnish maps. a) Strongly deformed (S_{cont}) K-feldspar-garnet-cordierite-sillimanite mica gneiss 4 m from a wide quartz monzonite dyke. Contact aureole of Luopa quartz monzonite. Length of hammer is 50 cm. $x = 6949890$, $y = 2525740$. b) Intensively homogenized K-feldspar-garnet-cordierite mica gneiss 4 m from a wide quartz monzonite dyke. Contact aureole of the Luopa quartz monzonite. Length of code bar is 12 cm. $x = 6945140$, $y = 2424820$.

Table 1. Mineralogical changes in metapelites as a function of the metamorphic zoning in the Seinäjoki–Ilmajoki area.

	And zone	Sil-Ms zone	Sil-Kfs zone	Crd-Kfs zone	Grt-Crd-Kfs zone	Contact aureole
Quartz	_____	_____	_____	_____	_____	_____
Plagioclase	-----	_____	_____	_____	_____	_____
K-feldspar	_____	_____	--	_____	_____	_____
Muscovite	_____	_____	--	_____	_____	_____
Biotite	_____	_____	_____	_____	_____	_____
Tourmaline	-----	-----	-----	-----	-----	-----
Staurolite	-----	-----	-----	-----	-----	-----
Andalusite	_____	_____	_____	_____	_____	-----
Sillimanite	_____	-	_____	_____	_____	-----
Kyanite	_____	_____	_____	_____	-----	_____
Cordierite	_____	_____	_____	_____	_____	_____
Garnet	-----	_____	-----	_____	_____	_____
Hercynite	_____	_____	_____	_____	_____	-----
Orthopyroxene	_____	_____	_____	_____	_____	-----

positions of the chemical compositions of the studied biotites, cordierites and garnets (see Tables 4 and 5).

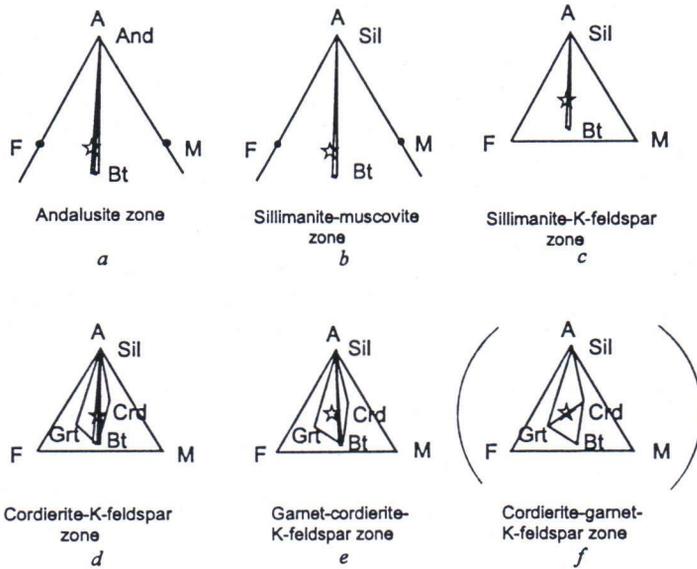
Andalusite zone

The metamorphic grade is lowest at the town of Seinäjoki, where andalusite mica schists and well-preserved sedimentary structures are common.

Mica schists usually occur as thick (1–15 m), homogeneous units, in which S_0 , S_1 and S_2 form a composite schistosity (Fig. 4c). Large, deformed porphyroblasts (\varnothing 0.5–2.5 cm) of andalusite are characteristic while this also occurs as grains elongated parallel to S_0 and S_1 (Fig. 3a). The mineral assemblage in these mica schists is muscovite-quartz-plagioclase-biotite-andalusite. The chemical composition of the mica schists favours the

Table 2. Average modal composition of metapelites as a function of metamorphic zoning in the Seinäjoki–Ilmajoki area. ‘Others’ include apatite, zircon, pinite, monazite etc. * = includes also plagioclase, + = occurs in small amounts, (r) = has retrograde origin.

	And zone	Sil-Ms zone	Sil-Kfs zone	Crd-Kfs zone	Grt-Crd-Kfs zone	Contact aureole
Quartz	47*	28	27	23	29	28
Plagioclase	n.d.	17	16	11	11	13
K-feldspar	–	+	8	15	15	14
Muscovite	15	5	3	–	–	–
Biotite	36	43	40	35	24	23
Tourmaline	+	+	–	–	–	–
Staurolite	+	–	–	–	–	+(r)
Andalusite	1	–	–	–	–	+(r)
Sillimanite	–	4	4	5	4	1
Kyanite	–	–	–	–	+(r)	–
Cordierite	–	–	–	7	6	9
Garnet	+	–	+	3	10	10
Hercynite	–	–	–	–	–	+
Orthopyroxene	–	–	–	–	–	+
Opagues	+	1	1	1	1	1
Others	+	+	+	+	+	+
Total	100	100	100	100	100	100



☆ = chemical composition of the metapelites

Fig. 6. AFM-diagrams (a–f) (Thompson 1957) for the regional metamorphic zones of the Seinäjoki–Ilmajoki area. The average chemical composition of the metapelites studied and their minerals are shown in the diagrams (see Tables 3–5). The garnet-cordierite-K-feldspar zone includes two different AFM-diagrams (e, f); the assemblage in parenthesis is rare.

formation of andalusite (see Fig. 6a). The accessory minerals in the mica schists are tourmaline, apatite, zircon, opaque minerals and retrogressive chlorite. In outcrops where sedimentary bedding is best preserved, there are also a few garnets and staurolites. Pegmatite granites, barren pegmatites and rare-element pegmatites occur commonly in the mica schists.

The andalusite is relatively rich in opaque inclusions, possibly indicating that the mineral is formed from Fe-Mg silicates such as staurolite or chlorite. Staurolite is surrounded by progressive coarse-grained muscovite and partly by biotite. Garnet is subhedral, with inclusion-free rims, and is in contact with andalusite. The abundant andalusite in the mica schists indicates that the pressure during metamorphism was low, some 1–3 kbar.

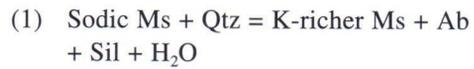
Sillimanite-muscovite zone

The metapelites of this zone are coarse-grained mica gneisses (Figs. 3c and 3d) having the mineral assemblage sillimanite (fibr.)-muscovite-biotite-plagioclase-quartz (Table 2). The accessory minerals include tourmaline, zircon, opaque minerals and apatite. Opaque minerals, mostly magnetite, occur with relatively high modes (0.5–1.5%), often as inclusions in biotite. The grain size of micas increases to the southwest. Muscovite usually occurs as individual coarse-grained (1–8 mm), discordant porphyroblasts and consequently these gneisses often appear speckled. Psammitic metasediments and narrow pegmatite dykes are common within this zone (see Fig. 3c). Compared to within the andalusite zone, pegmatite granites occur in smaller volumes.

