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Metasedimentary Rocks of the Lapland–Kolvitsa Granulite Belt of the Baltic Shield: Primary Mineral Composition and Petrogeochemistry

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Abstract—The normative mineral composition is reported on source rocks of metasediments from the granulite belt of the Baltic Shield. The primary composition, CIA index, and position of data points of studied rocks in discriminant diagrams indicate that a significant part of the studied rocks formed from immature sediments (graywackes and subgraywackes). The material supplied to sedimentation paleobasins was obtained from different (ultrabasic, basic, intermediate, and acid) rocks. The paleobasin was characterized by organic activity and reducing environment in the bottom layer. Correlation found between some elements, e.g., (Rb, Ba, Pb)–K; Sr–(Na, Ca), and so on, is also typical of Phanerozoic deposits. The possible contents of OM (C_{org}) and U were reconstructed in source rocks of metasediments of the Lapland–Kolvitsa granulite belt of the Baltic Shield.

INTRODUCTION

Study of lithogenesis at early stages of the Earth's evolution is of great scientific and practical significance. They were marked by the formation of the majority (80–85%) of high-grade (granulite) complexes. However, study of these granulite complexes is complicated by the obliteration of primary structural, mineral, and, occasionally, textural features during regional metamorphism. Therefore, reconstruction of the primary nature of high-grade sequences is a major issue in the Precambrian sedimentary geology.

Numerous investigations showed no significant change in the chemical composition of metasedimentary rocks up to the highest-grade metamorphism, except for water and volatile loss. Therefore, reconstruction of the primary mineral composition of metamorphic rocks from petrochemical data, lithochemical recalculations, and indicator ratios of some major and trace elements is the most powerful tool for deciphering the primary origin and sedimentation conditions of metasedimentary rocks.

Problems of the geological structure and genesis of the Lapland–Kolvitsa granulite belt were studied by Russian and foreign geologists (Eskola, 1952; Goroshchenko, 1969; Krylova, 1983; Barbey *et al.*, 1984; Kozlov *et al.*, 1990; Bibikova *et al.*, 1993; Mints *et al.*, 1994; and others). In this paper, first data on the normative mineral composition of source rocks of metasedimentary granulites are reported; primary contents of OM and U are reconstructed; and correlation between several minor elements and primary mineral composition of studied rocks is considered.

The work is based on the study of high-grade metasedimentary rocks (acid granulites) in the granulite belt of the Baltic Shield extending over Norway, Finland, and Russia.

GENERAL CHARACTERISTICS

The Lapland–Kolvitsa granulite belt of the Baltic Shield is an approximately 500-km-long arc-shaped structure divided into two different-sized blocks. The large Lapland Block includes the Sal'nye Tundry, Tuadash Tundry, and Lotta Zone (Russia), Finnish Lapland, and Norwegian Lapland, whereas the small Kolvitsa Block (~70 km) includes the Kandalaksha and Kolvitsa Tundry (Fig. 1). The granulites are overlain by Caledonides of Polar Norway in the northwest and dip beneath the Kandalaksha Bay (White Sea) in the southeast.

In 1874, Jersntrem first reported high-grade garnet-bearing rocks from the northern Lapland as granulites by analogy with Saxonian granulites. This was followed by numerous publications on the primary nature, composition, and metamorphism of granulites in the Baltic Shield and related mineral resources. The term "granulite" was initially used for high-grade magmatic, volcanosedimentary, and primary sedimentary rocks. Currently, most geologists (Kozlov, 1988; Kozlov *et al.*, 1990; Mints *et al.*, 1994; and others) suggest a primary volcanosedimentary origin of rocks of the granulite complex. The granulite complex is divided into two sequences (Kozlov, 1988; Kozlov *et al.*, 1990). The lower sequence is composed of mafic granulites (garnet–plagioclase–pyroxene, plagioclase–pyroxene, and two-pyroxene crystalline schists) derived from metamorphosed basalts, basaltic andesites, andesites, and dacites. The upper sequence mainly consists of metasedimentary rocks, acid granulites (garnet–

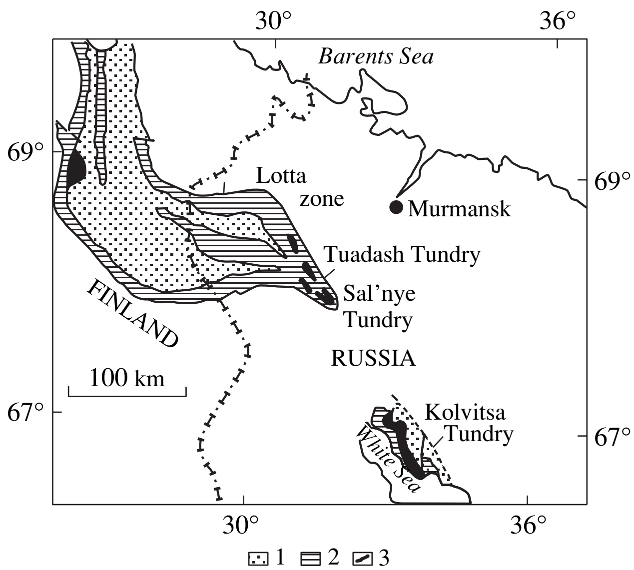

Fig. 1. Schematic location of the Lapland–Kolvitsa granulite belt of the Baltic Shield. (1) Upper sequence; (2) lower sequence; (3) metagabbro–anorthosite massifs.

quartz–feldspathic and sillimanite–garnet–quartz–feldspathic rocks).

The granulite belt is underlain by the gneiss–amphibolite sequence (Tana Belt) with gabbro–anorthosite plutons. The Tana Belt rests on diverse plagiogneisses and amphibolites of Upper Archean Belomorian and Kola complexes (Fig. 2).

