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Oleg A. Belyaev and Nikolay E. Kozlov

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GEOLOGY, GEOCHEMISTRY AND METAMORPHISM OF THE LAPLAND GRANULITE BELT AND ADJACENT AREAS IN THE VUOTSO AREA, NORTHERN FINLAND

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The southern part of the Lapland Granulite Belt (LGB) and the area outside it have been submitted to a petrological-geochemical study. Outside the LGB, within a gneiss complex of dacite-rhyolitic (plagiogranitic) composition, a greenstone complex (GSC) of presumably Late Archaean (Lopian) age was distinguished in addition to the earlier-known Early Proterozoic (Sumian-Sariolian) GSC.

The Late Archaean greenstone rocks, which have been observed as relics among the surrounding gneisses, have a structural and metamorphic history similar to that of the gneisses and marked by two tectonometamorphic cycles. The early cycle is associated with static granulite metamorphism and the late cycle with amphibolite tectonometamorphism. The development of garnet-amphibole and garnet-clinopyroxene-amphibole parageneses indicates high pressure at the culmination stage of tectonometamorphism; the decrease in pressure took place at the final stage.

The Early Proterozoic GSC forms a more extensive and thicker linear structure, probably as a component of the Central Lapland Greenstone Belt. This GSC is characterized by monocyclic metamorphism, an absence of migmatites and a relatively simple set of deformations compared with those of the ancient GSC. The intensity of the metamorphism and its petrological features are very similar to those of the repeated metamorphism in the ancient GSC and surrounding gneiss complex.

The identical structural position and geochemical similarity of the amphibole gneisses of the Tana complex and mafic granulites are established. On this basis and by analogy with the Salny tundra and Kolvitsa-Kandalaksha sections, the Tana complex rocks are considered to belong to the bottom of the granulite complex.

Three stages have been established in the tectonometamorphic development of acid granulites - early, syntectonic and retrograde, with P-T parameters of 705°C and 6.85 kbar; 745-810°C and 6.7-12.1 kbar; and 580-710°C and 4.6-7.8 kbar, respectively. The maximum pressure of the syntectonic granulite metamorphism (12.1 kbar) is established at the bottom of the LGB.

Key words (GeoRef Thesaurus, AGI): granulites, gneisses, migmatites, greenstone, amphibolites, geochemistry, mineral assemblages, electron probe data, metamorphism, Precambrian, Vuotso, Sodankylä, Finland

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Lapin granuliittijakson (LGB) eteläisellä reuna-alueella esiintyy granuliittijaksoon kuuluvien kivilajien ohella arkeeisia graniittigneissejä, arkeeisia (Lopi-) vihreäkiviä sekä proterotsooisia (Sumi-Sariola-) vihreäkiviä.

Arkeeisilla gneisseillä ja niiden yhteydessä esiintyvillä myöhäis-arkeeisilla vihreäkivillä on keskenään sama metamorfinen ja rakenteellinen historia. Niissä on havaittavissa kaksi tektonometamorfista vaihetta. Varhaisempi vaihe on staattinen granuliittimetamorfoosi ja nuorempi amfiboliittitektonometamorfoosi.

Varhaisproterotsooiset vihreäkivet kuuluvat todennäköisesti Keski-Lapin vihreäkivijaksoon. Niitä leimaavat monosyklinen metamorfoosi, migmatiittien puuttuminen ja suhteellisen yksinkertaiset deformaatiorakenteet arkeeisiin vihreäkiviin verrattuna. Metamorfoosin intensiteetti ja sen aikaansaamat petrologiset piirteet ovat hyvin samanlaiset kuin arkeeisissa vihreäkivissä ja gneisseissä.

Tana-kompleksin amfiboligneisseillä ja granuliittijakson mafisilla granuliiteillä on identtinen rakenteellinen asema ja ne ovat geokemiallisesti samankaltaisia. Tällä perusteella Tana-kompleksin kivien katsotaan kuuluvan Lapin granuliittijakson alaosaan. Myös Vuotson leikkauksen analogisuus Salnitunturin sekä Kolvitsan-Kantalahden leikkausten kanssa vahvistaa tätä tulkintaa.

Happamien granuliittien tektonometamorfisessa kehityksessä on todettu kolme vaihetta: varhainen, syntektoninen ja retrogressiivinen. Näitä vaiheita vastaavat P-T -parametrit ovat: 705°C ja 6,85 kbar, 745-810°C ja 6,7-12,1 kbar sekä 580-710°C ja 4,6-7,8 kbar. Syntektonisen granuliittimetamorfoosin korkein paine (12,1 kbar) on todettu Lapin granuliittijakson (LGB) pohjaosassa.

Avainsanat (Fingeo-sanasto, GTK): granuliitit, gneissit, migmatiitit, vihreäkivi, amfiboliitit, geokemia, mineraaliseurueet, mikroanalysaattoritiedot, metamorfoosi, prekambri, Vuotso, Sodankylä, Suomi

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INTRODUCTION

The present paper is based on the results of a study carried out in 1991 (within the framework of IGCP - Project 275) near the village of Vuotso. The paper deals with specific problems related to the geology, geochemistry and metamorphism of the rocks in the area, but makes no broad generalizations. The study is based on a field survey, structural and textural observations, sampling, thin-section studies, rock and mineral analyses and quantitative determinations of minor elements.

The electron probe microanalyses were made at the Geological Institute, Kola Sience Centre of the Russian Academy of Sciences, using a MS-46 "Cameca" microprobe. The acceleration voltage was 22 kV, the current of the electron beam 40 nA and the beam diameter 2-3 m. The standards used were albite (Na), light-blue diopside (Ca,Mg), almandine (Al,Mn), pyrope (Si), wadeite (K), rutile (Ti) and hematite (Fe).

The primary origin of the metamorphic formations was analysed with petrogeochemical techniques devised at the Geological Institute, Kola Science Centre (Predovsky, 1970; Kozlov, 1983).

REGIONAL SETTING

According to Mikkola (1941) and Meriläinen (1976), the area under investigation is composed of migmatites, gneisses, granite-gneisses and amphibolites of the Western Inari schist zone and also of "granulites" (sillimanite-garnet gneisses, quartz-feldspar gneisses with bodies and lenses of hypersthene-plagioclase rocks, charnockites, norites etc.).

In the opinion of Mikkola (1941), the strata of the garnet-bearing hornblende gneisses occur along the southern - south-western boundary of the Granulite Belt. Later these gneisses were related to the Tana complex (Gaál et al., 1989). More recently the rocks of the Western Inari shist zone (Meriläinen, 1976) were ascribed to the Central Lapland Greenstone Belt (Lehtonen et al., 1992).

A geological map of the study area, based on Lehtonen et al. (1992), is presented in Figure 1. In the lowermost part of the Granulite Belt, we distinguished a unit composed of a sequence of granulites of basic and intermediate composition up to 200 m thick. Further north-east, in a 2-km wide zone, basic and acid granulites alternate with a gradual decline in the amount of basic varieties.

Similar relationships were observed at points F-52, 53, 54, 55 (Fig. 1) in a band extending laterally for more than 12 km. An analogous sequence of basic and acid granulites at the bottom of the Granulite Belt appears to be typical of the belt and has previously been observed by us both in Northern Norway (in the area located south-east of Karasjok) and in Russia (Kozlov et al., 1990; Kozlov & Ivanov, 1991).

Aeromagnetic geophysical maps of the area of acid granulites show anomalies of highly magnetic rocks, some of which are identified as due to orthopyroxene-plagioclase bodies (Hörmann et al., 1980). In a similar magnetic zone, we have traced interlayers of bipyroxene-plagioclase schists and more acid varieties corresponding to charnockites in composition(F-7O, Fig. 1).

At point F-55 (Fig. 1) basic granulites are in direct contact with leucocratic, rather homogeneous fine-grained gneisses of clinopyroxene-plagioclase composition that are very similar to the gneisses of the surrounding complex. Their apparent thickness does not exceed 100-120 m, but further south-west the outcrops are absent.

Judging from the geophysical data, a complex of medium- and coarse-grained amphibole gneisses, studied by us at points F-32 - F-42 (Fig. 1), extends here along the strike. This complex is structurally similar to the granulite one, but differs essentially from basic granulites in mineral and lithological parageneses as well as in structural and textural features. In the Scandinavian literature this formation is considered as part of the Tana complex, whereas most Russian geologists, including the authors of this paper, commonly assign it to the lowermost strata of the Granulite Belt. The apparent thickness of the complex at points F-32 - F-42 is 3-3.5 km.