The sillimanite occurs as fibrolitic needles within coarse-grained muscovite and plagioclase and in small quartz inclusions in poikiloblasts of muscovite. Some sillimanite is also detected in quartz and plagioclase near the boundaries of muscovite. In addition, fibrolitic sillimanite forms clusters (ϕ 0.2–1.5 cm) with quartz and muscovite (Fig. 7a).

Muscovite-sillimanite-biotite gneisses are not unusual (e.g. Evans & Guidotti 1966, Tracy 1978)

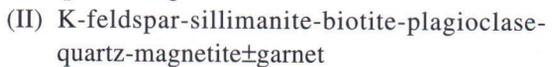
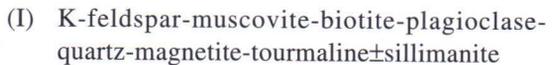
and many topological facies types involving muscovite have been discussed (e.g. Thompson & Thompson 1976). In the study area, sillimanite has probably formed in the muscovite-bearing gneisses by reaction (1) (below; for references to the reactions presented here, see Spear 1993). Some of the sillimanite may also have formed by base cation leaching reaction described by Vernon (1979). In places muscovite containing fibrolitic needles of sillimanite replaces deformed biotites. At such localities there is also contemporaneous magnetite.



The common occurrence of coexisting muscovite and sillimanite without K-feldspar in the sillimanite-muscovite zone indicates that the P-T conditions of metamorphism were slightly above the intersection of the andalusite-sillimanite inversion line and of dehydration reactions (2) and (3). The chemical composition of the metapelites plots partly on the tieline between sillimanite and biotite on the AFM-diagram shown in Fig. 6b.

Sillimanite-K-feldspar zone

The mica gneisses of the sillimanite-K-feldspar zone contain two separate mineral assemblages, named (I) and (II):



The different mineral assemblages reflect small variations in metamorphic grade and/or whole rock chemistry. Assemblage (I) mainly occurs in the northeastern part of the zone and assemblage (II) mostly in the southwestern part. Thus, the sillimanite-K-feldspar zone contains a 'muscovite out' -isograd, located approximately in the mid-

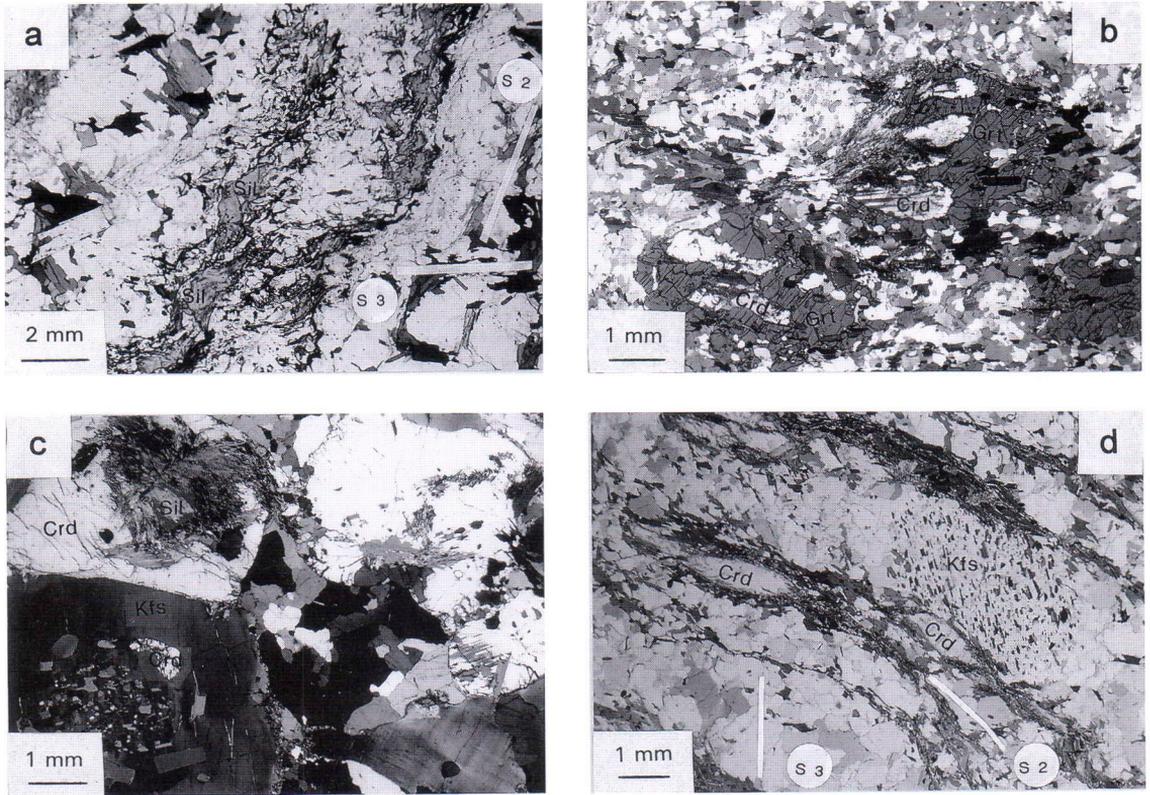


Fig. 7. Structures in metapelites of the Seinäjoki–Ilmajoki area. Coordinates are given as in the base coordination of the Finnish maps. a) Part of the crest of a large F_3 fold, with a cluster composed of sillimanite (fibr.), muscovite and quartz. Sillimanite (Sil) is folded, but some of it is segmented in the axial plane of F_3 , Sillimanite-muscovite zone. $x = 6961050$, $y = 2436900$. b) Cordierites (Crd) are rimmed by garnet (Grt). Garnet-cordierite-K-feldspar zone. $x = 6951940$, $y = 2428490$. c) A large cordierite (Crd) grain is partly decomposed to biotite, quartz and sillimanite (Sil) because of retrogressive metamorphism. K-feldspar (Kfs) is crystallized around older K-feldspar and includes cordierite (Crd) and biotite. Garnet-cordierite-K-feldspar zone. $x = 6949860$, $y = 2423240$. d) Cordierite (Crd) is crystallized parallel to S_2 , but a porphyroblast of K-feldspar (Kfs) is rotated during the F_{3b} folding. Metamorphic differentiation has formed microscopic layers. Cordierite-K-feldspar zone. $x = 6949850$, $y = 2423230$.

dle of the zone. Both zones contain rare anatectic granite patches.