It should be noted that the area and thickness of acid granulites are variable (Figs. 1, 2). According to Bibikova *et al.* (1993), the age of granulite metamorphism ranges within 2.2–1.9 Ga. According to Perchuk and Krotov (1999), acid granulites were metamorphosed at 825°C and 8 kbar.

In this work, we only the consider upper sequence of granulite belt, i.e. its metasedimentary section (acid granulites).

PETROCHEMICAL DATA AND PRIMARY MINERAL COMPOSITION OF METASEDIMENTARY ROCKS OF THE GRANULITE BELT

Acid granulites are high-grade acid (leucocratic) rocks. They consist of quartz, plagioclase, K-feldspar, garnet, and subordinate sillimanite, kyanite, biotite, cordierite, and pyroxene. Accessory minerals are rutile, ilmenite, zircon, monazite, apatite, graphite, and spinel. The most abundant granulites have garnet–quartz–feldspathic and sillimanite–garnet–quartz–feldspathic compositions. Their characteristic structural feature is the presence of elongated or lenticular quartz (ribbon quartz). Many geologists note that acid granulites of the Baltic Shield are similar to classical Saxonian granulites in mineral composition, texture, and structure.

Judging from published data (Kozlov *et al.*, 1990; Rosen, 1993; and others), acid granulites are metamorphosed graywackes, subgraywackes, and, to a lesser extent, metapelites. This is consistent with our data. In particular, data points of the studied rocks in diagrams of Rosen (1993) and Pettijohn are plotted in the fields of graywackes, subgraywackes, graywacke pelites, and arkoses (Table 1, Fig. 3).

In terms of SiO_2 and Al_2O_3 contents and mineral composition, the studied rocks are divided into several

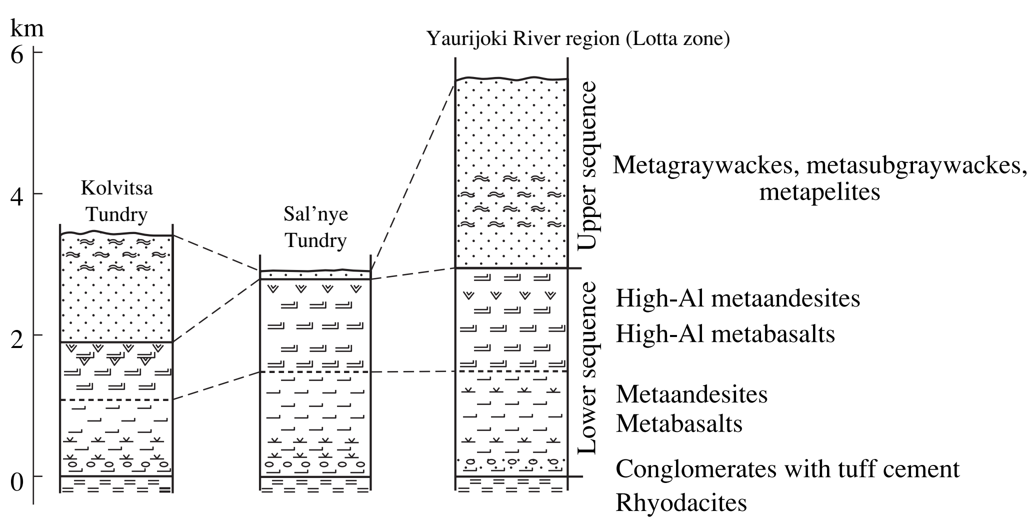

Fig. 2. Correlation of generalized lithosptratigraphic columns from different areas of the granulite belt of the Baltic Shield (Kozlov *et al.*, 1990).

types (Table 1). Data in this table suggest that source rocks were sandy clays, clayey sandstones, and quartzose sandstones. The studied rocks are characterized by the predominance of K_2O over Na_2O and often MgO over CaO, which is typical of Phanerozoic terrigenous rocks. Relative to sedimentary rocks, metasedimentary rocks of the granulite complex are characterized by lower MnO and P_2O_5 contents and predominance of FeO over Fe_2O_3 (Table 1).

Table 1 also lists chemical compositions of the well-studied Scottish and Saxonian granulites for comparison.

Metasedimentary complexes were studied to decipher their primary mineral composition and formation conditions. The primary mineral composition was reconstructed using the lithochemical recalculation method of Rosen (Rosen *et al.*, 1999). This method is based on the assumption that processes and products of decomposition, weathering, and sedimentation in Precambrian were similar to those in Phanerozoic. Moreover, the major chemical signatures of rocks were retained during the regional metamorphism. This method allows us to reconstruct the primary mineral composition of metamorphic rocks and compare rocks of similar type but different ages and metamorphic grades.

Lithochemical recalculations of silicate analyses of the most representative granulites are presented in Table 2. It shows that the clastic component of primary rocks was dominated by quartz. The content of feldspars (mainly, acid plagioclase) was often significant. The K-feldspar was absent or insignificant, thus indicating its deficiency in the source rocks. The provenance possibly consisted of basalts, basaltic andesites, and dacites.

The clay component of primary sediments mainly included alkaline aluminous clays dominated by hydromica with subordinate smectites (normative montmorillonite, Table 2). The Mg–Fe minerals were minor or absent. Judging from the Fe mole fraction of rocks (f = 0.58–0.68), normative chlorite was ascribed to the Mg–Fe prochlorite–ripidolite series typical of graywackes, polymictic and quartzose sandstones, and clays. Traces of goethite, Mg–Fe chlorites, and smectites are almost always present, indicating the intermediate–mafic composition of rocks in the provenance area. The primary rocks also contained a subordinate amount of carbonate minerals (calcite, dolomite, and ankerite), which typically occur in the matrix of Phanerozoic graywackes.