According to Mikkola (Mikkola, 1941), this com-

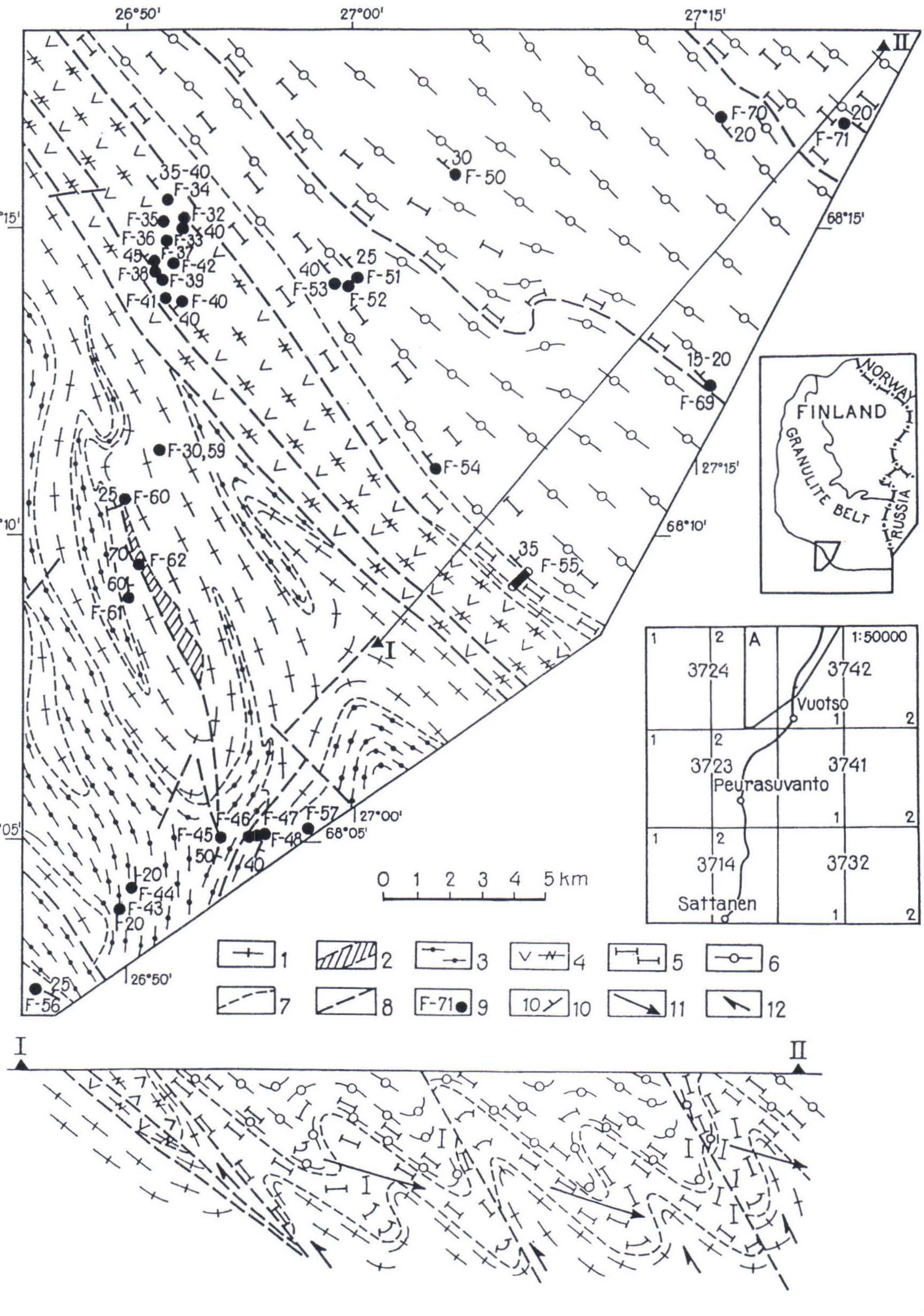

Fig. 1. Geological sketch map of the Vuotso area. Compiled by N. E. Kozlov and O. A. Belyaev using the data of Lehtonen et al. (1992) and aeromagnetic survey.

Legend: 1-3 - the surrounding complex: 1 - gneisses, granite-gneisses, 2- the Archaean greenstones and 3 - the Early Proterozoic greenstones; 4 - complex of garnet-amphibole gneisses (Tana complex); 5-6 - Lapland Granulite Belt (LGB): 5 - mafic granulites; 6 - felsic granulites; 7 - inferred geological boundaries; 8 - faults; 9 - observation points; 10 - foliation, strike and dip; 11 - inferred plunge of folded units; 12 - inferred direction of displacement of blocks. Vertical scale is arbitrary for the profile I-II.

plex wedges out entirely. However, similar formations structurally in the same position and with the same thickness occur in the Jaurujoki River, near the Finnish - Russian border (Kozlov et al., 1990).

In structural plan the granite-gneiss complex underlying the Granulite Belt differs from the granulites and the Tana complex (see Fig. 1). It is moreover separated from the granulites by a distinct geophysical boundary.

Intersection I-II in Fig. 1 is a preliminary one and will have to be reviewed after detailed geological and geophysical mapping.

PETROGRAPHIC AND GEOCHEMICAL FEATURES OF THE ROCK TYPES

The surrounding gneiss complex

Gneisses and migmatites

The mineral assemblages of the fine-grained gneisses, granodiorite- and granite-gneisses and migmatites of the complex are composed of plagioclase, quartz, clinopyroxene, amphibole and commonly also biotite.

Megascopically the gneisses are relatively homogeneous or weakly banded in places, and commonly contain thin (1-2 - 10-12-cm) interlayers of more melanocratic amphibole gneisses. Aplitic bodies up to 4-5 m thick and greisenization zones with quartz-hematite mineralization were also seen in places (F-30, F-59, Fig. 1).

The strike and dip of the foliation in gneisses vary greatly, the dip being to NE, SE, SWW and NW at an angle ranging from 50-60° to subvertical.

Extensive signs of ultrametamorphic processes are seen in the gneisses of the surrounding complex. Early segregations of migmatites (migmatites-1) are composed of quartz, plagioclase and amphibole, rarely of clinopyroxene. Amphibole segregations are common along the margins of migmatite veins, and in places fine-grained garnet occurs. Porphyroblasts of plagioclase have developed in some gneissic interbeds. Gneisses and early migmatites (migmatites-1) are folded into small isoclinal folds with steep to subvertical axial

Table 1. Chemical composition of rocks (Vuotso area, Northern Finland). Petrogenic elements - wt%, rare elements - ppm, Au - c. 10^{-7} %.

Group	I-a*	I-b				II	
Sample	F-36	F-62-1	F-62-2	F-62-3	F-55-12	F-32-3	F-33
SiO_2	65.29	69.32	65.95	73.28	77.14	58.98	59.64
TiO_2	0.33	0.41	0.60	0.33	0.16	0.43	0.37
$Al2O_3$	14.53	11.86	12.20	10.98	10.13	15.54	14.96
Fe_2O_3	1.62	2.59	3.02	1.76	1.05	2.53	3.06
FeO	4.99	4.97	6.00	3.99	3.34	8.10	6.82
MnO	0.11	0.15	0.16	0.11	0.07	0.22	0.17
MgO	1.59	0.16	0.32	0.15	0.10	2.57	3.14
CaO	5.35	2.73	4.22	2.06	2.68	6.55	7.16
Na_2O	3.44	4.16	3.90	3.24	4.52	2.97	2.53
K_2O	1.00	2.11	2.12	3.03	0.16	0.49	0.78
Cu	57	32	24	23	22	48	45
Ni	8	5	4	5	5	7	19
Co	6	3	3	3	3	10	10
Cr	6	4	4	4	4	-	25
V	58	10	8	9	10	150	160
Ba	570	990	950	1260	170	280	290
Sr	293	123	131	99	85	197	254
Zn	63	250	250	220	61	140	96
Nb	15	32	36	41	16	13	12
Zr	106	433	453	709	97	36	56
Y	23	72	66	82	60	26	17
Rb	25	71	77	99	5	7	9
Au	2.2	1.6	0.8	0.7	0.7	1.5	1.6

*) I - metarhyodacites and metarhyolites of the Tana complex (Ia) and surrounding gneiss complex (Ib); II - meta-andesites of the Tana complex; III - meta-andesite-basalts of the Tana complex; IV - aluminous metabasalts of the Tana complex (a) and surrounding complex (b); V - tholeiitic basalts of the Granulite Belt (a) and surrounding complex (b); VI - metatuffites; VII - meta-arkoses and metasubgreywackes; VIII - metagreywackes; IX - metagabbro-anorthosite.

Table 1, contd

Group	II			III	IVa		IVb
Sample	F-34	F-35	F-38-1/1	F-32-1	F-38-2	F-41-1	F-62-14
SiO_2	58.77	59.57	58.19	53.50	50.63	49.28	50.42
TiO_2	0.41	0.53	0.70	0.74	0.66	0.54	1.06
Al_2O_3	15.08	15.70	15.94	15.24	16.13	18.96	16.67
Fe_2O_3	2.34	2.30	1.86	2.57	2.66	2.24	2.40
FeO	7.64	7.21	8.81	9.81	10.20	8.70	8.07
MnO	0.17	0.16	0.23	0.19	0.23	0.21	0.14
MgO	3.55	2.39	2.58	3.50	4.18	3.40	5.44
CaO	7.87	6.97	7.12	9.41	9.13	10.59	10.37
Na_2O	2.08	3.35	2.84	2.53	3.05	3.65	2.78
K_2O	0.55	0.59	0.18	0.47	0.51	0.41	0.52
Cu	60	51	46	98	70	80	23
Ni	18	9	4	24	24	8	71
Co	11	9	12	17	14	14	18
Cr	22	5	-	26	5	5	52
V	160	30	130	170	190	210	100
Ba	290	500	150	280	180	360	570
Sr	253	358	356	191	307	313	472
Zn	100	77	150	150	190	140	160
Nb	12	13	11	8	12	13	20
Zr	43	90	21	22	11	15	167
Y	16	22	16	14	14	13	25
Rb	5	11	9	7	11	13	16
Au	3.9	2.6	1.5	6.4	2.0	0.8	0.8

Table 1, contd

Group	Va				Vb		VI
Sample	F-52-3	F-54-2	F-55-10	F-70-2	F-62-4	F-62-8a	F-38-1/2
SiO_2	46.31	50.66	51.64	49.05	52.58	52.99	71.64
TiO_2	1.59	1.10	0.98	0.91	1.12	2.01	0.30
$Al2O_3$	13.62	15.28	13.64	14.36	13.05	14.87	13.04
Fe_2O_3	2.65	3.53	1.49	2.56	3.06	2.07	1.35
FeO	12.83	9.58	14.99	8.94	10.59	8.76	3.97
MnO	0.10	0.22	0.23	0.19	0.20	0.13	0.09
MgO	7.66	6.03	4.29	6.71	4.91	4.85	0.68
CaO	12.60	9.01	7.62	12.54	9.16	8.20	4.49
Na_2O	0.89	2.77	2.59	1.60	2.87	2.68	3.04
K_2O	0.33	0.36	0.10	0.48	0.46	0.66	0.19
Cu	-	-	130	-	41	26	57
Ni	-	-	14	-	35	46	4
Co	-	-	40	-	23	14	3
Cr	-	-	4	-	13	65	5
V	-	-	280	-	140	120	16
Ba	30	120	40	110	220	-	150
Sr	15	218	106	198	204	-	351
Zn	78	140	190	-	140	190	64
Nb	10	9	13	10	17	-	10
Zr	72	105	27	64	108	-	95
Y	27	23	31	26	25	-	7
Rb	6	5	6	10	21	-	5
Au	1.6	2.8	2.2	0.5	1.6	0.5	1.2