The mica gneisses of assemblage (I) are slightly coarser in grain size and show a more pronounced schistosity compared to the gneisses of assemblage (II). However, the grain size of sillimanite is usually coarser in the latter assemblage. Most of the K-feldspar in the sillimanite-K-feldspar zone forms as a product of the common dehydration reactions (2) and (3). Changes in the mineral abundances in the rocks agree with these reactions (see Table 2).

Evans and Guidotti (1966) noted in their detailed study of reaction (2) in Maine, USA, that the muscovite-K-feldspar-sillimanite assemblage can occur over a distance of several kilometres from the reaction line (2). Moreover, the tieline switching reaction (3) usually occurs over a relatively wide range of temperatures (Evans & Guidotti 1966), partly due to the CaO content of plagioclase (e.g. Tracy 1978). The 'muscovite out'-isograd in the Ilmajoki area is an irregular line, probably partly due to the gentle plunge of the F_3 fold axis (Fig. 2a). In the study area the isograd

occurs in a zone two kilometres wide.

In the mica gneisses with assemblage (I), biotite both rims K-feldspar porphyroblasts and occurs as inclusions in K-feldspar. Muscovite is coarse-grained (0.3–1 cm), intergrown with biotite and typically contains fibrolitic sillimanite. There are some sillimanite needles in quartz and plagioclase inclusions in muscovite poikiloblasts. Fibrolitic sillimanite also occurs in biotite. The muscovite contains clusters of an unidentified, fibrolitic aggregate. Clusters composed of fibrolitic sillimanite, quartz and muscovite are locally common. Apatite is often relatively coarse-grained. Mica gneisses containing muscovite, sillimanite and K-feldspar indicate the P-T conditions of discontinuous reaction (3).

Tourmaline is present in the metapelites of assemblage (I). Boron decreases the solidus temperature of a granitic melt, and locally high amounts of boron possibly had a role in forming the present K-feldspar-bearing mineral assemblage (interstitial K-feldspar being crystallized from a melt?). Thus, the high boron content may partly explain the varying position of the 'K-feldspar in' -isograd in the muscovite-bearing gneisses.

The metapelites of assemblage (II) differ from those of assemblage (I) in their clearer plagioclase twinning, in their lower amounts of opaque minerals and sulphur, and in an absence of muscovite and tourmaline. Sillimanite often occurs as individual clusters with a size of 1–3 mm. There are irregular porphyroblasts (1–2 mm) of K-feldspar that often contain the S_2 schistosity. There are less pegmatite granites than in the andalusite and sillimanite-muscovite zones, in a decreasing amount to the southwest. On an AFM-diagram, the chemical composition of the metapelites partly plots on the between K-feldspar and sillimanite tieline (Fig. 6c).

Cordierite-K-feldspar zone

The metapelites in the cordierite-K-feldspar zone occur usually between psammitic layers as homogeneous rocks with no intensely developed schistosity. From the middle part of the zone towards the southwest, metamorphic differentiation (seg-

regation) is common (Fig. 3f). The mica gneisses of the zone have the mineral assemblage cordierite, K-feldspar, biotite, sillimanite, plagioclase, quartz with or without garnet. Garnet is absent near the sillimanite-K-feldspar zone. The garnet-cordierite ratio increases to the southwest. Garnet and cordierite are never in grain contact. Magnetite is an accessory mineral.

Cordierite and most of the K-feldspar form in the continuous reaction (4). This decomposition reaction of biotite is evident from comparison of the modes of the sillimanite-K-feldspar zone and cordierite-K-feldspar zone (see Table 2). Some garnets have crystallized in the relatively Fe-rich parts of metapelites by reaction (5), but, usually, the relatively high MgO-FeO_{tot} ratio in metapelites has favoured the formation of cordierite (see Fig. 6d). The average chemical composition of the metapelites does not clearly plot in the field of Sil-Bt-Crd on the AFM-diagram, as it should if reaction (4) was to dominate (Fig. 6d). However, the position of the average whole rock composition at the Sil-Bt tieline corresponds to the abundant sillimanite and biotite in the cordierite-K-feldspar zone.



Cordierite porphyroblasts near the sillimanite-K-feldspar zone are partly zoned: there is a core containing fibrolitic sillimanite and a rim containing biotite inclusions. K-feldspar porphyroblasts contain biotite, quartz and plagioclase inclusions. In the northeastern part of the zone, sillimanite occurs as individual, medium-grained grains forming clusters, but elsewhere individual sillimanite is usually intergrown with biotite. In the zone, anatectic granitic patches and veins occur in small amounts while pegmatite granite intrusions and pegmatite dykes are rare.

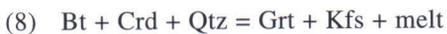
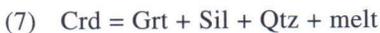
Garnet-cordierite-K-feldspar zone

The metapelites of this zone are migmatitic garnet-cordierite-sillimanite mica gneisses (Fig. 4b).

Garnet coexists with cordierite (coexistence is an index of the zone) but mostly equilibrated mineral-pairs are rare. Therefore, the isograd between the cordierite-K-feldspar zone and the garnet-cordierite-K-feldspar zone does not indicate the P-T conditions of equilibrated garnet and cordierite.

Melting occurred in the mica gneisses of this zone. The anatectic material appears as patches, rarely as narrow, elongated veins, and includes garnet and cordierite (Figs. 3e and 4b). Between psammitic intercalations, these gneisses are often composed of a relatively homogeneous, medium- to coarse-grained garnet-cordierite-K-feldspar-plagioclase-quartz-sillimanite-biotite rock without an intense foliation, but with some indistinct patches of anatectic material.

The mode of garnet and cordierite is high, together about 15 % (Table 2). The high content of biotite and sillimanite in these gneisses indicates that the temperature was not high enough to cause intense dehydration and melting by reaction (6). In places, garnet surrounds cordierite (Fig. 7b), particularly at the boundary between the cordierite-K-feldspar zone and the garnet-cordierite-K-feldspar zone. This texture, which resembles corona structure, may be interpreted in at least two different ways. Either garnet has formed from cordierite during increasing pressure in a reaction such as (7), or during increasing temperature by reaction (8). In coronas, the grain contacts between garnet and cordierite are usually sharp without intergrowths of sillimanite and quartz.



The Mg-Fe ratio of biotite is higher in the garnet-cordierite-K-feldspar zone compared to that in the cordierite-K-feldspar zone causing a shift of the tieline between biotite and sillimanite on the AFM-diagram to the right (see Table 4 and Figs. 6d and 6e). This partly explains why in reactions (4) and (5) more garnet forms than cordierite. Due

to the rarity of clearly equilibrated garnet-cordierite pairs, the AFM-diagram showing a tieline between garnet and cordierite is in parenthesis in Fig. 6f.

