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by Jorma Paavola

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ON THE ARCHEAN HIGH-GRADE METAMORPHIC ROCKS IN THE VARPAISJÄRVI AREA, CENTRAL FINLAND

by
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with 15 figures and 14 tables

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A block of relatively well-preserved granulite facies rocks occurs in the fractured Archean basement about 60 km north of Kuopio, Central Finland. The main rock types consist of enderbites and pyroxene amphibolities with minor garnet-cordierite-sillimanite rocks and quartzose cordierite rocks. A short description of these rocks is given with analytical data. The analyses indicate calc-alkalic compositions with a trondhjemitic trend for the enderbitic-pyroxene amphibolitic rocks and their variants of an obviously lower metamorphic grade outside the block area.

Mineral analytical data for the high-grade metamorphic rocks are also presented. The PT evaluations according to the mineral parageneses and the Fe-Mg distribution of certain coexisting mineral pairs of the rocks dealt with indicate a moderate-pressure type of metamorphism (~8 kb) with the temperature at about 700° C. These correspond quite well to the Archean metamorphic PT-gradients generally reported for related rocks.

Key words: metamorphism, metamorphic rocks, chemical composition, high-grade metamorphism, granulite facies, PT-conditions, Archean, Varpaisjärvi, Finland.

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INTRODUCTION

In the near past, the Archean granitoid area in eastern Finland has not been subjected to extensive studies as the adjoining greenstone belts have been. Recent investigations in the Archean areas of Central Finland (excluding the greenstone belts) have been mainly concentrated in North Karelia, where Nykänen (1968, 1971) and Lavikainen (1977) have studied the Prekarelian basement.

The metamorphism of the Archean basement has generally been dealt with only briefly (e.g., Korsman, 1982; Pekkala, 1982), partly because the progressive mineral assemblages of granitoids and migmatites are usually difficult to interpret or have been destroyed by retrogressive phenomena.

The Archean rocks in the Varpaisjärvi–Nilsiä area (fig. 1) are in a way more variable than the so-called granite gneiss complex in general. Large areas of the basement are still, it is true, insufficiently known and therefore considered too homogeneous and uninteresting.

Wilkman (1938) described a garnet-bearing antophyllite schist and a hypersthene-hornblende granodiorite from the Varpaisjärvi area, but he did not include them in the basement. The twofold fact that the rocks in the Varpaisjärvi area are Archean and that most of them, moreover, contain high-grade metamorphic mineral assemblages has not drawn attention prior to the beginning of the remapping of the area in 1976.

The broken block character of the bedrock around has been noted by several authors (Talvitie, 1971; Kauppinen, 1973; Marttila, 1976). On the aeromagnetic map (fig. 2), strong anomalies with sharp borders caused by fractures and faults can be clearly seen.

The high-grade rocks of the Varpaisjärvi area are also bounded by fractures and faults. Usually, the occurrence of high-grade rocks coincides with magnetic anomalies. The general geology of the eastern part of the present area is described by Paavola (1980) and the preliminary results of the metamorphic history are also reported by Paavola (1982).

The aim of the present work is to describe briefly the Archean high-grade rocks of the Varpaisjärvi area as well as to examine the chemistry of these rocks and their minerals for the purpose of determining their metamorphic PT-conditions.

GENERAL DESCRIPTION OF THE AREA

The Varpaisjärvi area (fig. 1), about 60 km north of Kuopio, belongs to the Archean granite gneiss complex. Most of the isotope determinations of zircon (U-Pb) indicate for this western part of the basement an age of about 2680 Ma, which most probably correlates with the time of metamorphism.

The Proterozoic Tahkomäki quartzite ridge runs N-S through the granitoids. It is thrust into a vertical position between the basement

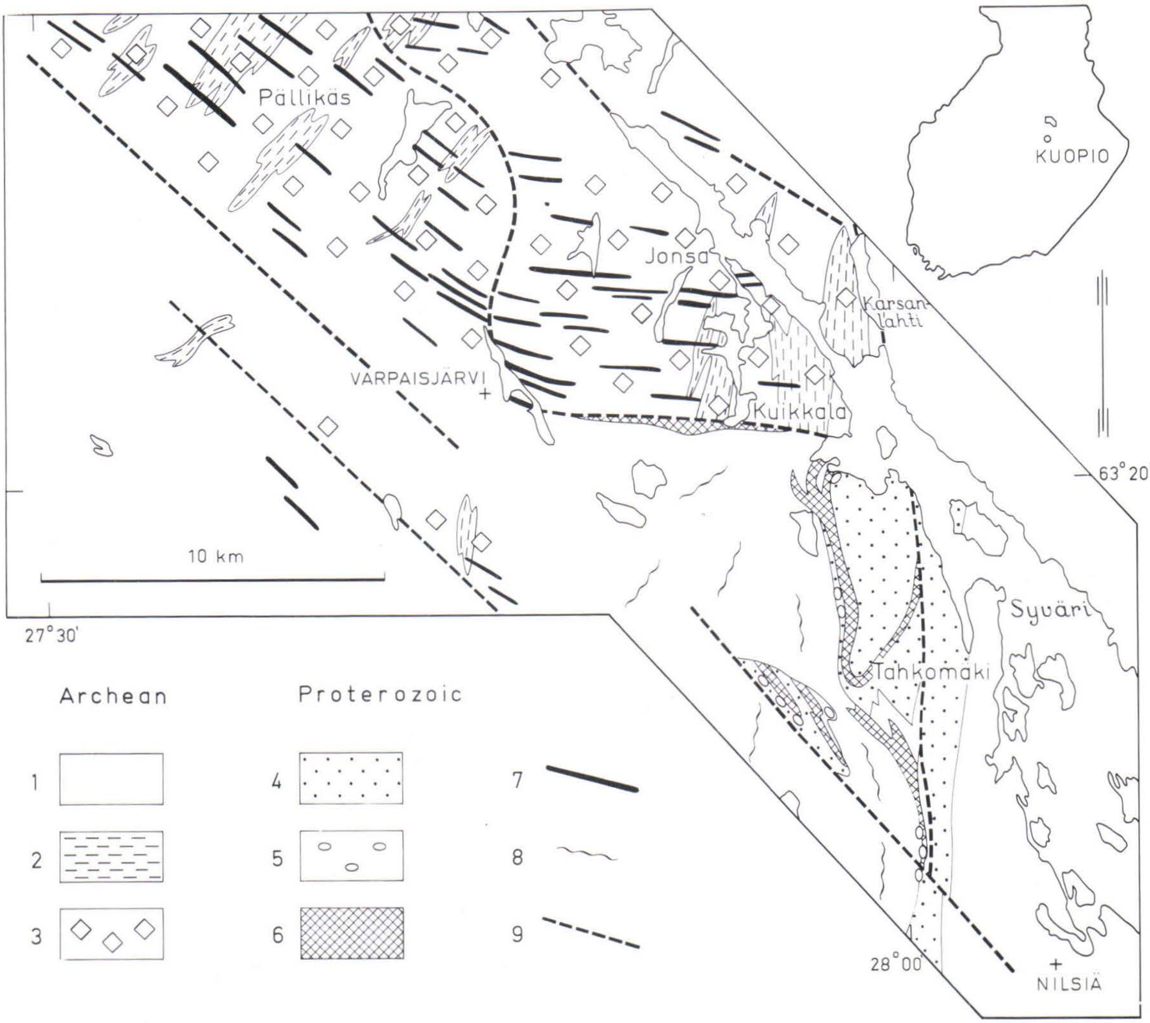

Fig. 1. Geological sketch map of the Varpaisjärvi–Nilsiä area. Symbols: 1. Archean basement in general, 2. amphibolitic basement, 3. orthopyroxene-bearing, 4. Proterozoic schist (predominantly quartzite), 5. conglomerate, 6. metadiabase or amphibolite, 7. diabase dyke, 8. remarkably cataclastic, 9. significant fracture zones and/or faults.

rocks. Basal conglomerates are met with on the western side of the ridge. The eastern contact against the basement is tectonic.

The basement is characterized by banded and migmatized gneisses of varying composition. Different types of conformable mica gneissic and ortho-, para-amphibolitic horizons in the granitoids are typical occurrences in the Lake Syväri area. Differences in the chemical composition of the paragneisses are reflected by different metamorphic mineral parageneses. Kyanite-cordierite rocks, garnet-cordierite-staurolite rocks and cordierite-orthoamphibole rocks are common. Koistinen (1965) described the geology of the area west of Lake Syväri.

The rocks in the granite gneiss area west of the quartzite ridge are conspicuously cata-

Fig. 2. Aeromagnetic map of the Varpaisjärvi–Nilsiä area. The contours limit the map area of fig. 1. Courtesy of the Geological Survey of Finland.

clastic and granitized, including secondary minerals (epidote, chlorite, carbonate). Farther in the west, the basement complex seems to be better preserved and consists predominantly of banded – migmatitic tonalitic-trondhjemitic material with amphibolitic horizons, lenses and inclusions. This type of basement is most typical also around the present study area and according to descriptions in other Archean shields, too.

The usual predominant minerals of that banded rock are oligoclase, quartz, biotite, amphibole with secondary chlorite and epidote. The biotite and amphibole often occur in two generations.

The tonalitic-trondhjemitic rocks with their amphibolitic inclusions represent an obviously lower grade of metamorphism than the rocks in the Varpaisjärvi block area, which is characterized by metamorphic rocks of the granulite facies. The main rock type of the high-grade area is a banded, hypersthene-bearing tonalite-trondhjemite (enderbite) with pyroxene amphibolitic horizons, lenses and inclusions. In the pyroxene amphibolite, in the eastern part of the block, there are conformable, tightly folded horizons of garnet-cordierite-sillimanite rocks with quartzose cordierite-bearing rocks. The high-grade rocks of the Varpaisjärvi area are the main subject of the present study.

Especially in the area of the high-grade block, a swarm of Proterozoic pyroxene- and hornblende diabase dykes cut the basement (fig. 1). These diabases were described by Wilkman (1924, 1938) and Neuvonen *et al.* (1981). The dykes outside the high-grade area are predominantly metadiabases, while the notable alteration phenomena of the diabases in the enderbitic basement area are more or less local.