Table 1, contd

Group	VI				VII			
Sample	F-40-1	F-40-2	F-41-2	F-51-3	F-50-3	F-50-4	F-51-1	F-54-1
SiO_2	66.01	66.54	68.53	60.05	83.20	82.66	73.21	76.69
TiO_2	0.38	0.35	0.40	1.58	0.29	0.27	0.05	0.38
Al_2O_3	15.35	15.31	14.56	14.40	7.13	7.77	14.66	10.77
Fe_2O_3	1.05	1.86	2.33	2.20	0.20	0.18	0.29	0.43
FeO	5.51	4.84	3.67	8.71	3.13	3.46	2.20	4.03
MnO	0.12	0.13	0.11	0.07	0.04	0.04	0.02	0.04
MgO	1.33	1.33	0.75	3.69	0.74	0.96	0.46	1.34
CaO	5.79	5.47	4.74	6.70	1.82	1.78	2.71	1.45
Na_2O	3.08	2.96	3.62	0.90	1.30	1.43	3.33	1.59
K_2O	0.39	0.42	0.14	0.36	0.98	0.44	1.81	2.08
Cu	52	53	41	-	-	-	-	-
Ni	7	7	3	-	-	-	-	-
Co	4	5	-	-	-	-	-	-
Cr	5	5	4	-	-	-	-	-
V	38	45	19	-	-	-	-	-
Ba	310	440	160	210	320	70	490	930
Sr	296	279	330	242	180	140	407	219
Zn	80	72	110	170	30	40	80	80
Nb	15	11	12	15	7	12	7	14
Zr	140	62	25	181	225	304	71	219
Y	25	13	13	32	10	12	20	18
Rb	11	10	6	15	24	7	40	68
Au	0.8	0.7	4.0	3.9	0.7	0.9	0.5	0.9

Table 1, contd

Group	VII		VIII					IX
Sample	F-55-2	F-70-1	F-50-7	F-50-8	F-53-1	F-53-2	F-55-1	F-62-7
SiO_2	80.46	75.31	71.39	60.66	72.24	63.75	70.68	55.38
TiO_2	0.40	0.18	0.74	0.47	0.33	0.68	0.60	0.54
$Al2O_3$	9.09	11.60	13.53	18.59	13.40	16.25	14.22	20.86
$Fe2O_3$	1.16	0.46	0.29	0.75	1.55	0.45	0.61	1.10
FeO	3.14	3.07	5.73	5.30	3.67	4.73	5.78	6.19
MnO	0.04	0.07	0.04	0.09	0.06	0.04	0.06	0.10
MgO	1.01	0.35	2.08	2.68	1.81	2.58	1.99	0.71
CaO	0.44	0.99	1.44	5.53	1.66	5.71	1.77	8.37
Na_2O	1.43	3.83	1.46	2.82	2.58	3.02	1.58	4.76
K_2O	1.85	3.16	2.36	0.93	1.70	0.83	2.09	0.59
Cu	27	30	-	-	-	-	24	21
Ni	27	9	-	-	-	-	20	6
Co	4	3	-	-	-	-	6	5
Cr	36	4	-	-	-	-	47	4
V	45	9	-	-	-	-	60	9
Ba	840	1410	1050	610	2020	620	870	400
Sr	126	78	199	523	291	536	168	355
Zn	80	240	130	70	70	60	100	89
Nb	23	17	18	9	12	7	22	13
Zr	332	259	328	112	236	35	252	90
Y	25	20	20	15	22	6	23	19
Rb	57	51	69	37	56	18	79	14
Au	2.2	1.3	1.6	7.7	2.2	0.9	1.5	0.6

planes (AP), with hinge lines plunging to NW 340° at 15°. More coarse-grained pegmatoid material (migmatites-2) with quartz + plagioclase + potassium feldspar + minor amounts of amphibole, magnetite and rarely garnet, biotite and epidote has intruded the axial planes of these folds. The first and second migmatites are dislocated in moderately compressed and open folds within local, thin (0.5-0.7 m) zones. The AP of the latter folds is at an angle of 30° to that of the early isoclinal folds; segregations of the late pegmatoid quartz-plagioclase-potassium feldspar material lie on their axial planes.

Typomorphic mineral assemblages Amph*+ Pl + Qtz + Kfs and Amph + Bt + Pl + Qtz + Kfs + Ep are dominant in gneisses; Gar + Amph + Pl + Qtz + Kfs, Gar + Cpx + Amph + Pl + Qtz + Kfs and Cpx + Pl + Qtz are less common. The latter paragenesis is observed only in the direct contact with granulites.

The most abundant mafic mineral of the gneisses is a deeply coloured blue-green hornblende (amounting to 5-10%) that has sometimes developed after clinopyroxene (0-5%). Brown or dark-brown biotite (0-5%) is found in paragenesis with amphibole but frequently replaces it together with epidote (less than 1%). Isometric grains of quartz (10-20%) and plagioclase (70-80%) are identical, but larger porphyroblastic segregations of the latter are also found. Potassium feldspar (1-5%) is invariably present in the gneiss paragenesis (it is absent only from sample F-55-12). Distinct features indicating that it is a later occurrence than clinopyroxene, amphibole and plagioclase are lacking, although their presence is not fully ruled out. Garnet (0-2%) is encountered randomly in individual thin beds (laminae); it is most common at the paleosome-neosome contact or in neosome of migmatite. In gneisses with clinopyroxene, garnet generally occurs at the margins of clinopyroxene together with plagioclase. Higher contents (still in accessory amounts) of an opaque mineral (magnetite) and sphene are typical; zircon and apatite are also present.

Chemically the gneisses of the surrounding complex correspond to metarhyolite and metadacite (Table 1, analyses F-62-1,2,3). The special features of clinopyroxene-bearing leucocratic gneiss (Table 1, F-55-12), which underlies the granulites (see Fig. 1, point F-55), as well as the mineral and chemical composition and texture of the gneiss together with the correlation of iron, magnesium and alumina with silica (Fig. 2), indicate that it, too,

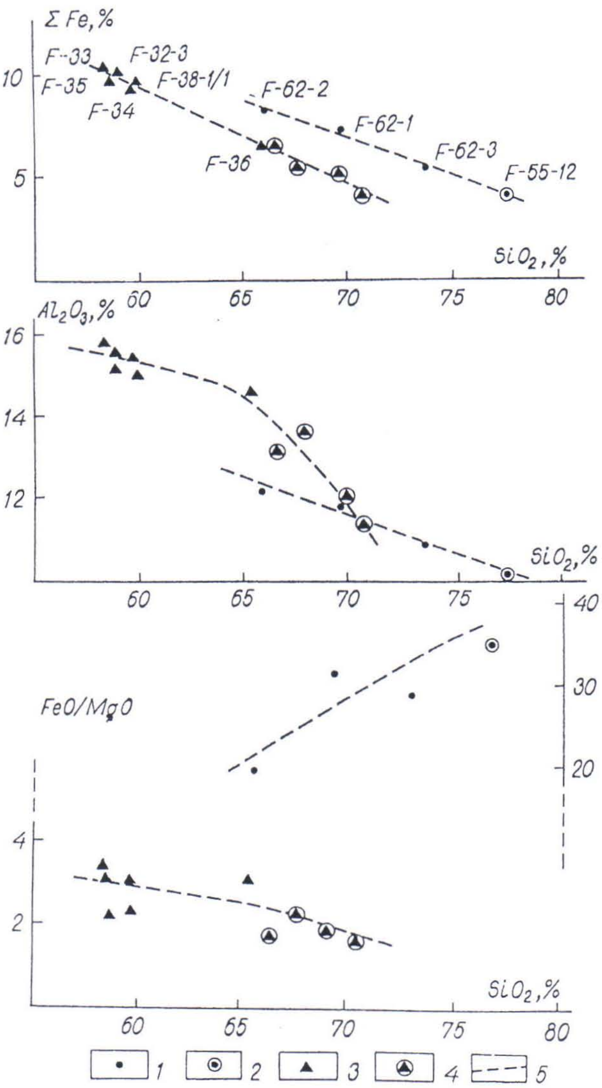

Fig. 2. Fetot- SiO_2, Al_2O3 - SiO_2 and FeO/MgO - SiO_2 diagrams for the rocks of the Vuotso area. Legend: 1 - gneisses of the surrounding complex; 2 - clinopyroxene-bearing leucocratic gneisses from exposure F-55 (-12); 3 - complex of amphibole and garnet-amphibole gneisses (the Tana complex); 4 - metadacites of the Granulite Belt, the Salny Tundra and Jaurujoki river area; 5 - variation trends of elements in groups.

belongs to the surrounding gneiss complex. The contents of rubidium, zinc, zirconium and barium are lower in sample F-55-12 than in other samples from the surrounding gneiss complex, most probably due to ultra-acid composition of the rock type. Gneisses such as F-55-12 underlie the granulites locally, separating them from the amphibole gneisses of the Tana complex (see Fig. 1) as a tectonic plate or wedge. Such a supposition is not in conflict with the aeromagnetic survey data.

*) Abbreviations in the text, Tables 2, 3, 5 and Appendix 1: Act - actinolite; Amph - amphibole; And - andalusite; Ap - apatite; Bt - biotite; Carb - carbonate; Chl - chlorite; Cpx - clinopyroxene; Crd - cordierite; Cum - cummingtonite; Ep - epidote; Gar - garnet; Hem - hematite; Kfs - potassium feldspar; Ky - kyanite; Ms - muscovite; Opx - orthopyroxene; Ore - ore mineral; Pl - plagioclase; Prh - prehnite; Qtz - quartz; Rt - rutile; Scp - scapolite; Ser - sericite; Sil - sillimanite; Sph - sphene; Spi - spinel; Tlc - talc; Trm - tremolite; Tur - turmaline; Zrn - zircon.

Amphibolites

Amphibolites, which are spatially associated with the gneiss complex of the surrounding zone, can be subdivided into two groups on the basis of their structural features and metamorphic and magmatic processes.