Thin layers rich in either ferromagnesian minerals or felsic minerals formed by microscopic metamorphic differentiation are common (see Fig. 3f). The cores of cordierite porphyroblasts often include fibrolitic sillimanite, which is probably a relict phase. However, some cordierites also include relatively coarse-grained sillimanites and biotites formed during decomposition of the cordierite (Fig. 7c). Sillimanite is often intergrown with biotite and in places sillimanite surrounds magnetite. K-feldspar porphyroblasts in the palaeosome of gneisses have a grain size of 0.2–1.5 cm, but the minerals do not usually contain garnet or cordierite inclusions. Apatite is often relatively coarse-grained.

The rocks also include some fine-grained kyanite. Reaction (6) has a steep positive dp/dT-slope. Thus, if the metamorphic pressure is relatively high (c. 5 kbar), initiation of this reaction requires temperatures over 700 °C (see Holdaway & Lee 1977).

Metamorphic orthopyroxene has crystallized in intermediate metavolcanic rocks in the garnet-cordierite-K-feldspar zone. In the study area the 'orthopyroxene in' -isograd is slightly south of the boundary between the garnet-cordierite-K-feldspar zone and the cordierite-K-feldspar zone. Locally the orthopyroxene is partly decomposed to clinopyroxene. This orthopyroxene does not necessarily indicate very high metamorphic temperatures because, for example, experimental studies have shown that in quartz-saturated mafic rocks, compared to quartz-undersaturated mafic rocks, the metamorphic temperature of the first appearance of orthopyroxene is lower (e.g. Spear 1981).

Contact aureole

The intrusion of the quartz monzonite stock of Luopa led to the formation of a narrow (c. 25 m) upper amphibolite grade to granulite grade contact metamorphic aureole (Fig. 1) (Mäkitie & Lah-ti 1991). This thermal event overprints the effects

of regional metamorphism. The contact metamorphic rocks display the effects of intense anatexis (Fig. 5b). In places there are equilibrated garnet-cordierite pairs, garnet-orthopyroxene pairs and coronas composed of hercynite, sillimanite and cordierite. Retrogressive andalusite and staurolite have formed during cooling. The contact aureole has a slightly higher cordierite-garnet ratio than the surrounding regionally metamorphic terrain indicating (with the retrogressive andalusite) lower pressures than in regional metamorphism.

Retrograde reactions

The most characteristic feature of retrograde metamorphism in the studied regional metamorphic terrain is the absence of retrogressive andalusite and muscovitization. Retrogressive, very fine-grained muscovite occurs only rarely in cracks in porphyroblasts and, in the garnet-cordierite-K-feldspar zone, in few grain contacts between cordierite and K-feldspar.

The andalusite of mica schists is partly decomposed to a light-coloured, unidentified aggregate. Retrograde chlorite occurs in some thin shear zones and rarely in decomposed garnets, often with biotite, in the high-grade mica gneisses.

In the garnet-cordierite-K-feldspar zone, parts of the relatively coarse-grained cordierites and garnets are decomposed to quartz, clusters of sillimanite and light green biotite indicating that reactions (4) and (5) proceeded also from right to left (Fig. 7c). The examples mentioned above usually contain polycrystalline coarse-grained K-feldspar and relatively abundant apatite (Fig. 7c). Hornblende replaces orthopyroxene in the intermediate metavolcanic rocks of the garnet-cordierite-K-feldspar zone.

The regional metamorphic garnet-cordierite-sillimanite mica gneisses contain fine-grained rare kyanite (identified by X-ray methods). It is noteworthy that progressive kyanite schists are not known up to 250 km from the town of Seinäjoki. The kyanite at Ilmajoki probably formed during crustal cooling.

MINERAL GROWTH IN RELATION TO DEFORMATION

Biotite and muscovite

Most of the biotite and muscovite have grown syn-kinematically with F_2 folding resulting in the formation of the dominant axial plane foliation (S_2) in the northern study area, particularly in the mica schists (see Figs. 3b and 4c). The mica gneisses include coarse-grained progressive muscovites that overgrow the S_2 schistosity with slight discordancy indicating that few muscovites crystallized after F_2 .

Very rarely, there are two intersecting (angle 10°) trends in the andalusite mica schists. One is S_0/S_1 , which indicates the position of the limb of a tight to isoclinal F_2 fold, and the other is the axial plane schistosity (S_2) of F_2 . The synkinematic (D_2) micas are folded by F_3 or F_{3b} as well as by F_4 and F_5 . All crenulate the mica-rich foliation (e.g. Figs. 3d and 4c). In a few places, coarse-grained biotites, segmented in the axial plane of F_3 and F_{3b} , occur in mica gneisses that have been metamorphosed on higher temperature side of the first sillimanite isograd.

Andalusite and sillimanite

Andalusite porphyroblasts in the mica schists predate F_5 (Fig. 4d). In outcrops with well-preserved sedimentary layering there are elongated andalusites parallel to S_0 and S_1 , which follow the curvature of F_2 folds (Fig. 3a). These andalusites have crystallized within thin layers parallel to S_0/S_1 as the result of their suitable, aluminium-rich chemical composition. Further, a later phase of andalusite including opaques formed more clearly overprinting S_2 at the crystal ends of earlier andalusites. Finally, retrogressive andalusite formed in the contact aureole of the Luopa quartz monzonite stock.

F_3 folds deform elongated clusters of sillimanite parallel to S_2 schistosity. In some large F_3 folds, because of the stress, part of the sillimanite needles are segmented parallel to the axial planes (Fig. 7a). In the garnet-cordierite mica gneisses,

Table 3. Average chemical composition of metapelites as a function of metamorphic zoning in the Seinäjoki-Ilmajoki area. *n* = amount of analyses.

	And zone (<i>n</i> = 8)	Sil-Ms zone (<i>n</i> = 7)	Sil-Kfs zone (<i>n</i> = 4)	Crd-Kfs zone (<i>n</i> = 10)	Grt-Crd- Kfs zone (<i>n</i> = 10)	Contact aureole (<i>n</i> = 5)
SiO ₂ (wt-%)	64.70	60.29	58.56	60.34	62.46	55.95
TiO ₂	0.70	0.85	0.84	0.81	0.80	0.94
Al ₂ O ₃	17.20	17.94	19.22	18.90	17.45	19.80
FeO _{tot}	6.57	7.68	8.17	7.80	7.24	9.01
MnO	0.06	0.07	0.08	0.07	0.08	0.10
MgO	2.61	3.27	3.40	3.37	2.97	3.74
CaO	0.98	1.32	1.07	1.32	1.68	2.40
Na ₂ O	1.75	1.68	1.89	1.81	2.24	2.37
K ₂ O	4.29	4.73	4.40	3.97	3.73	3.36
P ₂ O ₅	0.24	0.24	0.26	0.17	0.15	0.15
S	0.05	0.07	0.34	0.35	0.15	0.56
Total	99.15	98.14	98.23	98.91	98.95	98.38
Rb (ppm)	–	–	–	–	174	–
Sr	111	124	113	145	180	180
Ba	630	734	888	920	919	932
Zn	132	154	148	156	133	178
Zr	193	204	163	168	210	188
Cr	263	292	270	251	186	250
V	123	176	170	161	136	220
Th	–	–	–	–	16	–
U	–	–	–	–	3	–
Cs	–	–	–	–	7	–
Y	–	–	–	–	7	–
La	–	–	–	–	43	–

sillimanite has also formed during the relatively late decomposition of cordierite (Fig. 7c), when reaction (4) was reversed.