In the modified Pettijohn diagram (Rosen, 1993), data points of recalculated rocks are mainly plotted in the fields of graywacke and subgraywacke pelites, with some points falling in the fields of pelites and quartzose sandstones. The trend of studied rocks significantly differs from that of Paleozoic graywackes from the genotype locality in Upper Harz, Germany (Fig. 4). This trend also differs, though to a lesser extent, from that of garnet granulites in the Upper Archean Khapchan Group of the Anabar Shield (Rosen, 1993), being

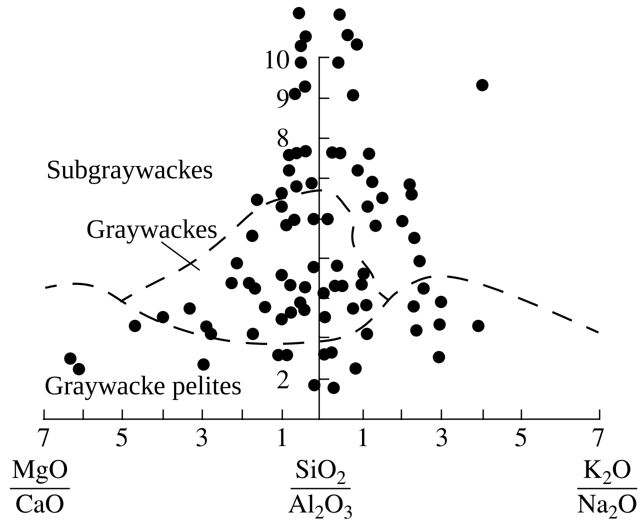

Fig. 3. Composition of metasedimentary rocks of the granulite belt of the Baltic Shield in the diagnostic diagram of Rosen (1993).

located closer to the quartz–pelitic side. This indicates that source rocks of granultes of the Baltic Shield were more differentiated and the matter supplied to the sedimentation paleobasin was more mature as compared to granulites of the Anabar shield, and, especially, graywackes of Upper Harz.

Comparison with the normative mineral composition (Table 2) and positions of data points of Scottish and Saxonian granulites (Fig. 4) showed that our results are consistent with conclusions of other geologists (Anderson, 1968; Noiman *et al.*, 1984) who considered that source rocks of granulites were quartz–feldspathic sandstones (arkoses) with small amounts of clay cement.

It should be noted that the (Fe + Mn)/Ti (Strakhov, 1976) and Al/(Al + Fe + Mn) indices (Böstrom and Peterson, 1960) in the studied granulites universally show “exogenic” values of 8–18 and 0.5–0.8, respectively. Such values indicate that exhalative hydrothermal material was not introduced into sedimentation paleobasin during the formation of source rocks of the granulite complex. This conclusion is confirmed by the values of normative alkalinity module, i.e., Na_2O + K_2O/Al_2O_3, which mainly vary from 0.2 to 0.4, i.e. correspond to those for the typical Phanerozoic terrigenous rocks.

Metasedimentary rocks of the Baltic granulite belt universally contain small graphite flakes (0.5–1.0 mm, occasionally up to 2–5 mm), which account for 0.2–0.5% (occasionally up to 1–2%). Escola (1952) believed that like pyrite, graphite in acid granulites is metamorphosed sapropel. Analyses showed that the average C_{org} content is 0.14% in essentially quartz–feldspathic rocks and 0.40% in high-Al rocks. We attempted to reconstruct the approximate amount of organic matter (OM) and C_{org} in source rocks of granu-

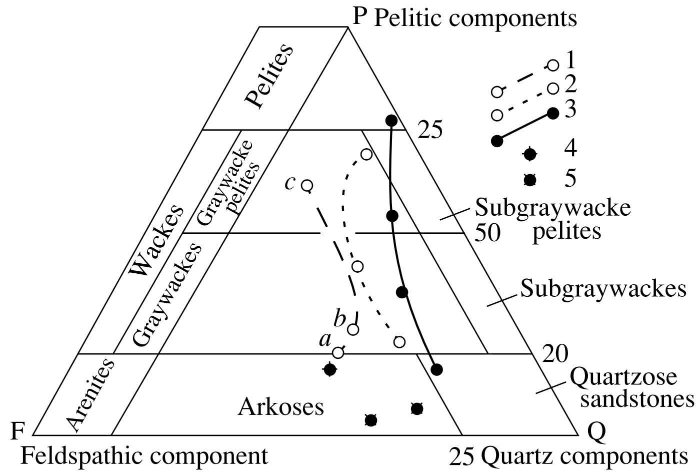

Fig. 4. Trends of metasedimentary rocks from granulite belt of the Baltic Shield, garnet granulites of the Anabar Shield, and graywackes from genotype locality in the modified Pettijohn diagram (Rosen, 1993). (1) Graywackes of Upper Harz (Germany) with (*a*) coarse-grained, (*b*) medium-grained, and (*c*) pelitic textures; (2) garnet granulites of the Anabar Shield; (3) metasedimentary rocks of the granulite belt of the Baltic Shield; (4) Saxonian granulites; (5) Scottish granulites.

lite complex based on the following assumptions: OM loss during diagenesis is 35%; 80% of the OM left after diagenesis is lost during subsequent catagenesis and metamorphsim; and the C_{org}/OM transition coefficient is 1.43. Calculations showed that source rocks probably contained from 1.5 to 4–4.5% OM and 1.1–3.1% C_{org}. Such OM and C_{org} contents presumably indicate a well-developed organic life in the Early Proterozoic sedimentation paleobasin and reducing environment in its bottom layer.

ABUNDANCE AND DISTRIBUTION OF TRACE AND RARE ELEMENTS IN METASEDIMENTARY ROCKS OF THE GRANULITE BELT

Contents of siderophile elements (Fe, Ti, Ni, Co, V, and Sc) in the studied rocks demonstrate a wide range (Cr 20–280 ppm, Ni 3–140 ppm, Co 4–72 ppm, V 36–300 ppm), with average contents corresponding to clarke values in mafic, intermediate, and acid rocks (Table 3). The studied rocks show a vague correlation of several elements with Al and Fe, indicating the low maturity of material supplied into the sedimentation paleobasin. However, some metasedimentary rocks show a distinct correlation of trace elements with Al and Ga with Ti.