The representatives of the first group are seen within gneisses as elongated lens-like interlayers mostly along the strike. The layers are some hundreds of metres to 1-2-km thick and up to a few kilometres long (see Fig. 1). At the observation points F-60 and F-62 (Fig. 1), in a garnet-bearing amphibolite interlayer, the primary porphyritic and amygdaloid structures are preserved in blocks or fragments 1-2 x 5-6 m in size. They contain quartz-filled amygdules up to 3 x 6 cm in size and plagioclase porphyric accumulations. The foliation zones show gradual transitions from massive metaporphyrites with ophitic structure through garnet-bearing amphibolites to schistose feldspathic amphibolites with typical nematogranoblastic and granonematoblastic textures. In addition, in some interbeds indistinct textures of tectonized pillow lavas were identified. The flattened "pillows" vary in size from 2 x 12 cm to 3-4 x 15-20 cm.

In metaporphyrite and amygdaloidal metadiabase the earliest mineral assemblage corresponds to the granulite facies: Opx_{43}*) + Cpx_{37} + $Amph_{54}$ + Pl_{39-57} + (Gar_{69} + Bt_{53}). The mineral analyses from observation site F-62 are given in Table 2.

Orthopyrexene and clinopyroxene are obviously metamorphic in origin. Their fine grains together with laths of andesine-labrador form the matrix, which has retained a relict ophitic structure. Larger orthopyroxene (hypersthene) grains have developed at the contact between the matrix and plagioclase porphyric segregations; recrystallised clinopyroxene grains occur at the contact between the matrix and quartz amygdules. Brown amphibole belongs to the same paragenesis as pyroxenes, which are replaced by a younger brownish-green amphibole. Garnet starts to develop with the formation of kelyphytic rims at the contact between the matrix and plagioclase laths; further recrystallization has resulted in the formation of skeleton poikiloblasts, and later on, of more idiomorphic grains. Garnet has the following end-member composition (as calculated from the mineral analyses in Table 2): spessartine 1.5%, pyrope 24.4%, almandine 53.7%, grossular 20.5%. Plagioclase (An 40-60) forms large elongated grains and porhyric segregations with rare zonality. Smaller laths together with pyroxenes produce an ophitic structure in the matrix. A distinctive feature is the decrease in the anorthite content of plagioclase towards the grain rims (Table 2). Quartz occurs only as rounded or lens-like amygdales. Biotite is an accessory mineral; it is red in colour and rich in titanium (5.0 wt% TiO2, Table 2).

Mineral assemblages of schistose amphibolites formed at the expense of porphyrites correspond to the amphibolite facies: Amph + Pl + Qtz, Gar + Amph + Pl + Qtz, Cpx + Amph + Pl + Qtz. Associations with clinopyroxene are more typical of transitional varieties from massive metaporphyrites to amphibolites: Gar + Cpx + Amph + Pl + Qtz. Amphibole is brownish green, especially in assemblages with clinopyroxene, or green and bluish green with garnet. Plagioclase (oligoclase-andesine) forms fine isometric or slightly elongated grains. Garnet contains numerous inclusions of opaque minerals and quartz, but amphibole is rarely encountered within it.

Table 2. Microprobe analyses of minerals in metaporphyrite (sample F-62-17). c = core, r = rim of grain, n.d. = not determined. For melanic minerals XFe = Fe/(Fe+Mg), for plagioclase XCa = Ca/(Ca+Na+K).

Code	Opx	Cpx	Amph	Gar	Bt	Plc	Plr
SiO2	51.90	52.74	42.39	38.55	36.41	55.67	55.93
TiO2	n.d.	n.d.	1.32	n.d.	5.00	n.d.	n.d.
Al2O3	0.86	0.82	12.56	20.65	16.15	28.65	28.81
FeOtot	26.39	13.16	19.07	25.81	14.40	0.10	0.10
MnO	0.58	0.24	0.14	0.70	0.06	n.d.	n.d.
MgO	19.58	12.35	9.03	6.57	14.82	n.d.	n.d.
CaO	0.56	20.56	11.34	7.70	0.03	9.39	8.12
Na2O	n.d.	n.d.	0.93	n.d.	n.d.	5.92	6.83
K2O	0.04	n.d.	1.72	n.d.	9.68	0.16	0.17
Total	99.81	99.87	98.50	99.89	96.55	99.89	99.96
XFe,Ca	0.430	0.374	0.542	0.688	0.352	0.463	0.393

*) Indices indicate 100xFe/(Fe+Mg) of the ferro-magnesian minerals and anorthite (%) of plagioclase?

Chemically, the rocks of this group are tholeiitic and aluminous metabasalts (Table 1, analyses F-62-4, F-8a, F-14). Their aluminous varieties differ from the basalts of the garnet-amphibole gneiss complex in having higher nickel, chromium, zirconium and yttrium contents; tholeiitic rocks are also enriched in nickel and chromium when compared with Granulite Belt basalts (Table 1).

A subconcordant body of metagabbro-anorthosite up to 3 m thick (Table 1, F-62-7) was encountered in the amphibolites of the surrounding complex. In the central part of the body, metagabbro-anorthosite has been transformed into a heterogeneous (spotted) garnet-amphibole plagiogneiss. It is more fine-grained and homogeneous at its contacts. Abundant plagioclase (An 42-50) is associated with the blue-green amphibole and garnet in metagabbro-anorthosite.

Abundant ilmenite + magnetite mineralization was observed in the amphibolite hosting the metagabbro-anorthosite body. As well as opaque minerals, the mineralized zones contain garnet and pale-green amphibole or garnet, amphibole and cummingtonite with a higher apatite content.

Structurally, the unit comprising fine-grained schistose feldspathic and garnet-bearing amphibolites (the second group) with restricted occurrence of fine-grained biotite, garnet-biotite and garnet-amphibole-biotite schists is more distinct (observation sites F-43-48, F-57 and F-58, Fig. 1). The unit constitutes a 6-km-wide linear zone trending NW-NS and studied by us along the Tankajoki River. In its northwestern extension, the unit joins the Tana complex. In the western part of the studied zone, the unit rocks dip to the east at an angle of 10-15°; in the eastern part the dip of is steeper but similar orientation.

These amphibolites have common mineral assemblages of Amph + Pl + Qtz and Gar_{85-86} + $Amph_{56}$ + Pl_{33} + Qtz; the association Cpx + Amph + Pl + Qtz is rarely encountered. Bluish green or green amphibole is associated with plagioclase (oligoclase-andesine), less frequently with garnet or clinopyroxene. Garnet forms rounded or slightly elongated poikiloblasts along the schistosity, including plagioclase, amphibole, opaques and, locally, quartz. Opaques, typically overgrown with sphene, are common among the accessory minerals.

In more leucocratic schists interbedded with these amphibolites, the mineral assemblages Bt + Pl + Qtz + Kfs, Gar + Bt + Pl + Qtz + Kfs and Gar + Bt + Amph + Pl + Qtz + Kfs predominate. A characteristic feature is the invariable presence of microcline, which, like plagioclase, occurs as evenly distributed grains throughout the rock. Together with the presence of relict porphyric textures and higher sphene and apatite contents, the above features suggest that the schists may have been formed at the expense of volcanites of intermediate-acid composition.

On the whole, the unit comprising amphibolites of the second group interbedded with microcline-bearing schists seems to be a fragment of a greenstone belt composed of metavolcanic rocks of basic and intermediate-acid composition. They form an intensely squeezed syncline or monocline (tectonic plate, remnants of the cover) overturned westwards and dipping to east - north-east. These metavolcanics which are practically unmigmatized, are the least metamorphosed of any of the complexes investigated in the area. The culmination of metamorphism corresponds to the low-grade amphibolite facies. Consequently, this unit might be included in the youngest formations within the surrounding complex of the Lapland Granulite Belt.

Complex of amphibole and garnet - amphibolegneisses (Tana complex)

The complex is composed mainly of coarse-grained amphibole and garnet-amphibole gneisses of mesocratic and sometimes meso-leucocratic type. Fine- and medium-grained garnet-bearing amphibolites occur in clearly smaller abundance as interlayers from 1-3 cm to 1 -1.5 m thick. The relations between the amphibolites and gneisses are not always clear, and in a number of places amphibolites have been observed to intersect gneisses. Transitions from massive to gneissose texture are fairly common. The maximum apparent thickness of the complex is 3-3.5 km. To the east of the village of Vuotso the complex gradually wedges out.

The gneisses dip to NE 40-50° at 45-55°. Occasionally a lineation of amphibole needles plunging to NNW 350-356° (angle 30-40°) has been observed.

The following mineral assemblages are typical of the complex: Amph + Pl + Qtz, Gar + Amph + Pl + Qtz, Cpx + Amph + Pl, $Gar8_{4-86}$ + CPx_{47} + $Amph_{59-61}$ + Pl_{33} + Qtz, Gar + Amph + Bt + Pl + Qtz and, very rarely, Cpx + Opx + Amph + Pl + Qtz. A more basic and massive rock type (metagabbro-diabase), whose relationship to enclosing gneisses is not clear due to insufficient exposure, displays an assemblage of Opx + Cpx + Amph + Pl + Qtz.

Orthopyroxene and clinopyroxene occur in more basic rocks - amphibolites and melanocratic gneisses. Amphibole forms prismatic grains with brown-green (in non-garnetiferous varieties) or blue-green pleochroism. Occasionally a blue-green amphibole replaces a brown-green amphibole and also orthopyroxene and clinopyroxene along grain boundaries. Plagioclase occurs as tabular and prismatic grains, commonly andesine and more rarely labrador-andesine in composition, grading to oligoclase-andesine towards the grain rims. In the gneissos evarieties the texture is nematogranoblastic, constituting a granulated, less idiomorphic and more fine-grained plagioclase with oriented amphibole prisms. Quartz is rare in amphibolites. In gneisses it usually occurs as elongated vein-like segregations. Garnet, mostly post-tectonic, has crystallized after clinopyroxene and amphibole, which it contains as inclusions. In the more massive varieties kelyphytic garnet margins are observed either around tabular and prismatic plagioclase or along the grain boundaries between amphibole and plagioclase. Garnet commonly occurs along the palaeosome-neosome contact in migmatized gneisses and also within concordant and cross-cutting granitic veins.

The aforementioned structural and textural features together with the rather homogeneous mineral and chemical composition of the rock types suggest that a major portion of the gneisses of the Tana complex was originally composed of magmatic rocks, mostly intermediary in composition (Table 1, analyses F-36, F-32-3, F-33, F-34, F-35, F-38-1/1, F-32-1). Amphibolites, forming only an insignificant part of the complex may be referred to as aluminous basalts (see Table 1, samples F-38-2 and F-41-1). On the basis of field observations, at least some of the amphibolites in the complex are dyke rocks in origin.