K-feldspar

K-feldspar is syn- to late-kinematic in relation to S₂. In the sillimanite-K-feldspar zone, this is indicated by the presence of folded (F₃) mica gneisses with K-feldspar porphyroblasts containing S₂-parallel biotite inclusions, or K-feldspar that occurs as interstitial material between other minerals. In the high-grade mica gneisses these K-feldspar porphyroblasts have often been reoriented by the sliding of metamorphically differentiated layers on fold limbs during F₃ or F_{3b} folding (Fig. 7d).

Later K-feldspar crystallized around older K-feldspars in the garnet-cordierite-sillimanite mica gneisses (Fig. 7c). The later K-feldspar is usually

free of inclusions, but in places can contain cordierite and garnet.

Garnet and cordierite

The S₂ schistosity curves around a few subhedral garnets in the andalusite mica schists. Most of the cordierite in high-grade rocks is synkinematic to F₂ but prekinematic to F_{3b} folds (Fig. 7d). Garnet and cordierite have also crystallized in the anatectic patches in the high-grade mica gneisses: some of these patches lie in the axial planes of F_{3b}.

CHEMICAL COMPOSITION OF THE METAPELITES AND THEIR MINERALS

Metapelites

The metapelites studied have excess aluminium in

Table 4. Average chemical composition of biotite in metapelites as a function of metamorphic zoning in the Seinäjoki–Ilmajoki area. *n* = amount of analyses. Oxygen: Bt 11.

	And zone (<i>n</i> = 6)	Sil-Ms zone (<i>n</i> = 3)	Sil-Kfs zone (<i>n</i> = 3)	Crd-Kfs zone (<i>n</i> = 6)	Grt-Crd- Kfs zone (<i>n</i> = 7)	Contact aureole (<i>n</i> = 7)
SiO ₂ (wt-%)	35.40	35.20	35.33	35.42	35.70	35.89
TiO ₂	1.87	2.13	2.33	2.80	3.11	4.19
Al ₂ O ₃	19.80	19.93	19.80	19.03	18.73	17.96
FeOtot	19.32	17.67	18.63	18.47	16.86	17.18
MnO	0.15	0.16	0.15	0.10	0.06	0.04
MgO	8.68	9.23	9.23	9.70	10.77	10.18
CaO	0.04	0.03	0.02	0.03	0.01	0.02
Na ₂ O	0.20	0.25	0.29	0.17	0.18	0.14
K ₂ O	8.40	8.80	8.97	8.33	9.29	9.30
Total	93.86	93.40	94.75	94.05	94.71	94.90
Si	2.977	2.963	2.943	2.950	2.940	2.945
Al	1.252	1.262	1.240	1.192	1.160	1.108
Ti	0.118	0.135	0.146	0.175	0.193	0.259
Mg	1.089	1.159	1.147	1.204	1.323	1.245
Fe	1.359	1.244	1.298	1.286	1.161	1.179
Mn	0.010	0.110	0.010	0.007	0.004	0.003
Ca	0.004	0.003	0.002	0.003	0.001	0.002
Na	0.032	0.040	0.047	0.027	0.029	0.023
K	0.902	0.945	0.953	0.885	0.976	0.973

relation to alkalis and calcium (Table 3, see also Appendix 1). The chemical compositions of rocks in the different metamorphic zones are relatively similar, except for those of the contact aureole of the Luopa quartz monzonite stock (Table 3). Thus, the principle of metamorphic facies established by Eskola (1915) is applicable.

The similar chemical composition of metapelites in the regional metamorphic zones studied agrees with the relatively low amount of anatexis: the content of K₂O has not notably decreased as a result of the formation of granitic neosome (Table 3). Moreover, the fairly high concentrations of Rb and Cs in the high-grade mica gneisses indicate that element depletion during metamorphism was not intensive (cf. Rudnick & Presper 1990). The concentrations of Sr and Ba in the highest-grade rocks appear to be higher than in the mica schists.

Biotite

The analysed points are in cores of biotites, which are not in contact with other Fe-Mg silicates. The mode of biotite is high in each metamorphic zone (Table 2).

The amount of titanium and the ratio of Mg-Fe increase, while the amount of aluminium and manganese decreases in biotites as a function of increasing metamorphic grade (Table 4, Fig. 8). In the andalusite, sillimanite-muscovite, sillimanite-K-feldspar and cordierite-K-feldspar zones the aforementioned overall increase of titanium is also compensated by a decrease in Ti with increasing Mg/(Mg+Fe) (Fig. 8). Many high-grade metamorphic terrains yield similar compositional trends (e.g. Guidotti et al. 1977, Bailey 1984, Schreurs 1985).

The biotite in the andalusite zone, in the sillimanite-muscovite zone, and in the sillimanite-K-feldspar zone has greenish pleochroism ($\beta = \gamma$). In the cordierite-K-feldspar zone, the pleochroic colour has a brownish shade, and in the garnet-

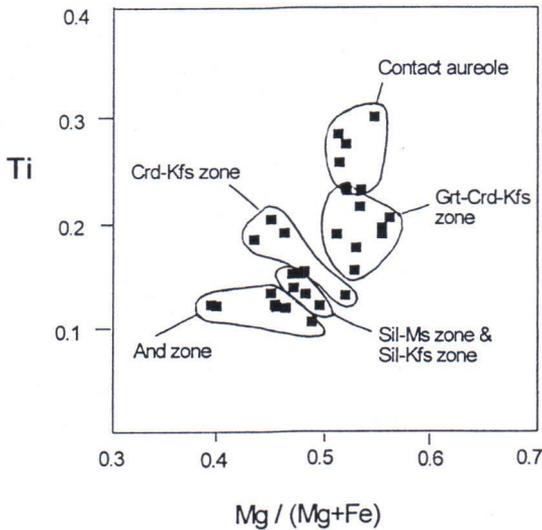


Fig. 8. Plot of Ti vs. Mg/(Mg+Fe) of biotites from various metamorphic zones of the Seinäjoki–Ilmajoki area. Oxygen: Bt 11.

cordierite-K-feldspar zone it is greenish brown with a reddish shade. In the contact aureole of the Luopa quartz monzonite, the pleochroic colour of biotite is brownish red.