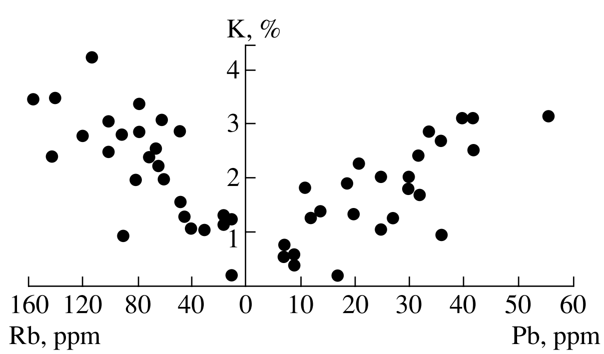

Fig. 5. Correlation of Pb and Rb with K in metasedimentary rocks of the granulite belt of the Baltic Shield.

The increased contents of Cr, V, and other trace elements in the granulite belt of Finland and the Kolvitsa zone can be explained by the presence of goethite (Table 2). It is known that iron hydroxides are strong concentrators of many trace elements, including Cr, V, Ti, and Sc.

Lead abundance in the studied rocks is higher than that in sedimentary and magmatic rocks (Table 3). In terms of the Pb content, the studied rocks are closest to acid varieties. In granulites, Pb well correlates with K (Fig. 5), which is typical of Phanerozoic sedimentary rocks and caused by close ionic radii of Pb (1.26 Å) and K (1.33 Å) and isomorphous substitution of K for Pb. This explains high Pb contents (up to 75–85 ppm) in K-feldspars and micas (Lubchenko, 1977). One can expect that the increased Pb content (30–38 ppm) in some studied granulites was related to the presence of K-feldspar (~5.40%), iron hydroxide (goethite) showing strong Pb adsorption, and hydromica (Tables 2, 3) in source rocks.

Rubidium exhibits a stronger affinity to K than Pb. The highest Rb content (980 ppm) is restricted to hydromica clays (Kremenetskii *et al.*, 1980). It should be noted that Rb correlation with hydromica, K-feldspar, and K_2O is well traced in the studied rocks (Fig. 5; Tables 2, 3). According to our data, smectite clays also adsorb Rb, whereas polymineral clays contain only 140 ppm Rb (average from 688 analyses). This presumably explains high Rb contents in some low-K rocks

Table 1. Chemical composition of metasedimentary rocks of the granulite belt, wt %

No.	*n*	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	$\frac{Fe + Mn}{Ti}$	$\frac{Al}{Al + Fe + Mn}$	$\frac{Na_2O + K_2O}{Al_2O_3}$	Rock
Finland [Barbey *et al.*, 1984]																
1	27	62.22	0.84	19.03	8.84	–	0.12	3.17	0.69	1.27	3.83	–	12.5	0.62	0.27	Sillimanite–garnet gneisses
2	12	68.58	0.58	15.75	4.84	–	0.08	1.82	2.47	2.83	3.02	–	10.0	0.71	0.37	Garnet gneisses
3	30	76.06	0.53	11.72	4.68	–	0.06	1.57	1.00	1.69	2.71	–	10.4	0.65	0.37	Garnet gneisses
4	9	84.70	0.39	7.59	2.79	–	0.04	0.73	1.36	1.55	0.86	–	8.6	0.67	0.32	Garnet quartzites
Lotta zone (original data)																
5	9	61.05	0.74	17.97	1.73	7.16	0.04	3.97	2.26	1.34	2.37	0.06	15.5	0.58	0.20	Sillimanite–garnet granulites
6	4	72.38	0.31	13.51	0.81	3.10	0.02	1.15	2.65	2.69	2.85	0.06	16.0	0.70	0.41	Garnet granulites
7	2	82.81	0.52	7.93	0.64	2.38	0.02	0.44	2.14	1.60	1.08	0.01	7.5	0.64	0.34	Garnet granulites
Tuadash Tundry (original data)																
8	2	66.46	0.65	15.01	–	6.19	0.04	2.30	2.90	2.77	2.79	0.05	12.0	0.62	0.37	Biotite–garnet granulites
9	4	76.39	0.52	11.18	0.45	3.95	0.04	1.54	2.01	1.31	1.96	0.03	11.0	0.63	0.29	Garnet granulites
10	2	80.80	0.41	7.98	–	3.99	0.04	1.02	2.19	1.50	1.10	0.03	12.5	0.57	0.33	Garnet granulites
Sal'nye Tundry (Kozlov, 1988)																
11	7	63.11	0.67	17.22	1.27	6.59	0.08	2.88	1.18	1.62	2.63	–	15.0	0.60	0.25	Biotite–garnet granulites
12	4	67.22	0.60	14.10	1.74	5.61	0.08	2.90	1.60	1.73	2.92	–	16.0	0.57	0.33	Pyroxene–garnet granulites
Kolvitsa Tundry (Kozlov, 1983)																
13	7	55.29	0.98	21.76	1.56	9.54	0.08	4.48	0.71	0.98	2.95	0.08	14.5	0.57	0.18	Sillimanite–garnet granulites
14	5	58.57	0.72	18.52	2.10	7.05	0.11	3.47	1.25	1.76	4.24	0.10	16.0	0.58	0.32	Biotite–garnet granulites
15	7	78.62	0.38	10.27	0.52	3.30	0.06	1.17	1.75	2.51	1.33	0.07	13.0	0.65	0.37	Garnet granulites
Scotland (Anderson, 1968)																
16	2	82.92	0.31	8.32	0.54	1.26	0.01	0.27	0.78	1.79	3.16	0.10	–	–	–	Quartz–feldspathic granulites
17	1	81.89	0.06	9.10	0.17	0.16	0.26	0.02	0.64	0.11	7.11	0.07	–	–	–	Quartz–feldspathic granulites
Saxonia (Noiman *et al.*, 1984)																
18	7	72.30	–	14.70	–	2.30	–	0.60	1.60	3.00	4.70	–	–	–	–	Granulite

Notes: (–) Data absent, (*n*) number of samples. Analyses were performed in the Chemical Analytical Laboratory, All-Russia Research Institute of Mineral Resources, Moscow (K.A. Tverdokhlebova, analyst) and the Geological Institute, Russian Academy of Sciences, Moscow (E.V. Cherkasova, analyst).