The early mineral assemblages of the complex probably conform to moderate-low pressure granulite facies (bipyroxene - amphibole subfacies). The orthopyroxene relics that survived exceptionally in rocks with a massive texture suggest that early granulite metamorphism developed under static conditions. In contrast, the superimposed metamorphism was associated with intensive movements; it took place under higher water activity, and resultated in practically total replacement of the early bipyroxene paragenesis by garnet + blue-green amphibole, showing an amphibolite facies of higher pressures.

Granulite Belt

The more basic rock types of the belt are represented by melanocratic bipyroxene-plagioclase and garnet-bipyroxene-plagioclase schists, mesocratic bipyroxene-garnet, bipyroxene-garnet-biotite, garnet-clinopyroxene-biotite, garnet-clinopyroxene and orthopyroxene-biotite plagiogneisses and their more leucocratic varieties. In the area under investigation, the above rocks are confined to the bottom (south-western margin) of the Granulite Belt and constitute a unit with an apparent thickness of about 180-200 m. They are in contact with the surrounding gneiss complex and the Tana complex in the south-west and south; towards the north-east, they are replaced by "acid granulites". In the transitional (2-3 km) zone the number of interbeds of basic granulites and their thickness gradually decrease, until in the area of acid granulites only individual 2-3-cm to 3-4-m thick interbeds of bipyroxene (+ amphibole) schists and thicker bodies (up to 130 m) of hypersthene granodiorites are observed. Zones with rocks more basic in composition show up on geophysical maps as magnetic anomalies.

Both basic and acid granulites dip exceptionally to NE (20-30°) at an angle of 25-40°; steeper dips (up to 60-70°) were noted only in individual zones. The axial planes of isoclinal folds are typically concordant with the rock dip, their hinge lines being subhorizontal with a gentle (up to 5-15°) dip to SE 100-120°. The lineation, best defined in ribbon quartz, also corresponds to the fold hinges.

Lower part of the Granulite Belt

Chemically, the melanocratic bipyroxene gneisses correspond to tholeiitic basalts (Table 1, analyses F-52-3, F-54-2, F-55-10, F-70-2). Mesocratic and leucocratic pyroxene- and pyroxene-biotite gneisses vary from andesite to dacite in composition (Barbey et al., 1984).

The following typomorphic mineral assemblages were observed: in melanocratic varieties Opx + Cpx + Pl + Qtz, Opx_{49-51} + Cpx_{32-37} + Gar_{72-76} + Bt_{46} + Pl_{79-87} + Qtz, Opx + Cpx + Gar + Pl + Qtz, Opx + Cpx + Amph + Pl_{30-40} and Opx + Cpx + Gar + Amph + Pl_{27-36}); in mesocratic varieties CPx + Gar + Pl and Cpx + Gar + Amph + Pl; and in leucocratic types Opx + Bt + Pl + Qtz + Kfs, Opx + Cpx + Gar + Amph + Bt + Pl + Qtz, CPx + Gar + Pl + Qtz and Opx + Pl + Qtz + Kfs.

Brown amphibole is in equilibrium with pyroxenes but in places replaces orthopyroxene. The anorthite content in plagioclase in the bipyroxene schists (without amphibole) varies within the range 48-63%, decreasing from core to rims. In amphibole-bearing schists plagioclase is oligoclase-andesine (An_{27-40}) and frequently has the same zonality pattern. Garnet forms rims at the grain margins between pyroxene and plagioclase, as well as between brown amphibole and plagioclase and at the boundary between bipyroxene schist (palaeosome) and veined leucocratic material (neosome) or leucocratic micaceous gneisses. More idiomorphic garnet typically has inclusions of orthopyroxene and clinopyroxene, more rarely brown amphibole, biotite and plagioclase. The sequence of mineral formation on the whole corresponds to the series: Opx + Cpx + Pl Amph (brown) Bt (red-brown) Gar + Pl (poorer in calcium).

Upper part of the Granulite Belt

The bulk of the area studied consists of acid granulites. On the basis of composition, three main types can be distinguished: the widely occurring leucocratic garnet- and/or sillimanite-bearing varieties; the less common garnet-sillimanite-biotite varieties with varying ratios of mafic and leucocratic components; and the fine-grained homogeneous garnet-biotite gneisses of limited occurrence that form interbeds or boudins up to 10-30 cm thick.

Chemically, the leucocratic and also the fine-grained varieties are similar to arkoses and subgreywackes, and the mesocratic garnet - sillimanite - biotite gneisses to subgreywackes and greywackes (Table 1, analyses F-50-3, F-50-4, F-51-1, F-54-1, F-55-2, F-70-1, F-50-7,8, F-53-1, H-53-2, F-55-1; and also Barbey et al., 1984; Kozlov & Ivanov, 1991).

In the leucocratic varieties typomorphic mineral assemblages are Gar + Pl + Qtz, Sil + Gar + Pl + Qtz + Kfs, Gar + Pl + Qtz + Kfs and Gar + Ep + Pl + Qtz. In fine-grained gneisses the following assemblages were frequently observed: Gar$_{59-63}$ + Bt$_{25-30}$ + Pl$_{32}$ + Qtz, Gar + Bt + Pl + Qtz + Kfs and more rarely Sil + Gar + Bt + Pl + Qtz.

The garnet shows regressive zoning with Fe

Table 3. Microprobe analyses of minerals from acid granulites (wt%). Bti/g = inclusion in garnet, Btm = matrix biotite, Btc = in contact with garnet. For garnet and plagioclase c = core, r = rim of grain. n.d.= not determined. For garnet and biotite XFe = Fe/(Fe+Mg), for plagioclase XCa = Ca/(Ca+Na+K). Location of samples - in Fig.1; sample F-3-1 - 10 km of point F-71.

Code	Gar-Bt plagiogneiss					Sil-Gar-Bi-Ksp gneisses					
	F-3-1					F-71-2			F-50-4		
	Bti/g	Btm	Garc	Garr	Pl	Btm	Garc	Pl	Btm	Garc	Pl
SiO2	36.82	36.68	38.79	38.81	56.94	35.74	39.54	61.79	35.51	39.03	62.80
TiO2	4.84	4.43	n.d.	n.d.	n.d.	5.14	0.04	0.00	5.36	n.d.	0.02
Al2O3	17.74	19.20	21.09	21.07	24.76	17.03	21.54	23.50	16.40	21.20	23.08
FeOtot	10.20	11.10	27.46	28.99	0.00	12.80	25.05	0.01	14.15	28.02	0.01
MnO	0.02	0.03	0.46	0.48	n.d.	0.03	0.32	n.d.	0.02	0.25	n.d.
MgO	17.00	14.83	10.88	9.36	n.d.	15.65	12.15	n.d.	15.08	10.31	n.d.
CaO	0.03	0.00	1.33	1.30	8.12	0.02	1.34	5.06	n.d.	1.20	4.45
Na2O	n.d.	n.d.	n.d.	n.d.	9.33	n.d.	n.d.	9.27	0.20	n.d.	9.29
K2O	9.86	10.24	n.d.	n.d.	0.38	10.06	n.d.	0.05	9.81	n.d.	0.09
Total	96.51	96.52	100.01	100.01	99.53	96.47	99.98	99.68	96.53	100.01	99.74
XFe,Ca	0.252	0.295	0.586	0.635	0.319	0.314	0.537	0.231	0.345	0.290	0.210

Table 3., contnd

Code	Sil-Gar-Bt-Ksp gneisses											
	F-54-1						F-55-1					
	Btm	Btc	Garc	Garr	Plc	Plr	Bti/g	Btm	Btc	Garc	Garr	Pl
SiO2	36.57	36.59	39.73	40.09	61.20	62.07	36.73	36.40	36.22	38.86	38.82	62.94
TiO2	4.13	3.48	0.06	n.d.	0.04	0.00	4.72	4.22	5.12	n.d.	n.d.	0.02
Al2O3	18.77	19.34	21.90	22.03	23.60	23.06	17.93	17.45	16.61	21.52	21.52	23.46
FeOtot	14.67	13.04	27.67	28.61	0.02	0.00	10.64	12.94	13.77	27.90	29.16	0.02
MnO	0.02	0.03	0.19	0.25	n.d.	n.d.	0.05	0.00	0.07	0.22	0.23	n.d.
MgO	12.28	14.28	8.91	7.96	n.d.	n.d.	16.58	15.44	15.10	9.17	9.36	n.d.
CaO	n.d.	n.d.	1.32	1.06	6.36	5.17	0.03	0.00	0.04	2.22	0.91	3.30
Na2O	0.29	0.00	0.22	n.d.	8.90	9.59	n.d.	n.d.	n.d.	n.d.	n.d.	9.58
K2O	9.77	9.85	0.02	n.d.	0.09	0.10	9.87	10.12	9.50	n.d.	n.d.	0.11
Total	96.50	96.61	100.02	100.00	100.21	99.99	96.55	96.57	96.43	99.89	100.00	99.43
XFe,Ca	0.401	0.338	0.635	0.669	0.281	0.228	0.265	0.320	0.339	0.631	0.636	0.160

increasing and Mg decreasing towards the grain rims (Tables 3 and 4, sample F-3-1). The reddish-brown biotite is rich in titanium (4.4-4.8 wt% TiO_2) (Table 3, sample F-3-1). The anorthite content of plagioclase ranges from 32 to 38 %, as calculated from the results in Table 3 and deduced from optical data.

An assemblage of Sil + Gar_{54-64} + Bt_{26-40} + Pl_{20-40} + Qtz + Kfs with a highly variable volume ratio of minerals is typical of medium- and coarse-grained mesocratic rock types. Mineral compositions of this paragenesis are also shown in Tables 3 and 4, samples F-71-2, F-50-4, F-54-1, F-55-1). The garnet from rocks spatially closer to the bottom of the Granulite Belt (samples F-55-1, F-54-1) exhibits core-rim zoning with calcium decreasing and iron increasing towards the rim but the magnesium content either slightly increasing (F-55-1) or decreasing (F-54-1) in this direction.