The block movements seem to be one of the most important factors to have had an effect on the Archean basement during the Proterozoic era. Tuominen *et al.* (1973) stated that the block system of the bedrock represents a permanent shear-net pattern, which has controlled the evolution of the shield since the early Proterozoic. Kauppinen (1973) demonstrated in the nearby Iisalmi region vertical block movements, which can be seen on the present erosion level as constituting a different lithology between adjoining blocks.

Marttila (1976) also recognized the important connection between the subsidence of the block and the partial or total melting and the recrystallization of the rocks.

The abrupt change in metamorphic grade and the strong, sharp-edged magnetic anomalies (fig. 2), with geophysically demonstrated fractures on the margins, all together strongly suggest, for the present area, a separate high-grade metamorphic block, which reached its present level and made its appearance as a result of vertical movements.

The well-preserved and measurable Archean paleomagnetic record (Neuvonen *et al.*, 1981) indicates that no significant post-Archean reheating has taken place in the present block area.

More or less analogous abrupt changes of the metamorphic gradient have been described also in other Archean shield areas, e.g., Churchill Province, Canada (Schledewitz, 1978).

THE HIGH-GRADE METAMORPHIC ROCKS IN THE VARPAISJÄRVI AREA

The rocks in the present block area are characterized by relatively well-preserved, high-grade mineral assemblages, indicating metamorphic PT-conditions of granulite facies. Although there exist shear zones and fractures as well as local granitization, which have sporadically destroyed the parageneses, this peculiar block area is no doubt an important indication of perharps quite a widespread, high-grade metamorphism in the Archean granite gneiss basement, at least at its deeper levels.

Hypersthene-bearing tonalitic-trondhjemitic rocks (enderbites)

Hypersthene-bearing tonalitic-trondhjemitic rocks are predominant in the block area. Their composition is tonalitic, quartz dioritic, even dioritic. Plagioclase is usually abundantly present; it often forms coarse-grained bands and gives a trondhjemitic appearance to the rock. These enderbitic rocks are banded-migmatitic in general. In spite of this predominant heterogeneity, they can be widely very homogeneous and may misleadingly resemble younger intrusive rocks. The massive parts may have been homogenized by the remelting connected with the metamorphism.

The typical minerals of the enderbitic basement are plagioclase, quartz, hypersthene, hornblende and biotite. Magnetite and apatite occur in greater amounts than usually in the basement granitoids.

Plagioclase ($an_{\sim 30}$) is abundant, generally 50–70 %. Potash feldspar occurs primarily only in the antiperthite. The hornblende is brownish in thin section. In places, hypersthene has slightly altered into light amphibole.

Especially in the central parts of the block area, granitization of the enderbite throughout is common. The granitization begins with an increase in the amount of antiperthitic potash feldspar, of which there is finally a large content in the rock. The granitization caused retrogressive alteration. For instance, the hypersthene disappeared and can now be seen only as relict mica aggregates.

There are two zircon (U-Pb)-datings of the enderbitic basement. They give an age of 2680 Ma (Neuvonen *et al*, 1981, 116–117).

Pyroxene amphibolites

Pyroxene amphibolites are most closely associated with the enderbitic rocks. They form conformable bands, lenses and inclusions as well as broad continuous horizons, especially in the Kuikkala–Karsanlahti area (see map, fig. 1). The resemblance between these two rock types is so close that a genetic relationship seems to be clear.

Many of the pyroxene amphibolites are veined by coarser-grained plagioclase-quartz differentiates. In places, the rock is homogeneous, gabbroic. The texture is granoblastic (fig. 3). The usual main mineral parageneses of the amphibolites are

plagioclase + hornblende + clinopyroxene + orthopyroxene
plagioclase + hornblende + clinopyroxene
plagioclase + clinopyroxene + orthopyroxene
plagioclase + hornblende

Garnet may be an additional phase in all the foregoing assemblages. Some biotite and quartz may be present, too. Plagioclase (an_{35-50}) usually constitutes about 50 % of the rock. Clinopyroxene (salite) and orthopyroxene (hypersthene) are principally unaltered, but partial or total uralitization is not rare

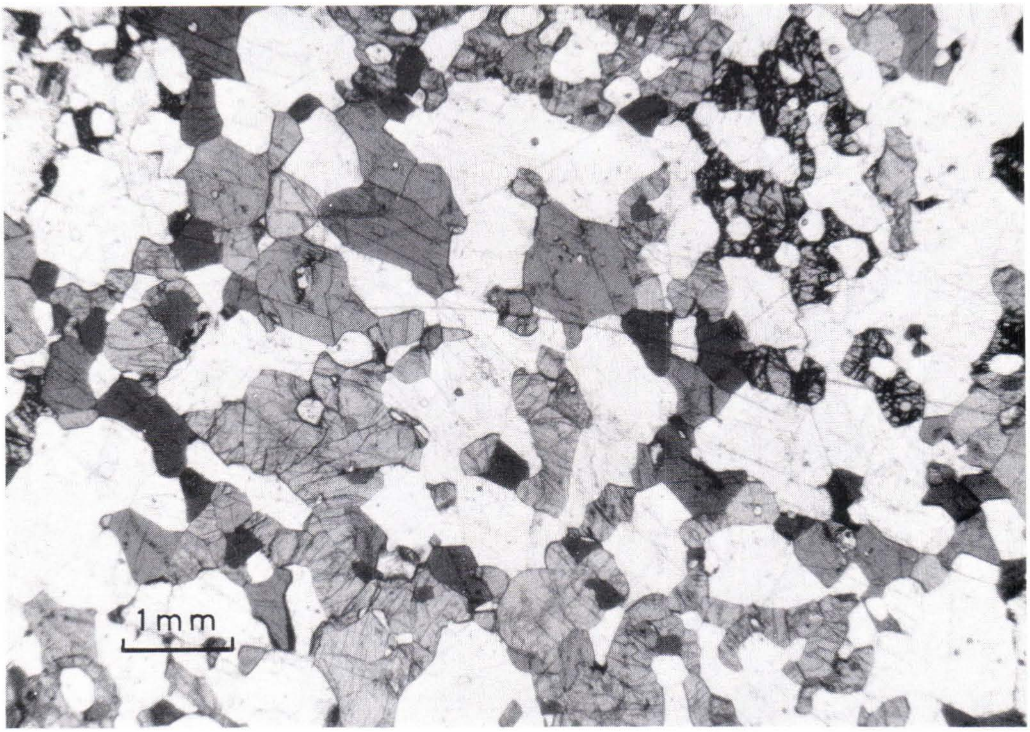

Fig. 3. Typical granoblastic texture in pyroxene amphibolite.

either. The brownish green hornblende is usually well preserved. The pyroxene amphibolites also seem to have been more resistant to granitization than the enderbitic rocks.

The pyroxene amphibolites in the Kuikkala–Karsanlahti area (fig. 1) contain conformable horizons of quartzose cordierite-bearing rocks, garnet-cordierite-sillimanite rocks and orthoamphibole-cordierite rocks. The enderbitic basement in the Jonsa area includes a small, interfolded occurrence of corundum- and sillimanite-bearing rock.

Quartzose cordierite-bearing rocks

Quartzose cordierite-bearing rocks typically consist of quartz and often strongly pinitized cordierite. With changing chemical composition, sillimanite and/or orthoamphibole may appear, too. A light-coloured, disappearing biotite is also often present. The biotite usually exhibits a sagenitic texture (fig. 4) with rutile needles orientated along crystallographical planes. This intergrowth demonstrates the instability of the earlier titaniferous biotite. Collerson and Bridgwater (1979) have investigated the sagenitic microstructure of the biotites in Archean high-grade gneisses from the Saglek area, Labrador. They concluded that the development of sagenitic biotite is related to the synchronous addition of volatiles and potassium to the rock previously depleted in these elements.

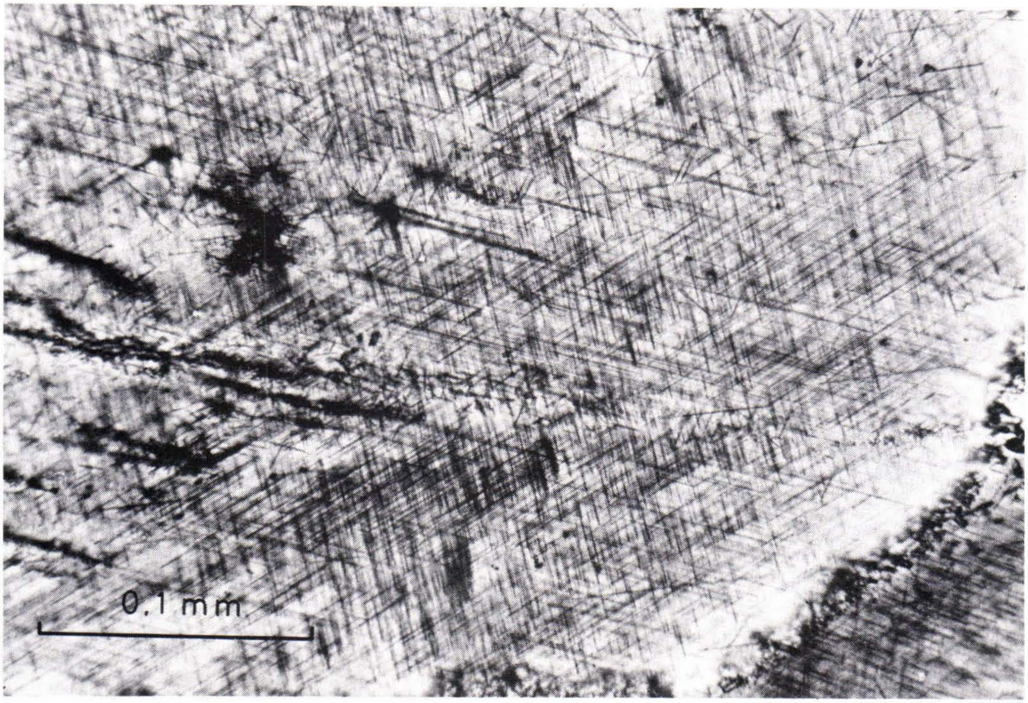

Fig. 4. Sagenitic texture in biotite of a garnet-cordierite-sillimanite rock.