Table 2. Normative mineral composition of metasedimentary rocks of the granulite belt

Components of source rocks		Finland				Lotta zone			Tuadash Tundry			Sal'nye Tundry		Kolvitsa Tundry			Scotland	
Mineral groups	Minerals	Sillimanite–garnet gneisses (27)	Garnet gneisses (12)	Garnet gneisses (30)	Garnet quartzites (9)	Sillimanite–garnet granulites (9)	Garnet granulites (4)	Garnet granulites (2)	Biotite–garnet granulites (2)	Garnet granulites (4)	Garnet granulites (2)	Biotite–garnet granulites (7)	Pyroxene–garnet granulites (4)	Sillimanite–garnet granulites (7)	Biotite–garnet granulites (5)	Garnet granulites (7)	Quartz–feldspathic granulites (2)	Saxonian granulites (7)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	18
Clastic	Quartz	33.46	37.02	53.86	67.88	28.38	42.63	64.47	34.47	57.12	62.16	33.68	42.07	15.60	26.40	55.97	59.60	37.10
	Plagioclase	12.44	27.60	16.29	13.39	8.16	24.92	14.91	26.18	12.17	12.62	13.88	17.11	2.18	17.80	23.35	16.91	28.85
	Orthoclase	–	1.21	3.02	–	0.10	5.42	2.12	4.10	–	1.18	–	–	–	–	–	15.64	14.53
	Total	45.90	65.83	73.17	81.27	36.64	72.97	81.50	64.74	69.29	75.96	47.56	59.18	17.78	44.20	79.32	92.15	80.48
Clayey	Kaolinite	–	–	–	–	0.34	0.35	4.48	–	–	–	–	–	–	–	–	–	–
	Hydromica	32.23	23.23	18.60	6.77	19.58	15.50	5.81	16.95	15.94	7.05	22.23	24.52	25.02	37.04	10.58	4.48	14.63
	Montmorillonite	–	–	–	4.30	17.57	1.65	–	–	0.92	5.71	7.80	–	28.42	–	–	–	–
	Chlorite	16.89	–	–	3.81	16.21	–	–	6.98	7.59	2.92	17.40	1.92	22.47	0.61	3.46	–	–
	Serpentine	0.45	–	1.39	–	0.44	0.37	–	0.60	–	–	–	2.64	–	4.88	–	–	–
	Total	49.54	23.23	19.99	14.88	54.14	17.87	10.29	24.53	24.45	15.68	47.43	29.08	75.91	42.53	14.04	4.48	14.63
Oxide	Goethite	1.97	3.45	3.88	–	2.82	2.59	1.26	2.92	0.23	1.56	0.49	6.53	2.69	7.86	1.66	1.42	0.74
	Pyrolusite	0.10	0.09	–	–	–	–	–	–	–	–	–	–	–	0.10	–	–	–
	Total	2.07	3.54	3.88	–	2.82	2.59	1.26	2.92	0.23	1.56	0.49	6.53	2.69	7.96	1.66	1.42	0.74
Carbonate	Calcite	–	–	–	0.63	1.64	1.43	0.40	1.50	1.20	0.95	–	–	–	–	–	–	–
	Dolomite	1.59	5.72	2.41	–	0.91	2.40	1.26	3.66	0.97	1.36	–	4.54	–	2.70	2.41	0.65	1.07
	Ankerite	–	1.08	–	2.83	3.05	2.33	4.67	1.91	3.16	3.88	3.76	–	2.54	–	2.17	0.80	3.09
	Total	1.59	6.80	2.41	3.46	5.60	6.16	6.33	7.07	5.33	6.19	3.76	4.54	2.54	2.70	4.58	1.45	4.16
Minerals of Ti, P, and others		0.90	0.60	0.55	0.39	0.80	0.41	0.64	0.73	0.71	0.61	0.76	0.67	1.08	2.61	0.40	0.50	–

Notes: (–) Mineral absent. Ordinal numbers correspond to those in Table 1. Numbers in parentheses denote the number of analyses. Inferred types of source rocks: (1) sandy–clayey rocks (graywacke pelites); (2, 3) hydromica–plagioclase–quartz sandstones (graywackes); (4) quartz sandstones with clay cement; (5) sandy–clayey rocks (subgraywacke pelites); (6) feldspar–quartz sandstones with hydromica cement (arkoses); (7) plagioclase-bearing quartz sandstones; (8) plagioclase–quartz sandstones with clay cement (graywackes); (9) clay–quartz sandstones (graywackes); (10) clay–plagioclase–quartz sandstones; (11) clayey–sandy rocks (graywackes), (12) clay–plagioclase–quartz sandstones with goethite (graywackes); (13) quartz-bearing clays; (14) plagioclase–quartz clays with goethite (graywacke pelites); (15) clay–plagioclase–quartz sandstones; (16) pure arkosic sandstones; (18) arkosic sandstones with hydromica cement. Normative mineral composition was calculated using the Rosen method (1999). Composition of quartz–feldspathic granulites (no. 17, Table 1) was not recalculated.