Garnet and cordierite

The present microprobe analyses of garnet and cordierite represent different parts of minerals and texturally different coexisting pairs (see Table 5). The rims of garnets usually contain slightly more Mn than their cores. The amount of MgO in the garnet is maximum of 5.4 wt% and in the cordierite 9.5 wt%.

The sum of oxides in the cordierites is often relatively low (96–98 wt%) probably due the H₂O content of the mineral (see Table 5). The H₂O content (wet chemical analysis) of cordierite from garnet-cordierite-sillimanite mica gneiss taken

Table 5. Microprobe analyses and geothermometric estimations of garnet-cordierite pairs from the garnet-cordierite-K-feldspar zone. Temperatures are calculated using the following thermometers: T₁ (Holdaway & Lee 1977) and T₂ (Perchuk 1989). Assumed pressure is 5 kbar for T₁ and T₂. Equilibrium = cores of equilibrated mineral pair. Disequilibrium = rims of coexisting minerals. Corona = analysed points from coronatic pairs. Oxygens: Grt 12, Crd 18.

Structure Sample Minerals	Equilibrium 800-B/1–2		Equilibrium 800-B/3–4		Equilibrium 800-BVA/25–26		Equilibrium 512/19–20		Disequilibrium 150-B/8–9	
	Grt	Crd	Grt	Crd	Grt	Crd	Grt	Crd	Grt	Crd
SiO ₂	37.25	48.37	37.28	48.21	38.03	48.46	37.53	47.26	36.88	48.07
TiO ₂	0.01	0.00	0.02	0.01	0.02	0.00	0.02	0.00	0.00	0.01
Al ₂ O ₃	21.26	32.85	21.05	32.64	21.53	32.19	21.50	31.88	20.94	32.59
FeOtot	33.44	8.16	33.98	7.13	32.00	7.20	33.48	7.27	33.74	7.62
MnO	1.19	0.04	1.11	0.05	1.02	0.07	1.20	0.11	1.45	0.06
MgO	5.11	8.80	5.27	9.23	5.26	8.27	5.01	8.66	4.95	8.92
CaO	1.09	0.00	1.04	0.05	0.97	0.01	0.88	0.01	0.96	0.05
Na ₂ O	0.04	0.03	0.00	0.21	0.12	0.17	0.05	0.15	0.25	0.21
K ₂ O	0.16	0.20	0.12	0.01	0.09	0.03	0.01	0.04	0.08	0.01
Total	99.55	98.45	99.87	97.54	99.04	96.40	99.68	95.38	99.25	97.54
T ₁ (°C)	686		640		689		652		651	
T ₂ (°C)	722		673		729		689		683	
Si	3.277	5.656	3.272	5.661	3.329	5.744	3.291	5.680	3.265	5.659
Al	1.407	2.889	1.389	2.882	1.417	2.870	1.418	2.882	1.394	2.885
Ti	0.001	0.000	0.001	0.001	0.001	0.000	0.001	0.000	0.000	0.001
Mg	0.670	1.534	0.689	1.616	0.686	1.461	0.655	1.552	0.653	1.565
Fe	2.460	0.798	2.494	0.700	2.343	0.714	2.455	0.731	2.498	0.750
Mn	0.089	0.004	0.083	0.005	0.076	0.007	0.089	0.011	0.109	0.006
Ca	0.103	0.000	0.098	0.006	0.091	0.001	0.083	0.001	0.091	0.006
Na	0.007	0.007	0.000	0.048	0.020	0.039	0.009	0.035	0.043	0.048
K	0.018	0.030	0.013	0.001	0.010	0.005	0.001	0.006	0.009	0.002

Table 5. (continues)

Structure Sample Minerals	Disequilibrium 150-B/11–12		Disequilibrium 150-B/11–10		Disequilibrium 512/15–16		Corona 340-D/13–14		Corona 145/1	
	Grt	Crd	Grt	Crd	Grt	Crd	Grt	Crd	Grt	Crd
SiO ₂	37.00	48.21	37.39	48.12	37.21	47.85	37.86	48.84	37.80	48.90
TiO ₂	0.00	0.05	0.00	0.02	0.04	0.01	0.03	0.06	0.01	0.03
Al ₂ O ₃	21.53	33.24	21.45	32.96	21.21	32.35	21.88	33.75	22.20	33.80
FeO _{tot}	34.06	7.25	34.08	7.91	33.86	7.39	33.78	7.25	34.10	7.40
MnO	1.51	0.07	1.37	0.12	1.14	0.05	1.21	0.07	1.30	0.10
MgO	4.85	9.32	4.92	8.85	5.10	9.09	5.11	9.38	4.90	9.40
CaO	0.98	0.02	0.94	0.00	1.01	0.03	0.95	0.03	1.00	0.10
Na ₂ O	0.13	0.21	0.13	0.20	0.12	0.18	0.16	0.44	0.00	0.05
K ₂ O	0.00	0.03	0.01	0.03	0.00	0.02	0.02	0.07	0.00	0.00
Total	100.06	98.40	100.29	98.21	99.69	96.97	101.00	99.89	101.31	99.78
T ₁ (° C)	619		659		645		633		625	
T ₂ (° C)	649		695		679		666		657	
Si	3.254	5.626	3.272	5.640	3.271	5.659	3.280	5.619	3.271	5.627
Al	1.424	2.917	1.412	2.905	1.402	2.877	1.425	2.920	1.445	2.925
Ti	0.000	0.004	0.000	0.002	0.003	0.001	0.002	0.005	0.001	0.003
Mg	0.636	1.621	0.642	1.546	0.668	1.603	0.660	1.609	0.632	1.613
Fe	2.505	0.708	2.494	0.775	2.490	0.731	2.447	0.698	2.468	0.712
Mn	0.112	0.007	0.102	0.012	0.085	0.005	0.089	0.007	0.095	0.010
Ca	0.092	0.003	0.088	0.000	0.095	0.004	0.088	0.004	0.093	0.012
Na	0.022	0.048	0.022	0.045	0.020	0.041	0.027	0.098	0.000	0.011
K	0.000	0.004	0.001	0.004	0.000	0.003	0.002	0.010	0.000	0.000

Table 5. (continues)