Garnets in gneisses far from the lower part of the Granulite Belt are homogeneous. Therefore Tables 3 and 4 list only compositions of the garnet core in samples F-50-4 and F-71-2. The TiO_2 content in biotite varies within the range 3.5-5.4 wt% and the anorthite content of plagioclase within 20-40%, often decreasing towards the grain rims. Potassium feldspar is microperthitic. Quartz occurs as long lenticular grains ("ribbon" quartz). Here the higher rutile content is a peculiarity. Mesocratic gneisses have rutile and leucocratic varieties clinozoisite as an accessory mineral.

Veined migmatite material is composed of plagioclase, quartz and potassium feldspar with a substantial amount of garnet, rarely sillimanite. Biotite occurs either in small amounts or is totally absent.

In the southern part of the Granulite Belt the parameters of the early stage of metamorphism can be estimated using assemblages of fine-grained garnet-biotite gneisses. These gneisses form lenses or boudins among coarse-grained sillimanite-bearing varieties. Our observations suggest that the latter can be formed under structural and mineral transformations of fine-grained gneisses during a culminating stage of granulite metamorphism (at least in the exposures studied). The same transformation of fine-grained garnet-biotite gneisses ("slice of dried bread") to coarse-grained gneisses - blastomylonites has been established in the Belomorian complex (Volodichev, 1990). In the present case, it can be supposed that the minerals of fine-grained gneisses have preserved the composition corresponding to the P-T conditions of early-stage metamorphism. The culmination of granulite metamorphism would then have taken place under low activity or low partial water pressure (as it did in Lapland granulites according to Hörmann et al., 1980) and without superimposed structural trans-

Table 4. Composition of garnet from acid granulites (%).

Component	F-3-1		F-71-2	F-50-4	F-54-1		F-55-1	
	core	rim	core	core	core	rim	core	rim
Spessartine	0.9	1.1	0.7	0.6	0.5	0.6	0.5	0.5
Pyrope	39.6	34.9	44.3	38.2	34.9	31.9	34.5	35.3
Almandine	56.0	60.6	51.4	58.1	60.8	64.4	59.0	61.8
Grossular	3.5	3.5	3.5	3.1	3.8	3.1	6.1	2.4

Table 5. P-T conditions of regional metamorphism in acid granulites in southern part of the Lapland Granulite Belt. Garnet-biotite temperatures calculated according to Perchuk et al. (1983), pressures calculated from garnet-plagioclase-biotite-muscovite-quartz barometer (Hoisch, 1990, 1991); matrix = matrix biotite, contact = biotite in contact with garnet, core = core of garnet and rim = margin of garnet.

Sample	Bt	Gar	$X_{Mg}Bt$	$X_{Mg}Gar$	$X_{Ca}Gar$	$X_{Ca}Pl$	T,°C	P,kbar
F-3-1	matrix	core	0.705	0.410	0.035	0.319	705	6.85
	contact	rim	0.748	0.361	0.035	0.319	584	4.57
F-50-4	matrix	core	0.655	0.394	0.031	0.210	745	6.73
F-71-2	matrix	core	0.686	0.460	0.035	0.230	812	9.15
F-54-1	matrix	core	0.599	0.363	0.038	0.281	801	9.00
	contact	rim	0.662	0.329	0.031	0.228	668	7.07
F-55-1	matrix	core	0.680	0.367	0.061	0.160	745	12.07
	contact	rim	0.660	0.362	0.024	0.160	711	7.77

formation in relic gneisses. If that is so, the P-T conditions of the early-stage metamorphism were 705°C and 6.85 kbar, as calculated from coexisting biotite, garnet and plagioclase compositions (Table 5, sample F-3-1).

The thermal and barometric regime of the culminating stage, which coincided with thrusting, as calculated from the mineral compositions (biotite-garnet-plagioclase) in blastomylonitized sillimanite-garnet-biotite granulites, indicates a temperature of 800-810°C and a maximum pressure of 9.0-9.1 kbar (Table 5, samples F-71-2 and F-54-1, matrix-core). On the whole, the data available indicate wide variations in the thermal and barometric regime during this period. Maximum pressure at the bottom of the acid part of the Granulite Belt was equal to 12.1 kbar at a relatively low temperature (745°C; Table 5, sample F-55-1, matrix-core). The garnet cores of these gneisses are rich in Ca but the plagioclase in the paragenesis is characterized by the lowest calcium content (Tables 3 and 5, sample F-55-1).

At a regressive stage, a rather short one if judged by the widths of the regressive rims in garnet, the temperature dropped to 580-710°C with pressure decreasing to 4.6-7.8 kbar, as calculated from the biotite and garnet in contact with each other (Table 5, samples F-3-1, F-54-1, F-55-1, contact-rim).

DISCUSSION

Taking into account the geological, petrological and geochemical data, at least three structural and metamorphic complexes can be distinguished in the region, each differing from the other in lithology, origin (of rock type complexes) and metamorphic history.

The oldest of the complexes is the gneiss complex surrounding the Lapland Granulite Belt (LGB). It is mainly composed of magmatic amphibole and biotite-amphibole gneisses and of granite-gneisses of dacite-rhyolite (plagiogranite) composition. The polymetamorphic nature of the gneisses has been established. The assemblages of the early metamorphic cycle represented by clinopyroxene, plagioclase and quartz have been observed in the tectonic plate of the gneisses on the border between mafic granulites and the Tana complex (point F-55 in Fig. 1). Here the clinopyroxene-bearing plagiogneisses are in a direct contact with the bipyroxene-amphibole rocks of the granulite complex bottom. The absence of orthopyroxene is obviously due to the low MgO content in these plagiogneisses (0.1 wt% MgO; Table 1, sample F-55-12). The clinopyroxene-plagioclase-quartz assemblage has also been observed as relict in amphibole and biotite-amphibole gneisses in the surrounding complex farther from the granulites (Fig. 1, point F-56). In other exposures of the surrounding gneisses (Fig. 1, points F-60 and F-62) early clinopyroxene is probably totally replaced by amphibole.

The early metamorphic cycle also contains a formation of thin migmatic banding. The neosome of this stage is composed of quartz, plagioclase and small amounts of clinopyroxene and brown-green amphibole.

The late tectonometamorphic cycle includes two deformation stages, which developed successively with decreasing plasticity of deformation; isocline folds formed during the first stage and open folds during the second stage. A generation of plagiomicrocline migmatites corresponds to each of these stages. Metamorphism of amphibolite facies simultaneously with the deformation took place under increased activity of water and potassium compared with the early cycle. These conditions caused intensive replacement of clinopyroxene and plagioclase by blue-green amphibole, garnet and potassium feldspar; at a later stage amphibole was partly replaced by biotite and epidote. The amphibole and biotite-amphibole assemblages of the second metamorphic cycle are widespread in the surrounding gneiss complex.

The sequence of mineral formation observed in the gneisses indicates regressive processes from granulite facies conditions (or so) in the early cycle to those of amphibolite facies in the late cycle. The appearance of garnet together with amphibole indicates a pressure increase at the early stage of the second metamorphic cycle.

Within the surrounding gneiss complex, two generations of greenstones of different age can be distinguished. The polymetamorphic rocks exhibiting features of repeated deformation, metamorphism and migmatization are interpreted as the more ancient of the two. These rocks occur as relics among gneisses and are also shown on the map (Fig. 1). We assume that some other lens-shaped greenstone inclusions in the gneisses shown on the map in Fig. 1 or by Lehtonen (1992) are also of a polymetamorphic nature and an even greater age. The early metamorphism of the ancient greenstones occurred under the conditions of granulite facies (bipyroxene-amphibole subfacies) in the absence of visible deformations (static granulite metamorphism). The formation of garnet-clinopyroxene assemblages at the expense of bipyroxene ones was probably due to the increasing pressure at late stages of granulite metamorphism. The superimposed metamorphism of the second cycle occurred under the conditions of amphibolite facies. Its culmination stage is reflected in the development of the garnet-amphibole assemblages shown by the high pressure regime. Pressure decreased at the final stage of the superimposed metamorphism, and garnet disappeared from the amphibolite assemblages.

The younger greenstone complex is characterized by monocyclic metamorphism, simpler deformation and a lack of migmatites. It forms a thicker and longer ? linear structure, extending from of the Tankajoki river to the north-west and being probably a component of the Central Lapland Greenstone Belt (Lehtonen et al., 1992). Its metamorphism was of a progressive nature and took place under the conditions of low-grade amphibolite facies. The development of the garnet-amphibole assemblages indicates high pressure.

The surrounding gneiss complex and the relics of the ancient greenstones seem to have had a similar evolutionary history with two tectonometamorphic cycles. The age of the granulite metamorphism of the early cycle is thought to be Late Archaean by analogy with the Belomorian Belt of Russia (Volodichev, 1990; Bibikova et al., 1992). According to petrological features, the superimposed second-cycle metamorphism of amphibolite facies in these complexes is close to, or identical with the progressive metamorphism of the younger monocyclic greenstone complex. The age of the complex was determined as 2526+/-46 Ma (Pihlaja & Manninen, 1988). On this basis, the second tectonometamorphic cycle in the surrounding gneiss complex and ancient greenstones, and also the progressive metamorphism of the young greenstones are Early Proterozoic.

The granulite complex is mainly composed of metasedimentary formations, among which greywackes and subgreywackes predominate. A higher content of strontium and barium is a characteristic feature of metasedimentary rocks of the Granulite Complex, probably due to their genetic relation to metavolcanites of the lower part of the section (Kozlov et al., 1989). The metavolcanites of the granulite complex are rather rare in the area studied. Geochemically, they plot into the field of island-arc volcanics on the Ti-Zr discrimination diagram, provided no contamination has occurred (see Fig. 3, points F-52-3, F-54-2, F-55-10, F-70-2).