Garnet-cordierite-sillimanite rocks

Garnet-cordierite-sillimanite rocks adjoin the quartzose rocks and they perhaps gradually change into each other, judging by the occurrence of intermediate types, too. The mineral composition is quartz, ± plagioclase, biotite, garnet, sillimanite and, usually cordierite, which in many cases is pinitized in varying amounts. The biotite is often sagenitic in this rock type, too. Sillimanite occurs as euhedral needles and prisms. Pyrope-rich garnet (p. 22) is abundant. It is colourless in thin section and may contain inclusions of quartz, biotite and sillimanite. In the Karsanlahti area, orthopyroxene is met with in the parageneses.

Orthoamphibole-cordierite rocks

Orthoamphibole-cordierite rocks also adjoin the present quartzose rocks in the Kuikkala area. Sporadically, the rock mainly consists of orthoamphibole, but usually it also contains cordierite (pinite), light-coloured biotite and occasionally garnet. Sapphirine has been met with in a couple of places.

Corundum-bearing rocks

Corundum-bearing rocks occur in the Jonsa area (fig. 1). It is a small synform relict of Al-rich material with large ($\varnothing \leq 7$ cm), euhedral corundum porphyroblasts. Sillimanite is also present in places. Dark biotite is common. The rock itself is plagioclase-rich, light-coloured and fine-grained. It might well represent an old weathered crust formed from the surrounding rocks.

The rocks described are most essential indicators of the evolution of the Archean crust and its metamorphism in the Varpaisjärvi area.

The distribution of the high-grade rocks is illustrated with orthopyroxene symbols in fig. 1.

WHOLE ROCK CHEMISTRY

Chemical analyses (XRF-method) of selected rock samples from the study area are presented in tables 1–5. The analyses were done by the geochemical department of the Geological Survey. The iron is reported mostly as $Fe_2O_3{}^T$.

Enderbitic-pyroxene amphibolitic rocks and their lower-grade equivalents

The chemical analyses of the enderbites are given in table 1 and those of the pyroxene amphibolites in table 2. The analyses of the corresponding rocks outside the block area appear in table 3: five tonalitic-trondhjemitic rocks with three adjoining amphibolites. The major elements in tables 1–3 are also shown in the Harker diagrams in figures 5–6. The

Table 1.

Chemical compositions of the enderbitic rocks.

	84 A*– JVP-76	84 B– JVP-76	122– JVP-76	58– JPK-77	15– JVP-76	17– JVP-81	96 A– JVP-76	5– JVP-81	90– JVP-80	153– JVP-78	298 A– JVP-77	96– JVP-79
SiO_2	56.64	57.46	58.19	58.37	52.55	52.73	53.84	56.54	57.03	57.91	64.55	67.00
Al_2O_3	18.88	18.36	18.01	16.19	19.42	20.25	16.13	18.19	19.21	18.87	16.77	16.89
$Fe_2O_3{}^T$	7.28	7.05	6.30	7.19	8.66	8.16	9.17	7.79	6.95	6.79	4.69	4.06
MgO	3.54	3.31	3.34	3.96	4.09	4.11	6.96	3.78	3.58	3.58	2.47	2.17
CaO	6.72	5.83	6.60	5.34	6.97	7.22	7.48	6.66	6.34	5.92	4.82	4.13
Na_2O	5.23	4.90	4.55	4.25	5.24	5.33	4.63	5.52	5.37	5.50	4.50	4.94
K_2O	0.97	0.80	0.92	0.70	0.83	0.75	0.80	0.42	0.77	0.79	0.83	1.09
MnO	0.11	0.09	0.08	0.15	0.12	0.12	0.14	0.11	0.13	0.10	0.09	0.05
TiO_2	0.76	0.70	0.68	0.62	0.91	0.85	0.72	0.89	0.73	0.69	0.45	0.43
P_2O_5	0.25	0.25	0.28	0.18	0.31	0.29	0.42	0.29	0.26	0.24	0.16	0.10
	100.45	98.73	98.96	96.95	99.10	99.81	100.28	100.19	100.38	100.40	99.32	100.85

* All sample numbers refer to the codes used in the course of mapping.

Table 2.
Chemical compositions of the pyroxene amphibolites.

	109– JVP-76	111– JVP-76	71 B– JVP-76	259– JVP-76	129 A– JVP-79	116– JVP-79	5– JVP-80	78– JVP-79	93– JVP-80	56 A– JPK-77	171– JVP-79	110 B– JVP-76	110 A– JVP-76
SiO_2	52.39	51.69	51.38	51.51	48.92	48.38	49.99	51.75	51.79	53.26	53.57	57.81	57.82
Al_2O_3	15.29	14.61	18.04	16.50	14.82	14.53	15.24	18.56	15.37	14.25	16.61	13.05	13.23
$Fe_2O_3{}^T$	9.94	11.77	9.16	9.49*	12.88	14.14	12.60	6.94	10.74	10.71	8.49	12.10	12.32
MgO	6.94	6.42	5.23	7.76	7.55	7.81	6.19	7.22	6.81	5.62	8.90	2.80	3.19
CaO	10.01	9.83	8.45	10.58	10.56	10.86	12.30	10.52	8.61	10.20	7.60	5.95	5.98
Na_2O	3.13	2.76	4.61	2.86	2.18	2.17	3.18	3.60	4.06	3.48	4.03	3.96	3.56
K_2O	0.52	0.37	1.21	0.47	0.03	0.21	0.74	0.56	0.96	0.87	0.57	1.86	1.26
MnO	0.14	0.19	0.13	0.15	0.20	0.20	0.22	0.12	0.19	0.18	0.16	0.15	0.15
TiO_2	0.51	0.64	0.97	0.53	0.77	0.92	0.86	0.54	0.73	0.60	0.29	1.09	1.13
P_2O_5	0.06	0.08	0.19	0.06	0.08	0.08	0.05	0.10	0.11	0.06	0.00	0.19	0.18
	98.93	98.37	99.37	99.11	98.00	99.32	101.38	99.90	99.37	99.23	100.21	98.97	98.82

* FeO: 7.00
Fe_2O_3: 1.69

Table 3.
Chemical compositions of the tonalitic – trondhjemitic and amphibolitic (*) basement rocks.

	113– JVP-81	78– JVP-81	46– JVP-81	85 A– JVP-80	112 A– RKV-79	40*– JVP-80	74*– JVP-81	155*– JVP-82
SiO_2	59.40	66.62	69.29	69.38	69.78	50.88	50.43	51.72
Al_2O_3	17.42	15.59	16.18	16.96	15.92	14.73	14.01	15.55
$Fe_2O_3{}^T$	7.06	5.42	1.83	2.92	3.38	12.04	11.60	12.18
MgO	2.76	1.86	0.77	1.29	1.46	7.80	8.44	7.51
CaO	5.99	3.97	2.20	3.14	3.45	11.23	10.78	9.59
Na_2O	4.45	4.13	4.30	4.58	5.01	3.16	2.96	3.47
K_2O	1.19	0.87	3.65	1.61	1.18	0.62	1.03	0.73
MnO	0.12	0.08	0.03	0.04	0.05	0.21	0.20	0.18
TiO_2	0.73	0.51	0.21	0.37	0.43	0.83	0.75	1.02
P_2O_5	0.17	0.13	0.05	0.12	0.10	0.05	0.03	0.10
	99.29	99.18	98.50	100.41	100.76	101.54	100.23	102.06

most characteristic features of the tonalitic-trondhjemitic rocks in the high-grade areas (table 1) as well as in related lower-grade areas (table 3) are a high Na/K-ratio and a rather high Al_2O_3-content (usually > 16 %). Especially the low K_2O-content is a dominant feature in all these rocks (< 2 %, mostly < 1 %). Occasional increased K_2O-contents are due to granitization.

By their composition, the amphibolites, representing the other prevalent rock component of the area, are essentially more basic than the enderbitic rocks and seem to be distributed at least into two compositional groups.

Most of the enderbites seem to be concentrated between 56 and 60 % SiO_2, but some of them are more basic (SiO_2 < 54 %), like the

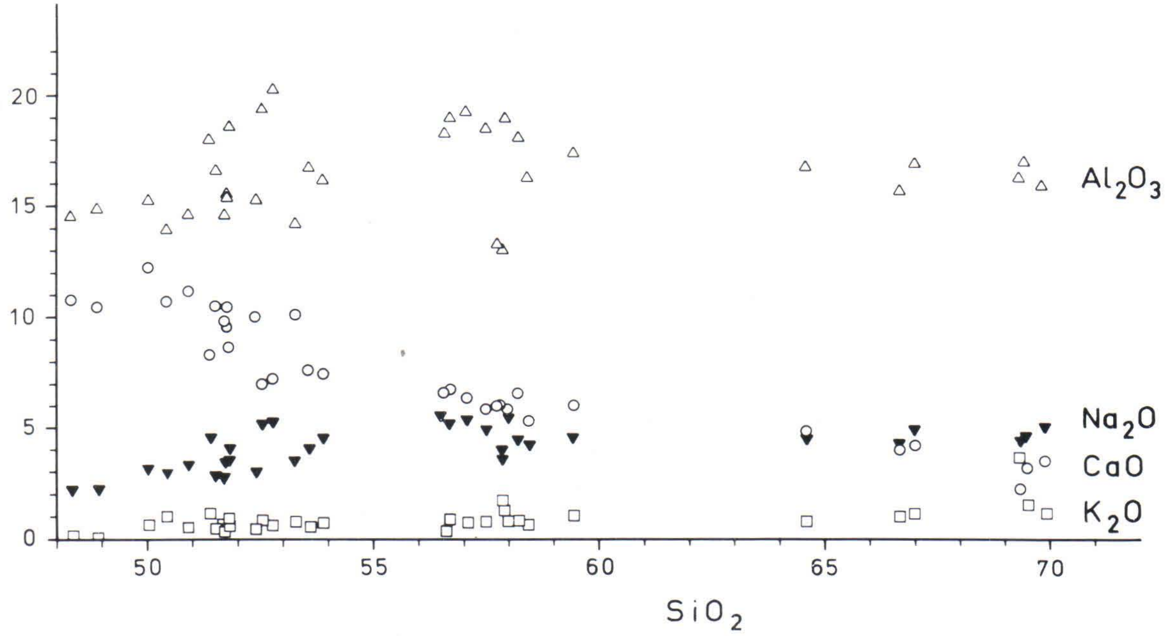

Fig. 5. Distribution of the main oxides of the tonalitic-trondhjemitic and amphibolitic rocks in the Varpaisjärvi area. Symbols: square = K_2O, black triangle = Na_2O, circle = CaO, open triangle = Al_2O_3.