Structure Sample Minerals	Corona 145/PII5-7		Corona 316-HMMOK		Corona 145/R1-OK		Core of coarse grains 390-S28 791A16	
	Grt	Crd	Grt	Crd	Grt	Crd	Grt	Grt
SiO ₂	37.56	49.00	37.18	47.95	38.16	48.92	39.19	37.35
TiO ₂	0.05	0.03	0.01	0.01	0.02	0.01	0.03	0.03
Al ₂ O ₃	21.86	33.97	21.38	32.39	21.71	32.45	21.88	21.46
FeO _{tot}	33.95	6.89	34.38	7.02	34.16	6.82	31.02	32.06
MnO	1.26	0.10	1.22	0.04	1.14	0.05	1.24	2.10
MgO	4.91	9.51	4.83	8.91	4.88	8.98	5.36	5.11
CaO	1.07	0.05	1.07	0.01	0.94	0.02	0.94	1.12
Na ₂ O	0.16	0.23	0.02	0.12	0.02	0.10	0.07	0.03
K ₂ O	0.00	0.07	0.00	0.00	0.00	0.02	0.03	0.01
Total	100.82	99.85	100.09	96.45	101.03	97.37	99.76	99.27
T ₁ (° C)	606		619		614			
T ₂ (° C)	637		650		645			
Si	3.268	5.628	3.265	5.687	3.302	5.728	3.378	3.286
Al	1.430	2.934	1.412	2.889	1.413	2.857	1.418	1.420
Ti	0.003	0.003	0.001	0.001	0.001	0.001	0.002	0.002
Mg	0.637	1.628	0.632	1.575	0.629	1.568	0.689	0.670
Fe	2.470	0.662	2.525	0.696	2.472	0.668	2.236	2.359
Mn	0.093	0.010	0.091	0.004	0.084	0.005	0.091	0.156
Ca	0.100	0.006	0.101	0.001	0.087	0.003	0.087	0.106
Na	0.027	0.051	0.003	0.028	0.003	0.023	0.012	0.005
K	0.000	0.010	0.000	0.000	0.000	0.003	0.003	0.001

from the southern part of the study area is 1.43 wt% (Pehrman 1932).

GEOTHERMOMETRY

The garnets and cordierites used in the present P-T determinations were taken from the garnet-cordierite-K-feldspar zone, maintaining a horizontal distance of more than one kilometre from the Luopa quartz monzonite stock. The contact metamorphic effects of the Luopa quartz monzonite are therefore probably minimal. However, the contact of the stock has a relatively gentle dip to the north-west and, thus, the real distance between the samples and the quartz monzonite may be less than one kilometre.

Metamorphic temperatures were calculated using the garnet-cordierite thermometers of Holdaway and Lee (1977) and of Perchuk (1989) (Table 5). Garnet-cordierite pairs are not ideal for making geobarometric estimates because of the unknown H₂O content of the cordierite. No geobarometric estimates are made in the present study, but a pressure assumption of 5 kbar was used in geothermometric estimates. Retrogressive kyanite in the garnet-cordierite-sillimanite mica gneisses indicates a relatively high (c. 5 kbar) pressure during the metamorphic peak.

The analysed mineral points are from (1) the cores of equilibrated pairs, (2) the rims of co-existing, but probably disequilibrated pairs, and (3) those pairs having corona structures (Table 5). Temperature estimates from equilibrated minerals range from 640 °C to 729 °C, but the estimates from rims and corona pairs are slightly lower, from 614 °C to 695 °C (Table 5). The highest temperatures were obtained with the thermometer of Perchuk (1989). The temperature estimates (< 750 °C) obtained agree with the fact that zircons in metapelites in the southern Ilmajoki area were not reset during the Svecofennian regional metamorphic peak. A U-Pb zircon age (c. 2.4 Ga) reported from these metapelites reflects the mixture of Archaean and Palaeoproterozoic material (see Huhma et al. 1991, Mäkitie & Lahti 1991).

SUMMARY AND DISCUSSION

Regional metamorphism in the Seinäjoki–Ilmajoki area has the following characteristic features. The highest grade of metamorphism took place at lower granulite facies conditions with a facies-series of the low-pressure intermediate type, and with metamorphic temperatures of about 730 °C. Retrogressive muscovite is practically absent and granitic neosomes occur in relatively low amounts, usually as patches and not as networks of narrow veins. Equilibrated garnet-cordierite pairs are rare and in places garnet surrounds cordierite. Retrogressive, minor kyanite occurs in the garnet-cordierite-sillimanite mica gneisses while retrogressive andalusite is absent. The 'muscovite out' isograd is an irregular line. Regional metamorphism was obviously contemporary with the emplacement of 1882±9 Ma old synkinematic tonalites. The lowest grade metapelites occur close to pegmatite granites and to the hinge of a regional-scale antiform, and the highest grade rocks are near the Luopa mangeritic stock (see Figs. 1 and 2).

The dominant schistosity (S₂) in the mica schists is a biotite and muscovite metamorphic axial plane foliation formed during isoclinal F₂ folding. The S₁ schistosity, usually parallel to S₂, is very weak. In areas of high-grade mica gneisses, tight to isoclinal late-metamorphic F₃ and F_{3b} folds, with the dominant S₃ and S_{3b} foliations associated, deform S₂. Consequently a composite schistosity (S₀±S₁±S₂±S₃ or S_{3b}) is very common. F_{3b} fold axes have steeper plunges than F₃ fold axes (Fig. 2a), but the reason for this difference is not clear. The vergence of F₃ and F_{3b} folds indicates regional-scale parasitic fold structures. Younger small-scale crenulating deformations (F₄ and F₅) are best seen in the ductile mica schist.

The regional metamorphic isograds are often subparallel to the dominant E–W-trending axes of F₃ and F_{3b} folds (see Figs. 1 and 2). The comparatively well-preserved layering in mica gneisses is due to, for example, relatively low strain during the main fold phases (F₂, F₃ and F_{3b}), the absence of mineral growth during F₃ and F_{3b} folding events, the relatively minor formation of

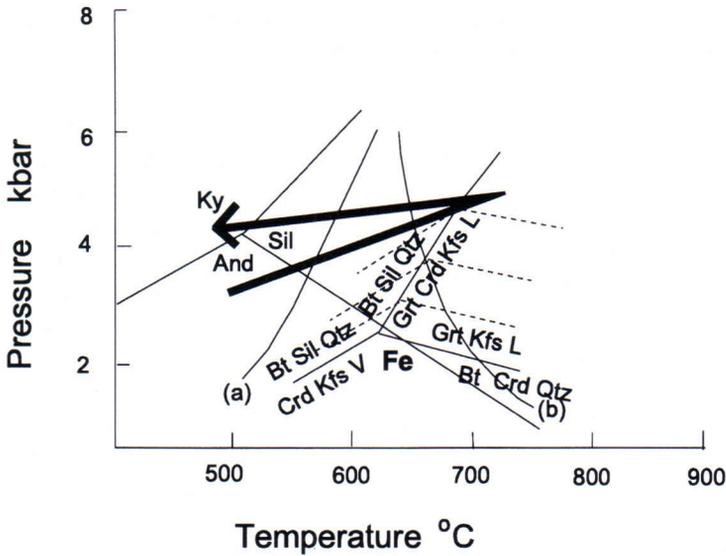


Fig. 9. Petrogenetic grid for metapelites and probable P - T path (thick arrow) for the regional metamorphism of the Seinäjoki–Ilmajoki area. The dehydration reaction (at $P_{H_2O} = 0.4 P_{tot}$) of biotite-sillimanite-quartz assemblage is adjusted according to Holdaway and Lee (1977) and the dashed lines represent contours for molar $Fe/(Fe+Mg)$ of cordierite. The triple point of aluminium silicates is after Salje (1986). Muscovite breakdown reaction (a) is from Chatterjee and Johannes (1974) and the granite minimum melting curve (b) is from Kerrick (1972).

melts or late neosomes, and the absence of muscovitization.