Early culmination and regressive stages have been distinguished in the metamorphic evolution of the acid granulites. The parameters of the early stage are 705,°C and 6.85 kbar, as determined from minerals of the fine-grained garnet-biotite gneisses. The culmination of metamorphism in acid granulites is related to the formation of blastomylonites (from fine-grained garnet-biotite gneisses), subhorizontal linearity and hinge lines of isoclinal

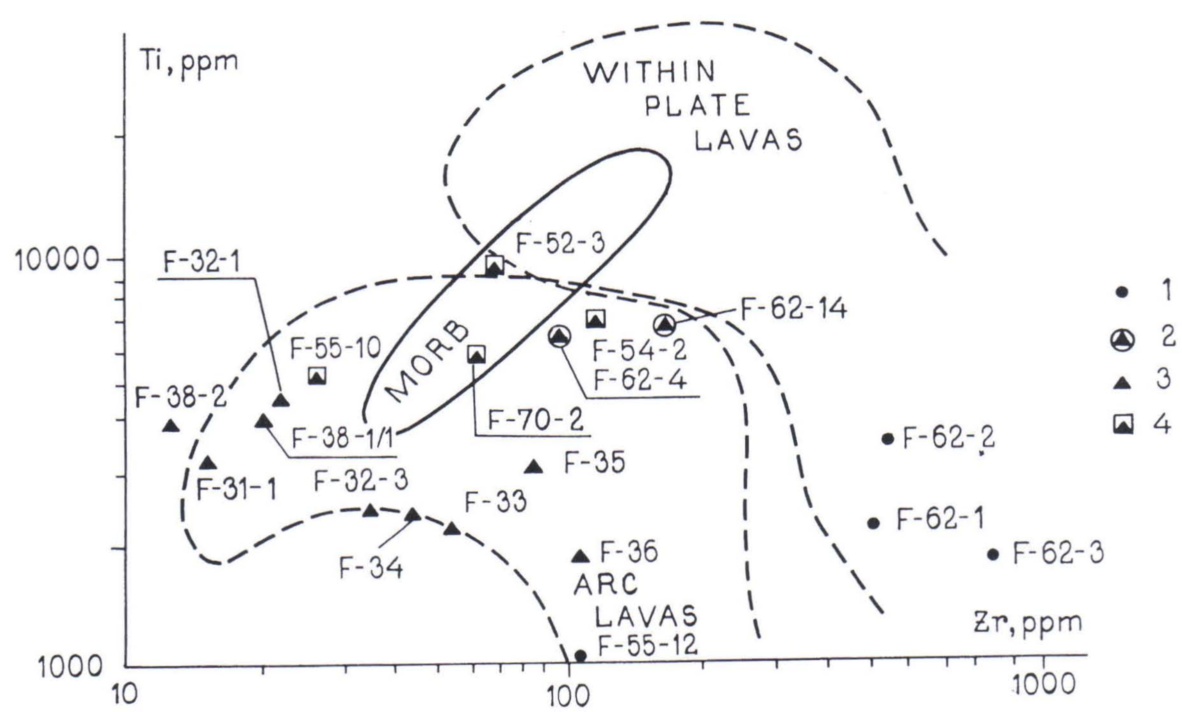

Fig. 3. Ti - Zr diagram of the metamagmatic rocks of the Vuotso area on the diagram of J. Pearce (1982).
Legend: 1 and 2 - gneisses and amphibolites of the surrounding complex, respectively; 3 - complex of garnet-amphibole gneisses (the Tana complex); 4- mafic granulites.

folds with schistosity parallel to their axial planes, indicating synchronism with intensive tangential (or horizontal) dislocations. The mineral chemistry reflects considerable variations in temperature and in pressure at this stage. The calculated temperatures are in the range 745-812°C and pressures 6.7-12.1 kbar; the maximum pressure is recorded at the bottom of the granulite complex (see Table 5). The age of the granulite metamorphism culmination is 1900-2000 Ma (Bernard-Griffiths et al., 1984; Daly & Bogdanova, 1991). The age of the early granulite metamorphism, which took place at lower pressure, has not yet been established. The regressive stage implied by a decrease in temperature (to 580-710°C) and in pressure (to 4.6-7.8 kbar) could have taken place 1870 Ma ago (Daly & Bogdanova, 1991).

The complex of amphibole and garnet-amphibole plagiogneisses (the Tana complex) is mainly magmatic in origin. Moreover, the presence of gradual transitions from massive, coarse-grained varieties to gneissose, more fine-grained ones is evidence of the intrusive nature of a considerable portion of these gneisses. Spatially, the complex is located in a contact zone between the granulite complex and the surrounding complex. These two complexes are characterized by structural features differing from each other. Structurally, the Tana complex is identical to the granulite complex of which it forms the southern and south-western border. The contact between the Tana complex and surrounding gneiss complex is tectonic, as is confirmed by the differences between the structural planes of these complexes, the presence of tectonic wedges of the surrounding gneisses in the Tana complex and the data of the magnetic survey.

The tectonic character of the contact between the Tana complex and the granulite complex is emphasized by the substantial (about 100°C) and rather sharp change in metamorphism temperature (Raith & Raase, 1986). However, the similarity in geochemical features between the Tana complex rocks and the mafic granulites of the granulite complex bottom, and the structural similarity between the Tana and Granulite Complexes indicate their possible consolidation in a united complex as is now accepted for the Kola Peninsula (Belyaev, 1971; Kozlov et al., 1990).

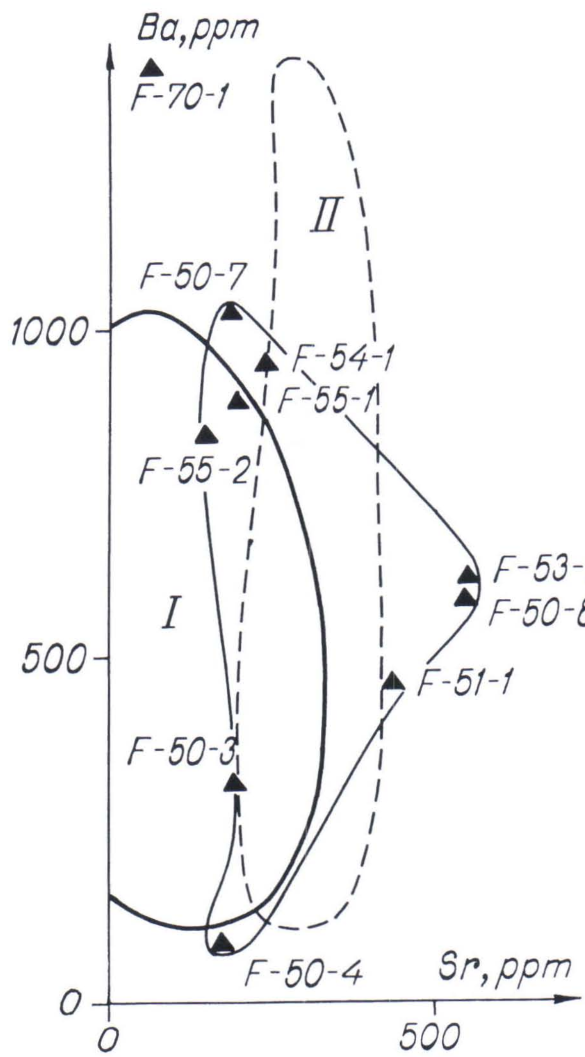

Fig. 4. Ba - Sr diagram for the metasedimentary rocks (felsic granulites) of the Vuotso area.Legend: I - field of Ba and Sr background content in metasedimentary and sedimentary rocks (Kozlov, 1983); II- field of Ba and Sr content in metasedimentary rocks of central and south-eastern parts of the Granulite Belt (Kozlov et al., 1989).

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Appendix 1. Mineral assemblages of rocks in Vuotso area, northern Finland. Secondary minerals are given in brackets, accessory minerals come last in the assemblage.

The surrounding gneiss complex

F-30 qtz+hem, qtz+ms rt, ore

The Tana complex

F-32-1 cpx+gar+amph+pl+qtz (ep+ser+chl) ap
F-32-2 cpx+gar+amph+pl+qtz (amph2-3+ep+ser) ore
F-32-3 gar+amph+pl+qtz (bt) ap, ore
F-32-4 cpx+gar+amph+pl+qtz ap
F-33 gar+amph+pl+qtz (ep+ser) ore, ap
F-34 gar+amph+pl+qtz (ep+ser) ore, ap
F-35 gar+amph+pl+qtz (bt+chl+ep) ore, ap
F-36 gar+amph+bt+pl+qtz (kfs+chl+ep) ore, zrn, ap
F-37 cpx+opx+amph+pl+qtz (act+ep+chl)
F-38-1 gar+amph+pl+qtz (ep+ser) ore
F-38-2 amph+pl+qtz (ep) ore
F-38-3 gar+amph+pl+qtz (ep+ser+bt+chl) ore, ap
F-38-4 gar+amph+pl+qtz (ep+ser+chl) ore
F-38-5 gar+amph+pl+qtz (ep+ser+bt+chl) ore, ap
F-39-1 amph+pl+qtz (ep+ser) ore, ap
F-39-2 amph+pl+qtz (ep+chl+ser) ore, ap
F-40-1 gar+amhp+pl+qtz (bt+ep+chl) ore, zrn, ap
F-40-2 gar+amph+pl+qtz (bt+ep+chl) ore, ap
F-41-1 cpx+amph+pl (ep+chl) ore, ap
F-41-2 cpx+gar+amph+pl+qtz (chl+ep) ore, ap
F-41-2-1 gar+amph+pl+qtz (ep+ser) ore, ap
F-42-2-2 opx+cpx+amph+pl+qtz ore

The Early Proterozoic greenstone complex

F-43-1 amph+pl+qtz sph, ore
F-43-2 amph+pl (chl)
F-43-3 gar+amph+pl (ep+chl) ore, sph
F-43-4 gar+amph+pl+qtz (ep) ore, sph
F-43-5 gar+bt+pl+qtz+kfs (ms) ore
F-44-1 gar+bt+amph+pl+qtz+kfs ore, zrn, ap
F-44-2 bt+pl+qtz+kfs (ser) ore
F-44-3 bt+pl+qtz+kfs (ms) zrn
F-44-4 gar+bt+pl+qtz+kfs zrn
F-44-5 gar+amph+pl+qtz (chl+ep+amph?52?0) ore
F-45-1 amph+pl (ep) sph, ore
F-45-2 amph+pl (ep)
F-45-3 amph+pl+qtz (act+ep) ore
F-46-1 amph+pl+qtz (ep+chl) ore
F-46-2 act+ep+pl+qtz+kfs sph, ore
F-47 qtz+pl (ms)
F-48 gar+amph+bt+pl+qtz+kfs ore, sph