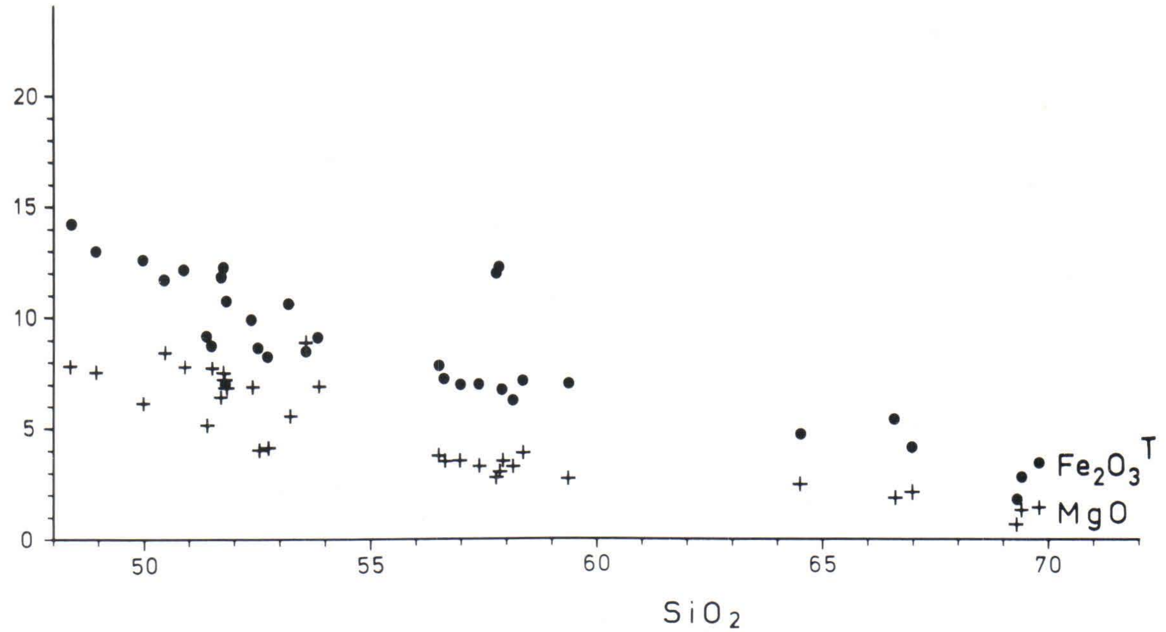

Fig. 6. Distribution of the main oxides of the tonalitic-trondhjemitic and amphibolitic rocks in the Varpaisjärvi area. Symbols: cross = MgO, spot = $Fe_2O_3^T$.

amphibolites. A couple of them, on the other hand, plot among the samples from the tonalitic-trondhjemitic area (SiO_2 64–70 %), where the increased trondhjemitic material adds to the SiO_2 content. The three amphibolite samples from the area of the lower metamorphic grade are similar in chemical composition to those of the pyroxene amphibolites. The field observations indicate that only the narrowest amphibolitic bands have been assimilated by the migmatizing trondhjemitic material.

Although the number of analyses is small, it is evident that by their chemical composition the enderbites and amphibolites form a bimodal rock series, which possesses features analogous to similar rocks from certain other Archean shield areas (e.g., Barker & Arth, 1976; Tarney *et al.*, 1979).

Other analyses

The chemical analyses of the quartzose cordierite rocks and garnet-cordierite-sillimanite rocks from the Kuikkala–Karsanlahti area are listed in table 4. Table 5 presents the chemistry of the corundum-sillimanite-bearing rocks, MgO-rich orthoamphibole rock and two kyanite-cordierite rocks from the adjacent Nilsiä area (fig. 1). Those two analyses of the kyanite-cordierite-bearing rocks are presented as compositional reference material with the related higher grade sillimanite rocks of the block area. All these analyses (except the high-aluminium corundum rocks) have been plotted on the $Al_2O_3-(Fe_2O_3T + MgO)-(alk + CaO)$ diagram (fig. 7). This clearly demonstrates the most typical compositional features of rocks of this kind adjoining the cordierite-antophyllite rock milieu: The deficiency of alkalies and calcium together with comparatively high iron and magnesium.

Similar chemical compositions have been reported also from certain Proterozoic garnet-cordierite-antophyllite rock associations in Central Finland (e.g., Marttila, 1976; Huhtala, 1979). These kinds of chemical composition are evidently related to the hydrothermal

Table 4.

Chemical compositions of quartzose cordierite rocks and garnet-cordierite-sillimanite rocks.

	8 A– JVP-77	8 B– JVP-77	3 B– JVP-78	108 B– JPK-77	227 A– JVP-77	5 B– JVP-78	107 B– JPK-77	227 B– JVP-77	8 C– JVP-77
SiO_2	66.01	49.90	65.97	78.46	83.37	76.93	76.53	73.58	71.04
Al_2O_3	12.56	22.84	12.05	10.82	9.48	12.55	11.12	12.66	12.66
Fe_2O_3T	8.45	10.31	12.23	3.23	2.76	1.35	1.39	3.58	6.75
MgO	8.03	10.60	6.57	4.02	4.17	6.19	6.42	6.36	5.29
CaO	0.32	0.34	0.36	0.88	0.09	0.09	0.16	0.10	0.18
Na_2O	0.43	0.49	0.21	1.02	0.40	0.78	0.79	0.86	0.69
K_2O	1.89	2.98	0.27	0.52	0.00	0.76	0.63	0.00	1.04
MnO	0.11	0.14	0.08	0.00	0.00	0.00	0.00	0.00	0.07
TiO_2	0.70	1.06	0.82	0.23	0.26	0.34	0.30	0.43	0.32
P_2O_5	0.04	0.06	0.06	0.00	0.04	0.04	0.00	0.00	0.04
	98.55	98.73	98.63	99.18	100.57	99.03	97.34	97.57	98.07

Table 4.
continued

	108 C– JPK-77	108 D– JPK-77	2– JVP-75	3 D– JVP-78	8 D– JVP-77	8 E– JVP-77	8 F– JVP-77
SiO_2	75.72	77.67	70.40	59.86	60.40	63.42	51.36
Al_2O_3	12.92	11.79	11.87	16.43	16.56	21.00	21.21
Fe_2O_3T	4.62	3.97	3.20	6.65	9.23	4.47	12.60
MgO	6.02	5.39	8.10	9.30	7.88	5.09	10.17
CaO	0.26	0.71	0.18	0.21	1.01	1.03	0.94
Na_2O	0.70	1.48	0.88	0.86	2.53	2.87	2.24
K_2O	0.68	1.14	0.56	1.22	2.17	2.32	2.38
MnO	0.05	0.00	0.00	0.06	0.16	0.06	0.26
TiO_2	0.30	0.29	0.54	0.75	1.01	0.91	1.04
P_2O_5	0.00	0.00	0.04	0.05	0.01	0.08	0.08
	101.26	102.45	95.77	95.39	100.99	101.26	102.28

Table 5.

Chemical analyses of the corundum bearing rock, orthoamphibole-cordierite rock (*) and kyanite-cordierite rocks (°). (Kyanite-cordierite rocks are from the Nilsiä area; see p. 6).

	298 E– JVP-77	298 D– JVP-77	227 C*– JVP-77	130 A°– JVP-75	130 B°– JVP-75
SiO_2	48.53	45.66	36.73	55.63	70.76
Al_2O_3	40.16	30.58	22.69	28.19	16.38
Fe_2O_3T	2.04	6.65	12.63	2.67	2.33
MgO	0.59	3.11	20.44	8.17	7.69
CaO	2.03	3.43	0.34	0.87	0.83
Na_2O	5.41	4.61	1.52	2.15	1.81
K_2O	1.31	3.34	0.87	1.12	0.19
MnO	0.00	0.05	0.06	0.00	0.00
TiO_2	1.85	1.54	0.47	0.84	0.69
P_2O_5.	0.00	0.00	0.05	0.04	0.15
	101.92	98.97	95.82	99.67	100.82

alteration connected to the early volcanism. Additional metasomatic alteration phenomena connected to the high-grade metamorphism are possible, too.

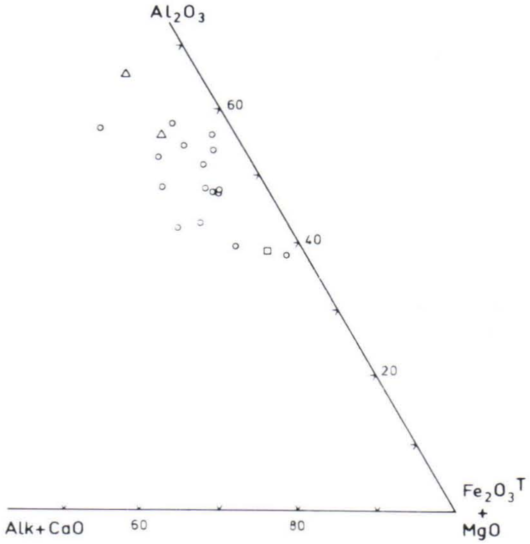

Fig. 7. Al_2O_3 – ($Fe_2O_3{}^T$+MgO) – (Alk+CaO) diagram for rocks in the Varpaisjärvi–Nilsiä area (see tables 4–5). Symbols: circle = quartzose cordierite rocks and garnet-cordierite-sillimanite rocks, triangle = kyanite-cordierite rocks (Nilsiä area), square = orthoamphibole-cordierite rock.

ROCK GENESIS

The prevailing rock types of the area, consisting of banded tonalitic-trondhjemitic material with amphibolitic lenses and horizons, evidently primarily formed a basic-intermediate igneous series. The magmatic processes probably produced both volcanic and more homogeneous plutonic rocks. As stated, it is possible, however, that at least part of the homogeneous and massive trondhjemitic, tonalitic or enderbitic rocks were homogenized by anatectic processes during the subsequent high-grade metamorphism.