Table 3. Average contents of trace elements in metasedimentary rocks of the granulite belt and Phanerozoic rocks

No.	*n*	Cr	Ni	Co	V	Cu	Sc	Ga	Sr	Pb	Rb	Ba	Zr	Y	B	Al	K	Fe	Ti	Rock
Finland [Barbey *et al.*, 1984]																				
1	11	130	34	15	125	–	–	–	211	–	110	985	203	39	–	10.07	3.18	6.18	0.50	Sillimanite–garnet gneisses
2	8	53	37	11	72	–	–	–	352	–	84	896	198	26	–	8.33	2.51	3.39	0.35	Garnet gneisses
3	14	82	25	11	75	–	–	–	206	–	69	877	219	28	–	6.20	2.25	3.27	0.32	Garnet gneisses
4	3	50	10	10	45	–	–	–	175	–	27	314	303	15	–	4.02	0.71	1.95	0.23	Garnet quartzites
Lotta Zone (original data)																				
5	9	167	50	25	224	158	20	15	329	32	73	553	274	–	18	9.51	1.97	6.77	0.44	Sillimanite–garnet gneisses
6	4	106	16	9	60	82	7	10	407	38	47	245	322	–	20	7.15	2.37	2.76	0.19	Garnet granulite
7	2	69	14	5	73	10	–	13	–	12	–	–	280	–	–	4.20	0.90	2.30	0.31	Garnet granulite
Tuadash Tundry (original data)																				
8	2	77	16	11	91	15	12	22	220	11	120	–	208	–	–	7.94	2.32	4.70	0.36	Biotite–garnet granulites
9	4	72	8	5	59	9	–	15	–	18	–	–	401	–	–	5.92	1.63	3.38	0.31	Garnet granulites
10	2	48	13	7	51	15	5	13	180	7	16	–	293	–	–	4.22	0.91	3.34	0.27	Garnet granulites
Lapland (Mintz *et al.*, 1994)																				
	6	222	36	17	203	29	14	–	352	30	–	1047	–	30	15	8.66	1.83	5.82	0.45	Biotite–garnet granulites
Kolvitsa Tundry (Kozlov, 1983)																				
13	3	145	106	35	143	18	–	–	470	–	142	1170	–	–	11	11.52	2.45	8.50	0.59	Sillimanite–garnet granulites
14	1	150	120	28	160	120	–	–	260	–	138	890	–	–	9	9.80	3.52	6.95	0.43	Biotite–garnet granulites
15	8	80	38	11	50	61	–	–	345	–	39	490	–	–	6	5.43	1.10	2.93	0.23	Garnet granulites
Phanerozoic sedimentary rocks (Turekian and Wedepohl, 1961)																				
		90	68	19	130	45	13	19	300	20	140	580	160	26	100	8.00	2.66	4.72	0.46	Shales
		35	2	0.3	20	–	1	12	20	7	60	–	220	40	35	2.5	1.07	0.98	0.15	Sandstones
Phanerozoic magmatic rocks (Vinogradov, 1962)																				
		200	160	45	200	100	24	18	440	8	45	300	100	20	5	8.76	0.83	8.56	0.90	Mafic
		50	55	10	100	35	2.5	20	800	15	100	650	260	–	15	8.85	2.30	5.85	0.80	Intermediate
		25	8	5	40	20	3	20	300	20	200	830	200	34	15	7.70	3.34	2.70	0.23	Acid

Notes: (–) Data absent. Ordinal numbers correspond to those in Tables 1 and 2; (n) number of samples. Elements from Cr to B are listed in ppm; from Al to Ti, in wt %. Analyses were performed in the Spectral Laboratory of All-Russia Research Institute of Mineral Resources, Moscow (K.V. Barsuk and N.V. Pavlova, analysts) and at the Geological Institute, Russian Academy of Sciences, Moscow (I.Yu. Lubchenko, analyst).

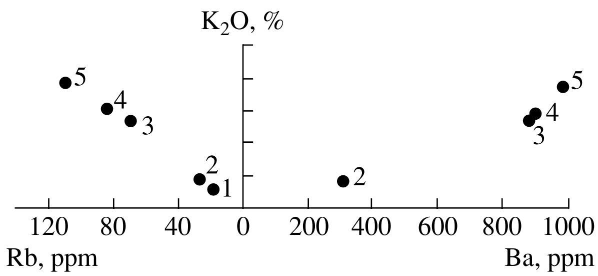

Fig. 6. Correlation of Rb and Ba with K_2O in metasedimentary rocks of the Finnish granulite belt according to (Barbey *et al.*, 1984). (1) calcareous gneisses (2 analyses); (2) garnet quartzites (3 analyses); garnet gneisses (14 analyses); (4) garnet gneisses (8 analyses); (5) sillimanite–garnet gneisses (11 analyses).

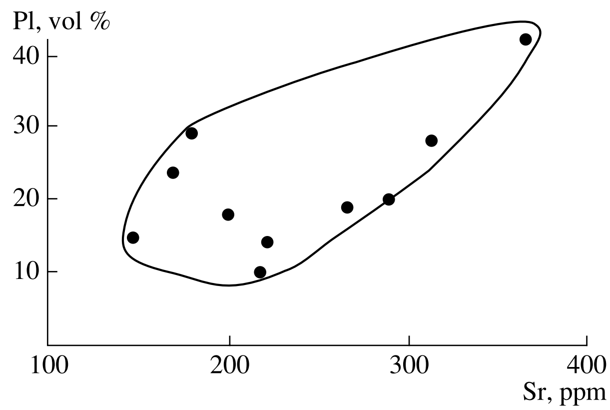

Fig. 7. Correlation between the Sr and plagioclase contents in rocks of the Lotta zone of the granulite belt (Bibikova *et al.*, 1993).

from the Lotta and Kolvitsa zones of the granulite belt (Tables 2, 3).

It is known that *barium* in sedimentary rocks is also chemically related with K, i.e. with hydromica clays and K-feldspars. Such a relation is explained by close ionic radii of K (1.33 Å) and Ba (1.38 Å). The highest Ba contents were found in K-feldspar (5000 ppm) and biotites (1400 ppm), whereas the lower Ba contents were observed in plagioclases (900 ppm) and smectite clays (Krylova, 1983; Ivanov, 1994). These data presumably explain Ba contents and distribution in metasedimentary rocks of the granulite belt (Tables 2, 3; Fig. 6).