The Lapland Granulite Belt

F-50-1 gar+bt+pl+qtz (ms, ser) ore, ap
F-50-2 gar+sil+bt+pl+qtz+kfs ore
F-50-3 gar+sil+bt+pl+qtz+kfs ore, rt
F-50-4 sil+bt+pl+qtz+kfs ore, zrn
F-50-5 sil+gar+bt+pl+qtz+kfs ore
F-50-6 sil+gar+bt+pl+qtz+kfs (ms) rt
F-50-7 sil+gar+bt+pl+qtz+kfs (ms,ser) rt, ore, zrn
F-50-8 gar+bt+pl+qtz+kfs (ep+ser) ore
F-50-9 gar+pl+qtz (ep+chl) zrn, sph, ore
F-50-10 opx+bt+pl+qtz ore, ap
F-50-11 gar+pl+qtz (ep+carb+ser) zrn, sph, ore
F-51-1 sil+gar+bt+pl+qtz+kfs (ser, chl) zrn, rt
F-51-2 opx+cpx+gar+bt+pl+qtz (ep+ser+ms) zrn, ore
F-51-3 sil+gar+qtz+pl+kfs (ms, ep) rt
F-52-1 gar+bt+pl+qtz (ms) ore
F-52-2 sil+gar+bt+pl+qtz spi, zrn
F-52-3 opx+cpx+gar+bt+pl ore, ap
F-52-4 opx+cpx+gar+bt+pl+qtz ore
F-53-1 opx+cpx+amph+bt+pl ore, ap
F-53-2 opx+bt+pl+qtz ore, ap
F-53-3 opx+gar+bt+pl+qtz ore, ap
F-53-4 opx+cpx+pl+qtz (amph) ore
F-54-1 sil+gar+bt+pl+qtz+kfs ore, rt
F-54-2 opx+cpx+amph+pl ore, ap
F-54-2a opx+bt+amph+pl+qtz
F-54-2b opx+cpx+bt+amph+pl+qtz
F-55-1 sil+gar+bt+pl+qtz+kfs rt
F-55-2 gar+bt+pl+qtz+kfs rt
F-55-3 cpx+pl (scp+ep+amph+qtz) sph, ap, ore
F-55-4 cpx+amph+pl (amph2+ep+ser) ore, ap
F-55-5 cpx+gar+amph+pl ore, ap
F-55-6 cpx+amph+pl+qtz (amph2-3+ep+chl+ser)
F-55-7 cpx+pl+qtz (ep+chl+bt)
F-55-8 opx+cpx+amph+pl+qtz (amph2) ore, ap
F-55-9 opx+cpx+gar+amph+bt+pl+qrz (amph2) ore
F-55-10 opx+cpx+gar+amph+pl ore, ap
F-55-11 cpx+gar+pl+qtz (amph+bt+ep+ser+chl+carb) ore

The surrounding gneiss complex

F-55-12 cpx+pl+qtz (amph) ore, sph, ap
F-56-1 amph+pl+qtz+kfs ore, zrn, ap
F-56-2 amph+pl+qtz+kfs (ep) zrn, ap, ore
F-56-3 amph+pl+qtz+kfs (bt+ep) sph, zrn, ap
F-56-4-1 cpx+pl+qtz (amph+kfs) ore, sph, zrn
F-56-4-2 cpx+pl+qtz (gar+kfs) ore, sph, zrn
F-56-5 gar+amph+pl+qtz+kfs ore, zrn
F-56-6 cpx+pl+qtz (gar+amph+kfs) sph, zrn, ore
F-56-7-1 cpx+pl+qtz (gar+amph+kfs+ep) ore, sph
F-56-7-2 gar+amph+pl+qtz+kfs sph, zrn

The Early Proterozoic greenstone complex

F-57-1 cpx+amph+pl+qtz (ep) sph
F-57-2 act+ep+pl+qtz sph
F-57-3 amph+pl+qtz sph
F-58-1 ep+act+pl
F-58-2 amph+pl+ep sph

The surrounding gneiss complex

F-59-1 amph+pl+qtz+kfs (ep+chl) sph, ore, ap
F-59-2 bt+ms+qtz rt, zrn
F-60-1 amph+pl+qtz+kfs sph, zrn
F-60-2 cpx+amph+pl+qtz (kfs) sph
F-60-3 amph+bt+pl+qtz+kfs zrn, ore
F-61-1 amph+pl+qtz+kfs ore, sph
F-61-2 amph+bt+pl+qtz+kfs (bt2+ep+chl) ore, sph
F-61-3 amph+bt+ep+pl+qtz+kfs (bt2+chl) ore
F-62-1 bt+amph+pl+qtz+kfs (bt2+amph2) ore, sph, ap
F-62-2 bt+amph+pl+qtz+kfs ap, sph, ore
F-62-2a amph+pl+qtz (bt+kfs) sph
F-62-2b amph+pl+qtz (kfs) sph, ap, ore
F-62-3 amph+bt+pl+qtz+kfs (bt2) sph, ore, ap
F-62-3a gar+amph+pl+qtz (bt+kfs+ep) sph, ore, ap

The Archaean greenstone complex

F-62-4 amph+pl+qtz (bt+chl) sph, ore, ap
F-62-4a gar+amph+bt+pl+qtz ore, ap
F-62-5 gar+amph+pl (qtz) sph, ap, ore
F-62-6 gar+amph+ore
F-62-6a gar+amph+cum+qtz+ore ap
F-62-6b gar+amph+pl+qtz (bt) ore, ap
F-62-7 gar+amph+pl+qtz (kfs+ep) ore, sph, ap
F-62-7a gar+amph+pl (bt+ep) ap, ore, sph
F-62-8 gar+amph+cum+ore+ap
F-62-8a amph+pl (bt) ore
F-62-8b amph+pl (ep) ore
F-62-9 gar+amph+pl (ep) ore, sph
F-62-9a gar+amph+pl (scp+ep+chl) ore
F-62-10 gar+amph+cum+pl (bt+chl) ore, ap
F-62-11 gar+cpx+amph+pl (bt) ore
F-62-12 gar+amph+pl (bt) ore, sph, ap
F-62-12a gar+cpx+amph+pl sph
F-62-13 gar+amph+bt+pl+qtz ap, ore, sph
F-62-14 opx+cpx+pl (gar+amph+bt) ore, sph
F-62-14a opx+cpx+amph+pl (bt+act) ore
F-62-14b gar+amph+pl (bt+ser+ep) ore
F-62-15 gar+cpx+amph+pl (ep) sph
F-62-16 gar+amph+bt+pl+qtz (bt2+ep+chl) ore, tur, ap
F-62-17 opx+cpx+pl (gar+amph+bt+ep) ore
F-62-18 ep+act+qtz sph

The Lapland Granulite Belt

F-67-1 sil+gar+bt+pl+qtz+kfs (and?+ms+chl) rt, ore
F-67-2 sil+gar+bt+pl+qtz+kfs ore, rt
F-67-3 opx+cpx+gar+bt+pl+qtz (trm) ore
F-67-4 opx+cpx+amph+bt+pl ore
F-67-5 opx+cpx+pl (gar+amph+bt) ore
F-67-6 opx+cpx+amph+pl+qtz ore
F-68-1 sil+gar+pl+qtz+kfs rt
F-68-2 opx+cpx+pl+qtz ore
F-69-1 bt+opx+pl+qtz+kfs ore, ap
F-69-2 sil+gar+pl+qtz+kfs (bt) rt
F-69-3 gar+bt+pl+qtz+kfs rt, ore
F-69-4 gar+bt+pl+qtz+kfs (ms+prh) rt, ap, ore
F-70-1 opx+pl+qtz+kfs (bt) zrn, ore
F-70-1a opx+cpx+bt+pl (gar) ore
F-70-2 opx+cpx+amph+pl+qtz ap, ore
F-70-3 sil+gar+bt+pl+qtz+kfs rt, ore
F-71-1 gar+bt+pl+qtz (bt?52?0+chl+ser) ap
F-71-2 sil+gar+bt+pl+qtz+kfs ore, rt
F-72-1 sil+gar+bt+pl+qtz+kfs (ms+pl2+ser) ore
F-72-2 sil+gar+bt+pl+qtz+kfs (bt2+ms+ser) ore, zrn
F-3-1 gar+bt+pl+qtz ap, zrn

Appendix 2. Map coordinates of sample localities (map sheets 3724 2 and 3742 1,1:50 000).

Code	Sheet	x-coord.	y-coord.	Code	Sheet	x-coord.	y-coord.
F-30	3724 2	7567.20	494.12	F-51	3742 1	7572.52	500.12
F-32	3724 2	7574.26	494.87	F-52	3724 2	7572.26	499.71
F-33	3724 2	7573.95	494.77	F-53	3724 2	7572.32	499.35
F-34	3724 2	7574.80	494.35	F-54	3742 1	7566.75	502.45
F-35	3724 2	7574.15	494.20	F-55-1	3742 1	7563.70	505.27
F-36	3724 2	7573.60	494.34	F-55-12	3742 1	7563.30	505.10
F-37	3724 2	7572.98	493.96	F-56	3742 1	7550.84	490.42
F-38	3724 2	7572.62	494.00	F-57	3724 2	7555.80	498.58
F-39	3724 2	7572.40	494.15	F-58	3742 1	7556.34	500.10
F-40	3724 2	7571.74	494.78	F-59	3724 2	7567.20	494.12
F-41	3724 2	7571.83	494.27	F-60	3724 2	7565.74	493.03
F-42	3724 2	7572.94	494.52	F-61	3724 2	7562.76	493.19
F-43	3724 2	7553.35	492.87	F-62	3724 2	7563.82	493.47
F-44	3724 2	7554.00	493.25	F-67	3742 1	7566.92	504.25
F-45	3724 2	7555.48	495.95	F-68	3742 1	7568.18	504.98
F-46	3724 2	7555.54	496.87	F-69	3742 1	7569.28	510.79
F-47	3724 2	7555.50	497.08	F-70	3742 1	7577.35	511.12
F-48	3724 2	7555.62	497.28	F-71	3742 1	7577.14	514.84
F-50	3742 1	7575.64	503.02	F-72	3742 1	7579.85	512.56

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