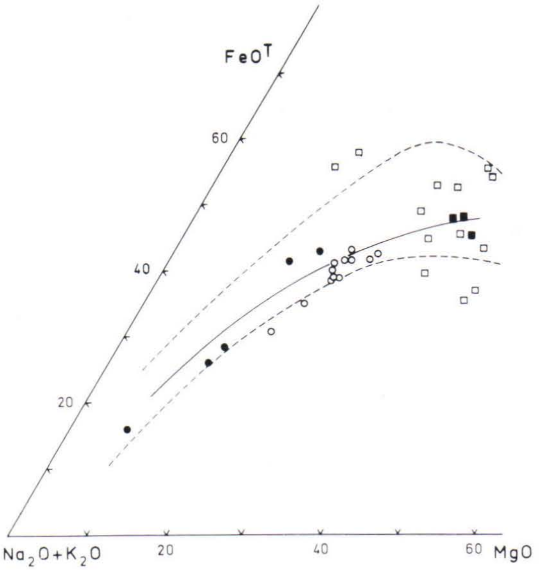

Fig. 8. (Na_2O+K_2O) – FeO^T – MgO diagram of the tonalitic-trondhjemitic and amphibolitic rocks in the Varpaisjärvi area. Symbols: circles = enderbites, open squares = pyroxene amphibolites, black spots and squares = tonalitic-trondhjemitic and amphibolitic rocks, respectively (outside the block area). Calc-alkaline field (broken line) and trondhjemitic trend (solid line) after Barker and Arth, 1976.

In spite of the compositional differences in the main components, the genetic relationship between the foregoing types is obvious. They became mixed in many places and formed, as can be seen on many outcrops, complex and heterogeneous migmatites, which were further overprinted by the younger trondhjemitic migmatization. It is in many cases difficult to tell what part of the rock is primary and what part is a result of mixing of the primary components or trondhjemitic mobilization.

In fig. 8, the main rock types have been plotted on the $(Na_2O + K_2O)-FeO^T-MgO$ diagram. Most of the rock compositions plot very clearly on the calc-alkalic field with a trondhjemitic trend emphasized in the lower-grade samples outside the block area. The bimodal main distribution is also evident. The amphibolitic material has some indications of more than one compositional group,

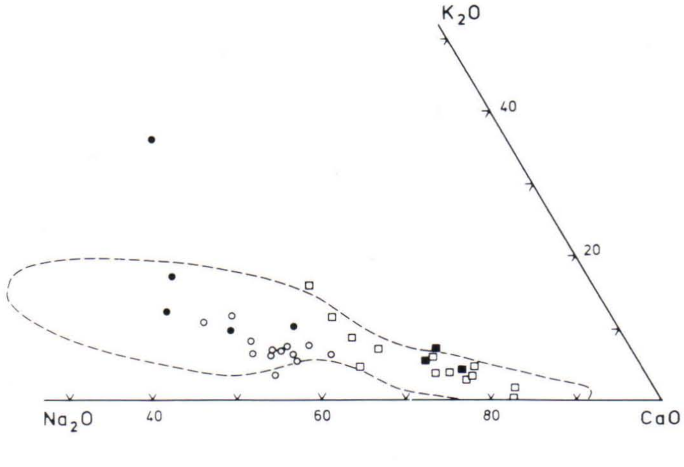

Fig. 9. Na_2O – K_2O – CaO diagram. Samples and their symbols as in fig. 8. Trondhjemitic field (broken line) after Hunter, 1979.

although the deviating samples form in any case a minority.

The same samples are also represented in the diagram of fig. 9 (Na_2O – K_2O – CaO). The typical distribution in the field of trondhjemitic series rocks can be seen.

The distribution of the samples in the diagrams produces trends similar to those of certain other Archean granulites, e.g., the Lewisian granulites in Scotland (Weaver *et al.*, 1978; Tarney *et al.*, 1979).

As mentioned (p. 10–11, fig. 7), the narrow horizons of quartzose cordierite rocks and garnet-cordierite-sillimanite rocks, enveloped by pyroxene amphibolites, possibly suggest a sedimentogenic origin in a volcanic milieu with subsequent hydrothermal alteration. Later metasomatic changes are possible, too.

Patchett *et al.* (1981) determined the initial $^{176}Hf/^{177}Hf$ of the zircon of the hypersthene quartz dioritic (enderbitic) basement in the Varpaisjärvi area. The ratio was interpreted to indicate a mantle origin for the rock.

Following the ideas represented by Barker and Arth (1976), it is suggested that the tonalitic-trondhjemitic and amphibolitic rocks of the present area are a primarily differentiated basaltic mantle melt with a relatively high H_2O-content. Where the rocks were metamorphosed under high-grade PT-conditions, the basaltic material turned into pyroxene amphibolites with plagioclase-quartz differentiates. The intermediate material partly homogenized, partly mobilized and caused trondhjemitic mobilization and rehydration prosesses in the adjoining rocks.

Accordingly, this basic-intermediate material as a whole metamorphosed into the banded tonalitic-trondhjemitic rocks with amphibolitic inclusions and horizons – in other words, the most common rocks in the Archean basement.

The scheme in fig. 10 offers a possible model for the general evolution of the present high-grade rocks.

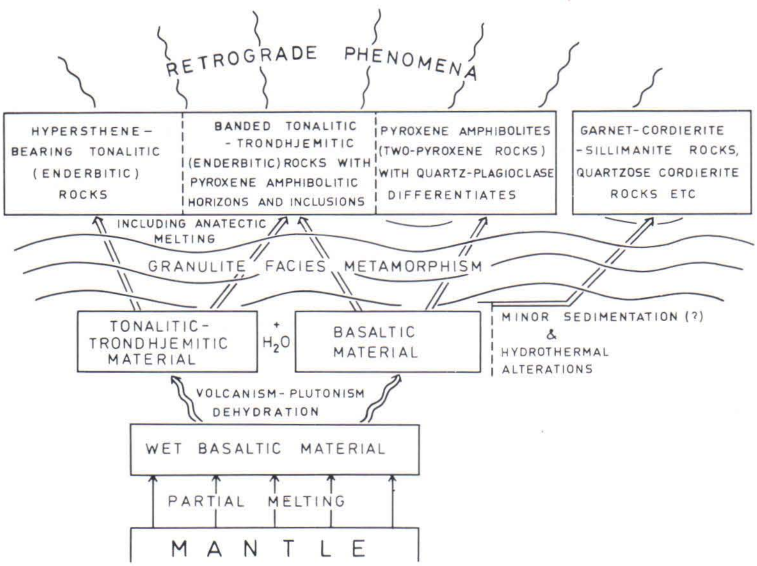

Fig. 10. A schematic model representing the possible evolution of the rocks in the Varpaisjärvi area.

MINERAL CHEMISTRY

The mineral analyses were done in the microprobe laboratory of the Geological Survey. The analyses comprise garnets, biotites and cordierites of the garnet-cordierite-sillimanite rocks, orthopyroxenes, clinopyroxenes, hornblendes and a garnet of the pyroxene amphibolites and orthopyroxenes and hornblendes of the enderbites.

The oxide percentages shown in tables 6–11 are mean values of two . . . four analysed points.

Pyroxenes

Seven coexisting pyroxenes of the pyroxene amphibolites and four orthopyroxenes of the enderbites were analysed (tables 6–7).

In fig. 11, seven coexisting pyroxenes and four orthopyroxene-hornblende pairs have been plotted on the Fe-Mg-Ca diagram. The clinopyroxenes indicate salite and orthopyroxenes, a hypersthene composition. One clinopyroxene has a lower Ca, resembling an augitic composition. It can also be seen that there is no systematic difference between the orthopyroxene compositions of enderbitic and amphibolitic rocks and that they all exhibit a typical metamorphic low Ca character.

Table 6.

Microprobe analyses of orthopyroxenes of enderbitic and pyroxene amphibolitic rocks.

	enderbites				pyroxene amphibolites						
	84– JVP-76	58A– JPK-77	129– JVP-79	90– JVP-80	109– JVP-76	111– JVP-76	259– JVP-76	56A– JPK-77	78– JVP-79	116– JVP-79	129A– JVP-79
SiO_2	50.8	51.2	52.6	52.8	52.3	50.0	53.4	51.9	53.2	51.6	51.2
TiO_2	0.2	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Al_2O_3	1.1	1.1	1.3	1.1	1.6	1.7	1.4	1.2	1.8	1.5	2.0
FeO	26.7	25.0	28.7	24.3	26.5	28.9	26.9	28.5	21.6	27.1	26.3
MgO	21.2	21.4	18.7	21.1	19.2	18.9	20.3	18.5	22.5	19.2	19.4
CaO	0.5	0.5	0.7	0.5	0.7	0.4	0.4	0.4	1.7	0.5	0.6
Na_2O	0.0	0.3	0.0	0.0	0.4	0.1	0.0	0.0	0.1	0.1	0.1
Tot	100.5	99.6	102.0	99.9	100.7	100.0	102.4	100.5	100.9	100.0	99.7
Number of ions on the basis of six oxygen atoms											
Si	1.925	1.944	1.971	1.980	1.969	1.925	1.972	1.974	1.957	1.961	1.947
Ti	0.006	0.003	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.003
Al	0.049	0.047	0.057	0.049	0.071	0.075	0.061	0.054	0.078	0.067	0.090
Fe^{2+}	0.848	0.795	0.899	0.762	0.834	0.929	0.831	0.906	0.665	0.861	0.836
Mg	1.197	1.210	1.044	1.179	1.079	1.088	1.118	1.049	1.234	1.091	1.101
Ca	0.020	0.020	0.028	0.020	0.028	0.019	0.016	0.016	0.067	0.022	0.024
Na	0.000	0.022	0.000	0.000	0.029	0.004	0.000	0.000	0.007	0.004	0.007

Table 7.

Microprobe analyses of clinopyroxenes of amplibolitic rocks.