Strontium in sedimentary rocks is geochemically more closely related with smectite clays than with hydromicas. Feldspars are the main Sr carriers; e.g., the Sr content is 1800 ppm in plagioclase and 1500 ppm in K-feldspar (Ivanov, 1994). These data are confirmed by correlation between Sr and plagioclase abundance (Fig. 7) in the studied granulites, as well as by ratios of smectite and hydromica clays in source rocks of the Lotta and Kolvitsa zones (Tables 2 and 3).

Zirconium is a very characteristic trace element of studied rocks. The Zr content increases from metapelites to metasandstones (Tables 2, 3), which is typical of Phanerozoic metasedimentary rocks. This trend is more distinctly expressed in modern sediments. In particular, the Zr content is 131 and 393 ppm in clays and aleuritic muds of the Barents Sea, respectively, and 139 and 413 ppm Zr in clays and sands of the Paria Bay, respectively (Taylor and McLennan, 1988). In some cases, high Zr contents can be related to the presence of iron hydroxides, which adsorb Zr (Lisitsyn *et al.*, 1978 and others).

Like Zr, *yttrium* is more readily accumulated in Phaneorozoic sandstones than clays. In modern sediments of the Barents Sea, the Y content in clays (28 ppm) is lower than that in aleuritic muds (34 ppm) (Taylor and McLennan, 1988).

However, the studied granulites show opposite relations (Table 3). It is known that yttrium is accumulated in monazite (up to 1% Y_2O_3), rutile and zircon (o. *n*%). These minerals are present in metasedimentary rocks of the granulite belt (monazite up to 178–262 ppm, rutile up to 0.3–0.6%, zircon up to 1200 ppm) (Goroshchenko, 1969). However, the major Y carrier in granulites is garnet (up to 1400 ppm, average 220 ppm) (Krylov, 1983). According to (Goroshchenko, 1969), the garnet content is higher in high-Al rocks (average 26%) relative to quartz–feldspathic rocks (average 13.7%). The high-Al rocks are also richer in rutile (0.6%) than quartz–feldspathic rocks (0.3%). These facts presumably explain the observed Y distribution in metasedimentary rocks of the granulite belt of the Baltic Shield.

U AND TH CONTENTS IN METASEDIMENTARY ROCKS OF THE GRANULITE BELT

Contents of radioactive elements were determined in metasedimentary rocks of the Finnish granulite belt (Table 4). It is seen that the U content in garnet quartzites (metasandstones) is higher than that in garnet gneisses (metagraywackes) and sillimanite–garnet gneisses (metashales). This is presumably caused by the higher abundance of zircon, which is among U carriers in garnet quartzites. This is indicated by the higher Zr content in studied quartzites (303 ppm) with respect to various gneisses (Table 4). The relatively high U content in calcareous gneisses (2.1 ppm) is possibly explained by the increased carbonate content (CaO = 7.8%) in these rocks. As known, Phanerozoic carbonate rocks are enriched in U (2.2 ppm) (Turekian and Wedepohl, 1961).

In addition to zircon, other carriers of radioactive elements, such as apatite and monazite, are also present in the studied metasedimentary rocks. The U content in monazite (440–520 ppm) is higher than that in zircon (20–420 ppm) (Tugarinov and Bibikova, 1980). It is known that apatite dominates in essentially calcareous

Table 4. Contents of U, Th, and Zr in metasedimentary rocks of the granulite belt and Phanerozoic sedimentary rocks, ppm

No.	Rock	*n*	U	Th	Th : U	Zr
	Metasedimentary rocks (Barbey *et al.*, 1984)					
1	Sillimanite–garnet gneisses	11	0.9	14.8	16.4	203
2	Garnet gneisses	14	0.6	9.4	15.7	219
3	Garnet–plagioclase gneisses	8	0.6	11.1	18.5	198
4	Garnet quartzites	3	1.2	14.8	12.3	303
5	Calcareous gneisses	2	2.1	11.6	5.5	185
	Phanerozoic sedimentary rocks (Turekian and Wedepohl, 1961)					
	Shales		3.7	12.0	3.2	160
	Sandstones		0.45	1.9	4.2	220
	Carbonate rocks		2.2	1.7	0.8	19

Note: (*n*) Number of samples.

rocks, while monazite dominates in sandy and clayey rocks with a low Ca content (apatite is minor or absent). Thus, the main U and Th carriers are monazite and zircon in sillimanite–garnet and garnet gneisses, as well as quartzites of the granulite complex, and apatite in calcareous gneisses.

It should be noted that the average Th and Zr contents in sillimanite–garnet gneisses (metashales) (Table 4) are close to those in post-Archean shales (Th 14.6 and Zr 210 ppm (Taylor and McLennan, 1988), whereas the U content in the studied gneisses is three times less (0.9 as compared to 3.1 ppm in post-Archean shales). Consequently, Th/U ratios are significantly different (16.4 in sillimanite–garnet gneisses and 4.7 in post-Archean shales). The studied gneisses and Phanerozoic shales show a more significant difference in the U content (Table 4).

Relative to Phanerozoic sandstones, Precambrian metasandstones (garnet quartzites) of the granulite belt are enriched in the trace elements mentioned above, especially Th and less typical U and Zr (Table 4). This is presumably explained by the high abundance of monazite, which serves as the main carrier of Th and U. This assumption is consistent with data reported in (Goroshchenko, 1969), according to which the monazite content in metasandstones (quartz–feldspathic granulites) reaches 262 ppm. In the Finnish granulite belt, metapelites (sillimanite–garnet gneisses) and metasandstones (garnet quartzites) have the identical Th content of 14.8 ppm. In contrast, shales are enriched in Th relative to sandstones in Phanerozoic sedimentary rocks (Table 4). In terms of the Th content (Table 4), Precambrian graywackes (garnet and garnet–plagioclase gneisses) are similar to Phanerozoic graywackes (7.8–12.8 ppm) (Taylor and McLennan, 1988) and significantly depleted in U (0.6 ppm relative to 1.81–3.0 ppm).