From observations of the relationship between metamorphism and deformation in the Seinäjoki–Ilmajoki area, it has been concluded that the age of metamorphism is approximately same in areas of higher and lower grade. During late-metamorphic F_{3b} folding, the metamorphic temperature in the southern part of the study area remained quite high because some granitic lenses, containing garnet and cordierite, formed along axial surfaces. From the isotopic U–Pb age of monazite in the garnet-cordierite-sillimanite mica gneisses, it has been estimated that crustal cooling below 600–650 °C took place c. 1.86 Ga ago (Mäkitie & Lahti 1991). The crust was locally heated during the emplacement of the 1871 ± 1 Ma old, post-kinematic Luopa quartz monzonite stock. This deformed the F_{3b} folds and intersected the main foliation of tonalites forming a narrow overprinting granulite-grade contact aureole. The occurrence in the mica gneisses of the garnet-cordierite-K-feldspar zone of a folded biotite-rich schistosity (S_2) and of

anatectic veins in F_3 axial surfaces is also evidence for polymetamorphism. The southern Ilmajoki area did not undergo notable deformation after c. 1.87 Ga.

A probable P - T path for the regional metamorphism of the Seinäjoki–Ilmajoki area is given in Fig. 9. The occurrence of retrogressive kyanite and the absence of retrogressive andalusite and muscovitization in the regional metamorphic garnet-cordierite-sillimanite mica gneisses may indicate nearly isobaric cooling of the crust. Moreover, the post-kinematic Luopa quartz monzonite may indicate heating processes in the lower crust with the formation of relatively dense magmas. This body possibly slowed the isostatic uplift of the crust locally, and this in turn partly caused the absence of retrogressive andalusite and of muscovitization. The anatectic melts formed in the garnet-cordierite-K-feldspar zone were intruded upwards in the crust into areas of lower metamorphic grade, where they intruded as pegmatite granites and pegmatites. In the high-grade mica gneisses, the removal of this melt extracted dissolved H_2O

and slowed down the progress of retrograde hydration reactions, such as those that occur in muscovitization. The P-T path shown only applies to the area studied because, about 20 km southeast, near the village of Ala-Valli, and about 30 km north, near the parish of Ylistaro, there are migmatitic garnet-cordierite mica gneisses that contain retrogressive andalusite and have undergone muscovitization. These last-mentioned areas do not contain any products of mangeritic magmatism and major shear zones partly separate them from the study area.

Unlike in southern Finland (see Kilpeläinen 1998 and references therein), the Seinäjoki area appears not to contain a growth of metamorphic micas (S_3) in the mica schists of the andalusite zone, when the mica gneisses of the cordierite-K-feldspar and garnet-cordierite-K-feldspar zones have undergone late-metamorphic F_3 folding. In the Seinäjoki–Ilmajoki area, the muscovite-sillimanite zone is clearly wider than in the high-temperature/low-pressure Rantasalmi area of southeastern Finland (see Korsman 1977, Korsman & Kilpeläinen 1986). In large-scale regional correlation, it should be noted that the lowest metamorphic grade in the Seinäjoki area is above greenschist-facies. Thus, it is not necessary that an earlier schistosity (S_1) observed elsewhere in Finland has been preserved or even developed in the Seinäjoki area. The feature called S_1 in this study is very weak and subject to interpretation.

The Luopa quartz monzonite is some 15 Ma younger than the pyroxene granitoids in the Pielavesi area, Raahe–Ladoga zone, eastern Finland (cf. Hölttä 1988). The Luopa intrusion was emplaced after the regional metamorphic culmination while the pyroxene granitoids of the Pielavesi area intruded mostly during it (see Hölttä 1995).

In the study area, regional metamorphism culminated at the same time (~ 1885 Ma ago) as the intense first phase of metamorphism in southern Finland (see Korsman et al. 1984). The high-grade terrain studied did not undergo the strong later thermal pulse (1.86–1.81 Ga ago) with intense potassium granite migmatization that is characteristic of the southern part of southern Finland (see Korsman *ibid.*). The Seinäjoki–Ilmajoki area also

differs from the northern part of southern Finland (which has been called the area of tonalite migmatites by Korja et al. 1994) because of the abundant aluminium-rich metapelite component and mangeritic magmatism of the former.

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Appendix 1. Chemically analysed metapelite samples taken from the Seinäjoki-Ilmajoki area. The analyses are archived in the KALTIE database in the Geological Survey of Finland. The database also includes locations of the samples.

Metamorphic zone	Samples
Andalusite zone	653-HMM-86, 397-HMM-85, 395-HMM-85, 17M-HMM-84, 657-HMM-86, 680-HMM-86, 380A-HMM-85, 380B-HMM-85
Sillimanite-muscovite zone	811-HMM-86, 783-HMM-86, 651-HMM-86, 760-HMM-86, 130M-PMK-83, 137M-PMK-83, 782-HMM-86
Sillimanite-K-feldspar zone	505-HMM-85, 798-HMM-86, 15M-HMM-84, 402-HMM-85
Cordierite-K-feldspar zone	242-HMM-85, 360-HMM-85, 509-HMM-85, 797-HMM-86, 721-HMM-86, 328-HMM-85, 723-HMM-86, 9M-HMM-84, 54P-HMM-86, 53-HMM-86
Garnet-cordierite-K-feldspar zone	390S-HMM-85, 512-HMM-85, 340A-HMM-85, 340B-HMM-85, 791-HMM-85, 145A-HMM-82, 145B-HMM-82, 145C-HMM-82, 145D-MM-82, 145E-HMM-82
Contact aureole of the Luopajarvi quartz monzonite	166D-HMM-82, 171E-HMM-82, 171K-HMM-85, 722-HMM-85, 167L-HMM-86