	109– JVP-76	111– JVP-76	259– JVP-76	56A– JPK-77	78– JVP-79	116– JVP-79	129A– JVP-79
SiO_2	51.3	50.0	53.2	53.7	53.3	50.2	50.0
TiO_2	0.3	0.3	0.0	0.0	0.0	0.5	0.4
Al_2O_3	2.6	2.8	2.0	2.7	2.7	3.4	3.6
FeO	10.6	11.1	10.2	12.1	7.8	10.4	10.4
MgO	12.5	12.0	13.2	11.9	13.9	12.1	11.7
CaO	21.5	21.3	21.3	18.5	22.1	21.8	21.5
Na_2O	0.6	0.0	0.5	0.7	0.5	0.7	0.8
Tot	99.4	97.5	100.4	99.6	100.3	99.1	98.4
Number of ions on the basis of six oxygen atoms							
Si	1.942	1.934	1.977	2.007	1.965	1.908	1.912
Ti	0.007	0.007	0.000	0.000	0.000	0.014	0.012
Al	0.116	0.125	0.088	0.119	0.117	0.152	0.162
Fe^{2+}	0.334	0.357	0.317	0.378	0.240	0.331	0.331
Mg	0.702	0.692	0.731	0.668	0.764	0.685	0.668
Ca	0.870	0.881	0.848	0.741	0.873	0.886	0.882
Na	0.044	0.000	0.036	0.051	0.036	0.052	0.056

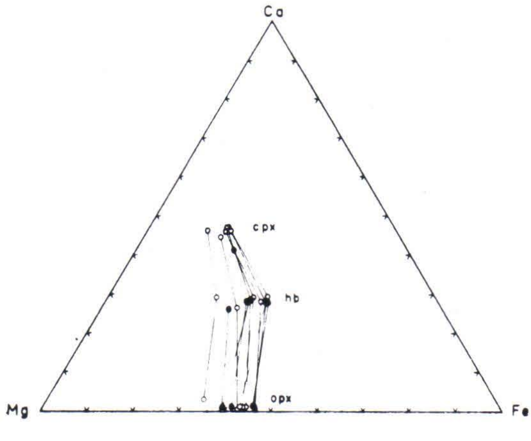

Fig. 11. Mg – Fe – Ca diagram representing the compositions of the coexisting pyroxenes-hornblende in the pyroxene amphibolites (circles) and coexisting orthopyroxene-hornblende in enderbites (spots) from the Varpaisjärvi area.

Hornblende

The chemical compositions of eleven analysed hornblendes are given in table 8.

Fig. 11 exhibits, in addition to the pyroxenes, the Ca-Fe-Mg distribution of the coexisting hornblendes. The scatter of the samples does not show any explainable trends between the different rocks.

Leake (1965) investigated metamorphic, igneous and skarn Ca-amphiboles to determine their $Al^{[4]}-Al^{[6]}$ contents. He plotted 936 cal-

Table 8.

Microprobe analyses of hornblendes of enderbitic and pyroxene amphibolitic rocks.

	enderbites				pyroxene amphibolites						
	84–JVP-76	58A–JPK-77	129–JVP-79	90–JVP-80	109–JVP-76	111–JVP-76	259–JVP-76	56A–JPK-77	78–JVP-79	116–JVP-79	129A–JVP-79
SiO_2	41.8	41.7	43.1	44.0	43.9	41.2	45.5	42.6	45.9	43.6	41.4
TiO_2	1.9	2.4	2.3	2.0	2.2	2.4	1.9	2.3	1.8	2.3	1.7
Al_2O_3	11.7	11.9	12.1	10.9	12.6	12.2	11.1	11.3	10.7	12.5	13.3
FeO	15.6	15.2	17.0	14.7	15.5	17.6	14.8	16.9	12.2	15.4	16.8
MgO	11.9	11.3	10.0	13.6	10.8	10.5	12.4	10.6	13.8	11.2	10.0
CaO	11.2	11.0	10.5	10.8	11.2	11.1	10.4	11.0	11.9	11.0	11.2
Na_2O	0.8	0.7	1.6	2.2	1.7	0.8	2.0	2.2	1.7	1.9	2.2
Tot	94.9	94.2	96.6	98.2	97.9	95.8	98.1	96.9	98.0	97.9	96.6
Number of ions on the basis of 23 oxygen atoms											
Si	6.381	6.395	6.480	6.465	6.471	6.297	6.648	6.425	6.657	6.435	6.273
Ti	0.218	0.271	0.260	0.221	0.244	0.270	0.209	0.261	0.196	0.255	0.194
Al	2.108	2.144	2.144	1.887	2.189	2.198	1.911	2.009	1.829	2.174	2.369
Fe^{2+}	1.994	1.952	2.138	1.806	1.911	2.250	1.808	2.132	1.480	1.895	2.125
Mg	2.700	2.586	2.241	2.978	2.373	2.392	2.700	2.383	2.983	2.453	2.250
Ca	1.834	1.809	1.691	1.700	1.761	1.809	1.628	1.778	1.849	1.739	1.821
Na	0.222	0.208	0.466	0.627	0.486	0.237	0.567	0.643	0.478	0.544	0.632

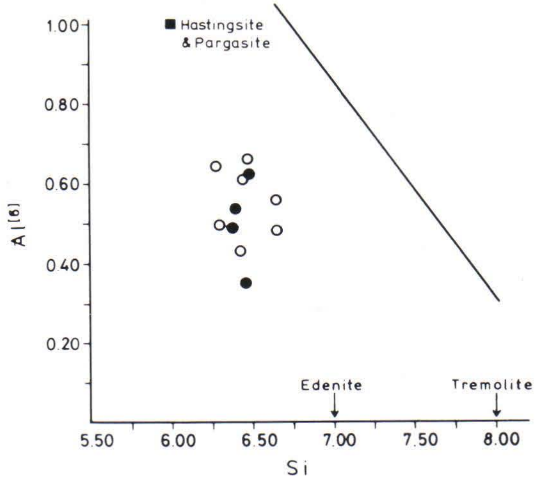

Fig. 12. The plot of $Al^{[6]}$ against Si in the hornblendes of the Varpaisjärvi area. Symbols: open circle = pyroxene amphibolitic rock, spot = enderbitic rock. The line shows the maximum possible $Al^{[6]}$ suggested by Leake, 1965.

ciferous and subcalciferous amphiboles on the Si–$Al^{[6]}$ diagram. Fig. 12 represents the eleven hornblendes of the present study in an analogous diagram. All the analytic points are concentrated in the typical area of the Ca-amphiboles of metamorphic origin.

Table 9.

Microprobe analyses of garnets of garnet-cordierite-sillimanite-bearing rocks.

	8A– JVP-77	8B– JVP-77	8C– JVP-77	8E– JVP-77	108B– JPK-77	108C– JPK-77	108D– JPK-77	227D– JVP-77	3B– JVP-78	111– JVP-76*
SiO_2	40.2	40.6	40.0	38.5	41.3	40.1	39.6	42.0	39.6	38.6
TiO_2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Al_2O_3	21.4	21.7	22.3	22.4	22.0	22.5	22.7	22.8	21.4	20.4
FeO	21.8	22.0	22.7	24.8	19.8	20.2	23.7	25.0	24.6	27.1
MnO	0.5	0.5	0.3	0.7	0.2	0.3	0.4	0.8	0.2	1.6
MgO	13.9	13.8	15.3	13.1	15.5	16.2	14.4	13.2	12.4	5.3
CaO	0.9	0.9	0.3	0.7	1.2	1.4	1.1	0.6	0.6	6.9
Tot	98.7	99.5	100.9	100.2	100.0	100.7	101.9	104.4	98.8	99.9
Number of ions on the basis of 24 oxygen atoms										
Si	6.092	6.101	5.934	5.840	6.089	5.913	5.862	6.065	6.057	6.072
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	3.813	3.834	3.899	4.005	3.831	3.910	3.960	3.880	3.858	3.787
Fe^{2+}	2.757	2.758	2.816	3.146	2.441	2.491	2.934	3.019	3.147	3.570
Mn	0.064	0.064	0.038	0.090	0.019	0.037	0.050	0.098	0.026	0.207
Mg	3.129	3.080	3.383	2.962	3.417	3.560	3.177	2.841	2.827	1.233
Ca	0.146	0.145	0.048	0.114	0.197	0.221	0.174	0.093	0.098	1.165

* garnet of pyroxene amphibolitic rock.

Garnet

The chemistry of the garnets of the present work is represented in table 9. The most characteristic feature is their high MgO content with relatively low, nearly insignificant MnO and CaO contents. The low Ca content is noticeable also in fig. 13, where the garnets are plotted on the Ca-Fe-Mg diagram with some garnets from related rocks from the granulite complex of Finnish Lapland (Hörmann *et al.*, 1980) as a reference. The garnets of the garnet-cordierite-sillimanite rocks from the Varpaisjärvi area have a really high content of the pyrope component (~ 47–57 %). This is also clearly more than the pyrope content of the garnets of the granulite facies rocks from Lapland (pyr % ~ 30–45). The garnets also are quite homogeneous (unzoned), which makes it easy to use them as thermobarometers.

The separate spot on the diagram indicates the composition of the analysed garnet (table 9, 111–JPK-77) from a pyroxene amphibolite. Rich in the grossular component, its composition is most typical of basic granulites.

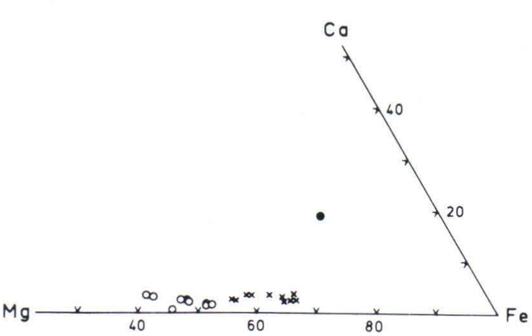

Fig. 13 The Ca – Fe – Mg diagram for garnets. Symbols: open circles = garnet-cordierite-sillimanite rocks from the Varpaisjärvi area, crosses = related rocks from the granulite complex of Lapland (Hörmann *et al.*, 1980), spot = pyroxene amphibolite from the Varpaisjärvi area.

Biotite

The biotite composition of nine garnet-cordierite-sillimanite rock samples is shown in table 10. The most conspicuous feature in the chemistry of the biotites is their high MgO and relatively low FeO. The TiO_2 is comparatively low, too. The average MgO, FeO and TiO_2 weight percentages of the biotites are 18.4, 7.3 and 2.0, respectively, while, e.g., the corresponding average values of biotites from five samples from Lapland are 13.4, 13.9 and 5.4 (Hörmann *et al.*, 1980, p. 53).