According to (Taylor and McLennan, 1988; Nozhkin, Turkina, 1993; and others), together with La, Ce, Sc, Zr, and other trace elements, Th shows an inert behavior during regional metamorphism up to ultrametamorphism. In contrast, the U content has a negative correlation with metamorphic grade.

Based on these data and the Th/U ratio in Phanerozoic sedimentary rocks, we may sufficiently reliably determine the U content in source rocks of the granulite belt.

Let us assume that the Th/U ratio in shales (mudstones) equals to 4.0, which corresponds to that in Ordovician mudstones from the Greenland Group, New Zealand (Taylor and McLennan, 1988) and is the average value between the values for Phanerozoic shales (3.2) (Turekian and Wedepohl, 1961) and post-Archean shales (4.7) (Taylor and McLennan, 1988). Substituting this value (4.0) in the Th/U ratio, where Th content is 14.8 ppm (Table 4), we obtain that the source rocks of sillimanite–garnet gneisses contained 3.7 ppm U, which corresponds to content in Phanerozoic shales (3.1–3.7 ppm) (Taylor and McLennan, 1988; Turekian and Wedepohl, 1961).

Taking Th/U ratio equal to 4.8 for metasandstones (garnet quartzites) and 4.3 for metagraywackes (garnet gneisses) corresponding to the value in high-quartz graywackes (SiO_2 = 81.13%) and graywackes (SiO_2 = 67.5–75.65%), respectively (Taylor and McLennan, 1988), the U content is equal to 3.1 ppm in source rocks of garnet quartzites and 2.2–2.6 ppm in source rocks of garnet gneisses. These values generally correspond to U contents in Phanerozoic sandstones (1.8–3.4 ppm) (Taylor and McLennan, 1988).

Based on the same values of Th/U ratio (shales 4.0, graywackes 4.3, and quartzose sandstones 4.8), we can determine the U content in source rocks of metasediments of the Lotta zone (Bibikova *et al.*, 1993). We obtain that source rocks contained 4.6, 3.5, and 1.5 ppm U in high-Al gneisses, garnet gneisses, and garnet quartzites respectively.

Thus, the calculated U contents in source rocks of the granulite complex are mainly within the range of U contents in Phanerozoic metasedimentary rocks.

According to Bibikova *et al.* (1993), Th directly correlates with Al_2O_3 in metasedimentary rocks of the Lotta zone. In particular, the Th content is 5.8–8.7 ppm in garnet quartzites, 7.7–24.3 ppm (average 14.9 ppm) in garnet gneisses, and 13.5–24.6 ppm (average 18.5 ppm) in high-Al gneisses. These data differ from those in Table 4 and are closest to the Th distribution in Phanerozoic sedimentary rocks.

CONCLUSIONS

(1) A significant part of metasedimentary rocks from the granulite belt of the Baltic Shield formed from immature sedimentary rocks. This is confirmed by the following observations: (1) lithochemical recalculations (Table 2) indicate that source rocks universally contained significant amounts of plagioclase, hydromica, and occasional chlorites and smectites, whereas kaolinite is alsmost absent; (2) the CIA index (Nesbitt and Young, 1982) is within 50–70; (3) data points of the studied rocks are plotted in the fields of graywackes, subgraywackes, and graywacke pelites in discriminant diagrams (Figs. 3, 4).

All these facts indicate high rates of denudation, transportation, and burial of terrigenous material, i.e., relatively active tectonic regime during the accumulation of source sediments in the granulite belt. This assumption is supported by the position of some data points in the fields of active continental-margin sediments in the $K_2O/Na_2O–SiO_2$ diagram (Roser and Korsch, 1986). However, more mature and differentiated sediments were probably deposited during occasional periods of quieter tectonic setting. This is supported by the increased contents of SiO_2 and Al_2O_3 (Table 1), lithochemical recalculations (Table 2), positions of some rocks in the fields of quartzose sandstones and clays (Fig. 4), and CIA index reaching 75–78.

(2) The presence of carbonaceous matter (graphite) and predominance of FeO over Fe_2O_3 presumably indicate a reducing sedimentation environment. However, the presence of graphite (1–2%) and traces of the vital activity of protozoa (stromatolitic bioherm) in the lower sequence (Ivliev, 1971) possibly indicates the presence of organic life in the sedimentation paleobasin as a result of the significant content of nutrient (mineral) matters (Fe, Mn, K, V, and others) in the paleobasin.

(3) High contents of some major and trace elements (Si, Fe, K, Cr, Ni, V, Sc, Y, Pb, Zr, and others) (Tables 1, 3) show that terrigenous and volcanogenic–terrigenous material, which was introduced into sedimentation paleobasin, was derived from both ultramafic–mafic and intermediate–acid rocks.

(4) One can see correlation between several elements (Rb, Ba, and Pb with K; Sr with Na and Ca; Ti and V with Al; Fe and Ga with Ti, and so on). This is typical of both Phanerozoic sedimentary rocks and high-grade metamorphic rocks (T = 800–900°C, P = 6–8 kbar) from the granulite belt of the Baltic Shield.

(5) Lithochemical recalculations suggest that distribution and contents of trace elements in the studied metasedimentary rocks can be explained by the mineral composition of source rocks (Tables 2, 3).

6. Reconstructed contents of C_{org} (1.1–1.3%) and U (1.5–4.6 ppm) in protoliths of metasedimentary rocks of the granulite belt correspond to those in Phaneorozic sedimentary rocks.

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