The comparatively low TiO_2 in the biotites of the Varpaisjärvi area may be at least partly due to the sagenitic texture (p. 11, fig. 4). In other words, the analyses are from more or less rutile-free spots and accordingly give lower TiO_2 values. The situation resembles that as regards the biotites from the Saglek area, Labrador, described by Collerson and Bridgwater (1979).

Table 10.

Microprobe analyses of biotites of garnet-cordierite-sillimanite-bearing rocks.

	8A–JVP-77	8B–JVP-77	8C–JVP-77	8E–JVP-77	108B–JPK-77	108C–JPK-77	108D–JPK-77	227D–JVP-77	3B–JVP-78
SiO_2	40.3	40.0	41.3	40.6	42.0	41.9	41.3	40.8	36.2
TiO_2	2.6	1.7	1.7	1.9	2.4	2.4	1.7	1.4	2.6
Al_2O_3	20.0	19.8	18.6	18.8	17.8	17.0	18.0	18.5	15.7
FeO	8.6	7.2	6.7	7.1	7.7	6.1	7.6	6.8	7.6
MnO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MgO	16.8	17.9	19.5	18.3	18.5	20.1	19.4	20.0	14.9
CaO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
K_2O	9.5	8.9	9.6	9.9	9.5	9.6	9.5	8.7	8.9
Tot	97.8	95.5	97.4	96.6	97.9	97.1	97.5	96.2	85.9
Number of ions on the basis of 23 oxygen atoms									
Si	5.860	5.900	5.981	5.954	6.070	6.342	6.000	6.212	6.020
Ti	0.284	0.189	0.185	0.210	0.261	0.269	0.186	0.163	0.325
Al	3.428	3.442	3.174	3.250	3.032	3.029	3.082	3.327	3.077
Fe^{2+}	1.046	0.888	0.811	0.871	0.931	0.771	0.923	0.861	1.057
Mn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	3.642	3.935	4.209	4.000	3.985	4.539	4.201	4.553	3.693
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K	1.762	1.675	1.773	1.852	1.751	1.845	1.761	1.689	1.888

Cordierite

Four samples of cordierite coexisting with garnet and sillimanite were analysed. The results are listed in table 11. As can be seen, they are almost identical in composition. The characteristic feature is also in this case an extremely high MgO content with low FeO. This composition indicates quite high pressure during metamorphism.

The X_{Mg} value varies between 0.87 and 0.92, while in the garnet-cordierite-sillimanite gneisses of the Lappish granulites it is between 0.74 and 0.80 (Hörmann *et al.*, 1980, p. 50).

Descriptions and analyses of Archean garnet-cordierite-sillimanite rocks are quite scarce in the literature compared with, e.g., the analytical data for other Archean high-grade rocks. In any case, the available garnet, cordierite and biotite analyses from Archean high-grade areas (e.g., Harris *et al.*, 1982) do not usually exhibit quite as high MgO/FeO ratios as these minerals do in related rocks in the study area. However, nearly analogous chemical compositions have also been reported for Archean metamorphic minerals – recently, for instance, from the Limpopo Mobile Belt, southern Africa (Horrocks, 1983).

Table 11.

Microprobe analyses of cordierites of garnet-cordierite-sillimanite-bearing rocks.

	108B–JPK-77	108C–JPK-77	108D–JPK-77	227D–JVP-77
SiO_2	49.6	51.4	51.6	51.2
TiO_2	0.0	0.0	0.0	0.0
Al_2O_3	35.0	33.8	34.0	34.9
FeO	2.2	2.0	3.0	2.0
MgO	12.7	12.1	11.7	12.5
CaO	0.0	0.0	0.0	0.0
Na_2O	0.1	0.1	0.1	0.2
Tot	99.6	99.4	100.4	100.8
Number of ions on the basis of 18 oxygen atoms				
Si	4.914	5.073	5.066	4.992
Ti	0.000	0.000	0.000	0.000
Al	4.081	3.932	3.934	4.011
Fe^{2+}	0.182	0.165	0.246	0.163
Mg	1.868	1.780	1.712	1.817
Ca	0.000	0.000	0.000	0.000
Na	0.000	0.019	0.019	0.038

GEOTHERMOBAROMETERS

Pyroxene geothermometer

Experimental petrologists have repeatedly tried to solve the distribution of elements between ortho- and clinopyroxenes and its dependence on temperature. On the basis of the miscibility gap between diopside and enstatite, the Fe-Mg distribution has been used successfully as a thermometer to determine not only magmatic but high-grade metamorphic equilibrium temperatures as well (Wood & Banno, 1973; Fleet, 1974; Saxena & Nehru, 1975; Wells, 1977; . . .). The Fe-Mg distribution in the two-pyroxene assemblage has been found to be mainly dependent on temperature. Evidently, the role of the pressure is not very important, especially at metamorphic temperatures. The distribution is probably most ideal at about 1000°C (Saxena & Nehru, 1975).

Wood and Banno (1973), who first worked out a formula for the purpose of determining temperature, assume the $Fe^{2+}-Mg^{2+}$ ion distribution to be random between the M_1 and M_2 sites of the pyroxenes. This assumption holds well with the calculated standard free-energy changes in the reaction. Wilson (1976) criticized the random distribution between the M_1 and M_2 sites and considered aluminium in the coexisting pyroxenes to be

Table 12.

Metamorphic temperatures according to the coexisting pyroxene pairs (see text).

Sample	x_{Fe}^{opx}	$a_{Mg_2Si_2O_6}^{cpx}$	$a_{Mg_2Si_2O_6}^{opx}$	Temperature (°C) Wood & Banno (1973)	Wells (1977)
111–JVP-76	0.461	0.047	0.284	847	895
109–JVP-76	0.436	0.043	0.288	847	887
259–JVP-76	0.426	0.051	0.313	864	909
56A–JPK-77	0.463	0.062	0.275	886	955
78–JVP-77	0.350	0.046	0.377	872	890
116–JVP-79	0.441	0.037	0.296	824	854
129A–JVP-79	0.432	0.034	0.301	817	841
				av. 851	av. 890

a more sensitive indicator of the metamorphic grade than $K_{D_{Fe\text{-}Mg}}^{opx\text{-}cpx}$

Kretz (1981) reported more detailed information on the distribution of the Fe^{2+} and Mg^{2+} ions between the M_1 and M_2 sites of the pyroxenes of the granulite facies rocks.

The two-pyroxene thermometer assemblages analysed from the Varpaisjärvi samples are presented in table 12. The temperature have been calculated according to the equations proposed by Wood and Banno (1973) and Wells (1977). As can be seen, the Wood and Banno equation gives temperatures of 817–886° C, with an average of 851° C. The Wells equation gives even higher temperatures: 841–955° C, with an average of 890° C. As suggested by Hewins (1975) and Wood (1975), the Wood and Banno equation may overestimate the temperatures by about 50–60°C.

Although the significance of the Fe^{3+} portion in the Fe_{tot} of the pyroxenes is often estimated to be nearly negligible (e.g., Weaver & Tarney, 1977), it seems evident that its proportion nevertheless drops the temperature estimations by about 10–40° C. Accordingly, the temperature estimations of the present material are very likely at least 60–100° C too high. The overestimations of the temperatures of the Wells equation accordingly seem to be still greater. The garnet-cordierite thermobarometer of the adjoining garnet-cordierite-sillimanite rocks suggests the same (p. 26).

As can be seen in table 9, one garnet analysis of the pyroxene amphibolites has also been done. Although it is the only one, it is worth noting that the garnet-clinopyroxene method (Ellis & Green, 1979) gives a temperature of 751° C (est. P = 7.5 kb).

Biotite-garnet geothermometer

The distribution of the elements (Fe, Mg, Ca, Mn) between the coexisting biotite and garnet is widely accepted as a sensitive geothermometer of the metamorphism. Generally accepted theoretical considerations or PT-diagrams have been represented by, e.g., Kretz (1959), Albee (1965), Saxena (1968, 1969), Sen and Chakraborty (1968), Perchuk (1970), Lyons and Morse (1970), Thompson (1976), Goldman and Albee (1977) and Ferry and Spear (1978).

It has been shown that the distribution of Fe and Mg between coexisting biotite and garnet depends primarily on the temperature but also on the possible compositional variation. The compositional peculiarities of the biotites and garnets from the Varpaisjärvi area have been discussed earlier. In any case, table 13 reports the K_D-values$\left(\frac{(Mg/Fe)gn}{(Mg/Fe)bt}\right)$, the $\frac{Mg}{Mg + Fe_{tot}}$ ratios of garnet and biotite and the corresponding metamorphic temperatures evaluated after Perchuk (1970, Thompson (1976) and Ferry and Spear (1978).

Ferry and Spear (1978) calibrated their equation for the thermometer with synthetic minerals at 2.07 kb. The temperatures (568–837° C, av. 700° C) of the Ferry and Spear

Table 13.

Calculated K_D-values $= \frac{(Mg/Fe)gn}{(Mg/Fe)bt}$ and the $\frac{Mg}{Mg + Fe_{tot}}$ values of the coexisting garnet and biotite pairs from the Varpaisjärvi area. Temperature evaluations after Perchuk (1970), Thompson (1976) and Ferry and Spear (1978).

Sample	$\left(\frac{Mg}{Mg + Fe_{tot}}\right)gn$	$\left(\frac{Mg}{Mg + Fe_{tot}}\right)bt$	$\frac{(Mg/Fe)gn}{(Mg/Fe)bt}$	Temperatures (°C) Perchuk (1970)	Thompson (1976)	Ferry & Spear (1978)
8A–JVP-77	0.532	0.777	0.326	735	750	835
8B–JVP-77	0.528	0.816	0.252	700	662	703
8C–JVP-77	0.546	0.838	0.231	700	641	665
8E–JVP-77	0.485	0.821	0.205	660	600	618
108B–JPK-77	0.583	0.811	0.327	740	750	837
108C–JPK-77	0.588	0.855	0.243	700	648	687
108D–JPK-77	0.520	0.820	0.238	695	644	678
227D–JVP-77	0.485	0.841	0.178	650	567	568
3B–JVP-78	0.473	0.777	0.257	690	670	712
				av. 696	av. 659	av. 700

Table 14.

Calculated $\frac{Mg}{Mg + Fe_{tot}}$ values of the coexisting garnet and cordierite pairs from the Varpaisjärvi area. Temperature and pressure evaluations after Thompson (1976), Holdaway and Lee (1977) and Martignole and Sisi (1981).

Sample	$\left(\frac{Mg}{Mg + Fe_{tot}}\right)gn$	$\left(\frac{Mg}{Mg + Fe_{tot}}\right)cd$	Thompson (1976) T(°C)	Thompson (1976) P(kb)	Holdaway & Lee (1977) T(°C)	Holdaway & Lee (1977) P(kb)	Martignole & Sisi (1981)* T(°C)	Martignole & Sisi (1981)* P(kb)
108B–JPK-77	0.583	0.911	685	8.0	675	9.7	650	7.1
108C–JPK-77	0.588	0.915	680	8.1	663	9.9	675	6.9
108D–JPK-77	0.520	0.874	720	7.5	730	8.8	710	7.2
227D–JVP-77	0.485	0.918	600	8.2	540	10.6	570	5.6

* est. $nH_2O = 0.5$

method for the present material seem to vary considerably while the Perchuk's diagram (1970) is most usable (650–740° C, av. 696° C). The isotherms of his diagram are fixed on the basis of the garnet-amphibole equilibrium temperatures. Thompson (1976) based his diagram on the T-X(Fe-Mg) phase relations at $P_{H_2O} = 5$ kb. This diagram also shows values (567–750° C, av. 659° C) with a moderate dispersion for the present samples. Furthermore, the most deviating sample (227D–JVP-77) probably reflects fallacious retrograde temperatures (tables 13 & 14).

Garnet-cordierite geothermobarometer

The compositions of the garnet and cordierite and the Fe-Mg distribution between them in the assemblage garnet-cordierite-sillimanite-quartz have turned out to be a highly usable thermobarometer of metamorphic conditions, and consequently many P-T-X(Fe-Mg) diagrams have been reported (e.g., Hensen & Green, 1971, 1973; Thompson, 1976; Holdaway & Lee, 1977; Newton & Wood, 1979; Martignole & Sisi, 1981). Their usability especially as a geobarometer of metamorphism is generally accepted, particularly because it has been demonstrated that a high magnesium and water content can stabilize cordierite up to 10–11 kilobars.

Consequently, the important relation between the Fe-Mg partitioning of the coexisting garnet-cordierite pair and the molecular H_2O content in cordierite is repeatedly emphasized in the literature. Newton and Wood (1979) confirmed that the hydration state of cordierite can make a difference of three kilobars in pressure, calculated from coexisting magnesian garnet and cordierite. Martignole and Sisi (1981) considered imperfect data on cordierite hydration and on the thermodynamics of pyrope and Mg-cordierite to be the greatest source of imprecision in calculations. They also demonstrated the significance of nH_2O in cordierite with respect to metamorphic pressure estimations.

The estimation of relevant nH_2O in cordierite is, in any case, quite uncertain. Martignole and Nantel (1982) suggested that the estimation can be made by, e.g., combining information on the oxide sums and the optical data of the analysed cordierite samples.

No accurate estimation of the number of H_2O moles has been done with the present samples. In any case, their oxide sums are very close to 100 (table 11); accordingly the H_2O values should be estimated to be very low.

Table 14 shows the $X_{Mg} = \frac{Mg}{Mg + Fe}$ values for the analysed coexisting garnet-cordierite pairs.

The related temperatures and pressures in the table were calculated or estimated after the researches of Thompson (1976), Holdaway and Lee (1977) and Martignole and Sisi (1981).

However, it is possible that the dispersing values given by the afore-mentioned thermobarometers do not quite follow the unusually high magnesium contents of the present garnets and cordierites. Especially the systematic differences in the estimated pressure values between the methods used are conspicuous.

PT-CONDITIONS AND TYPE OF METAMORPHISM

The mineral parageneses with the elemental distribution between certain coexisting mineral pairs all strongly suggest that the Archean rocks of the Varpaisjärvi area were metamorphosed under the PT-conditions of granulite facies. These PT-conditions also clearly differ from the Proterozoic metamorphic conditions, which can be demonstrated in the nearby Proterozoic Tahkomäki schist zone (fig. 1), where, e.g., chlorite-biotite-bearing pelitic rocks occur.

Fig. 14 represents the Archean metamorphic temperatures and pressures registered by the thermobarometers, as mentioned in the foregoing. As can be noticed, the calculated values are quite variable. This may indicate that there is a lack of utilizable and reliable thermobarometers calibrated to the rocks of the present chemistry and metamorphic conditions. However, it seems evident in the light of the most relevant knowledge that the temperature can be limited most probably between 650° C and 750° C. The pressure estimations vary around 8 ± 1 kb.

These values are quite well in accordance with the metamorphic PT-gradient reported from other Archean granulite areas. Fig. 15 shows the Archean metamorphic PT-trend according to the present material and the Scourian granulites (Rollinson, 1981). It also reveals the fact that the high-grade rocks of the Varpaisjärvi area quite typically represent the type of moderate-pressure metamor-

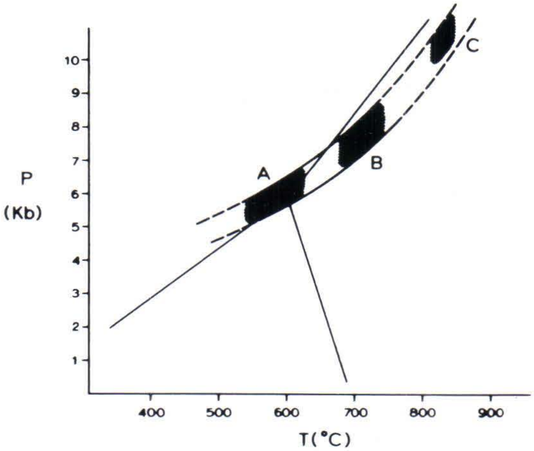

Fig. 15. The Archean metamorphic PT-gradient according to A: Nilsiä area, B: Varpaisjärvi area and C: Scourian area (Rollinson, 1981). The triple point is an average adopted by Winkler, 1979; p. 247.

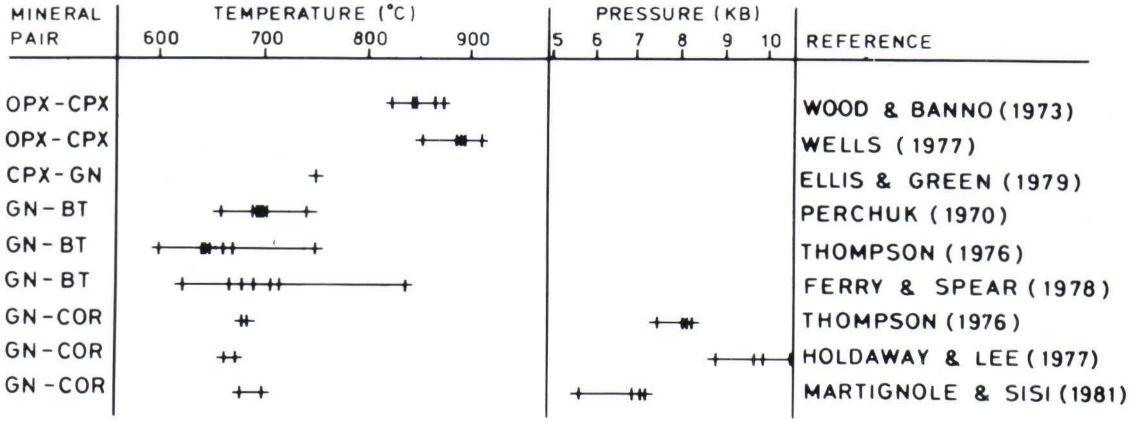

Fig. 14. The metamorphic PT-conditions of the rocks from the Varpaisjärvi area according to the thermobarometers worked out by different authors. The maximum and minimum temperatures of tables 12–14 have been ignored.

phism (kyanite-sillimanite type) introduced by Miyashiro (1961).

As already suggested (p. 18), the banded tonalitic-trondhjemitic rocks with amphibolotic horizons outside the high-grade block area are considered lower-grade derivatives of the high-grade rocks. They probably represent a higher level of the Archean crust than the upraised block. They also seem to have been affected more by retrogressive phenomena.

CONCLUSIONS

The predominantly Archean bedrock north of Kuopio is cut by several fractures and strongly tectonized zones. In the Varpaisjärvi area, there is a block that is bounded and broken by faults and sheared zones and the rocks of which generally differ from the ones outside the area. The block causes a strong positive anomaly on the aeromagnetic map and its rocks mostly contain mineral assemblages of granulite facies. This demonstrates that the Archean regional metamorphism of the area culminated, at least locally, in granulite facies PT-conditions.

The genesis of the high-grade rocks seems to have been predominantly magmatic, probably both plutonic and volcanic, the main types consisting of enderbites, pyroxene amphibolites and their combinations and variants with trondhjemitic migmatization. The amount of sedimentogenic material is small.

In spite of several obvious differences in the present erosion level, it is evident that the high grade rocks of the block area can be correlated as to origin with the lower-grade banded tonalitic-trondhjemitic rocks with amphibolitic lenses and horizons outside the block area. The mutual structural relationship of those rocks can be demonstrated, too. Most probably, they have metamorphosed primarily in different PT-conditions (granulite facies/amphibolite facies). The lower-grade rocks include more trondhjemitic neosome material and their textures also exhibit more retrogressive phenomena than the high-grade rocks do.

The chemical analyses of the dominant rocks in the present area indicate a bimodal distribution of the composition in the calc-alkalic series with a trondhjemitic trend.

The mineral parageneses, the mineral compositions and the element partitioning between certain coexisting minerals in the high-grade rocks suggest metamorphic PT-conditions of 700 ± 50° C and 8 ± 1 kb. These conditions correspond quite well to the typical Archean metamorphic gradient of the moderate-pressure type, while the Proterozoic formations of the region belong rather to metamorphism of the low-pressure type. Their metamorphism is also most probably the main episode in the rehydration processes and reheating of the Archean rocks of the area.

The Archean rocks in the Varpaisjärvi area, with their well-preserved granulite facies mineral assemblages, give at any rate a convincing indication of the high-grade metamorphic conditions that prevailed deep in the crust of the Baltic Shield during Late Archean times.

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