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Petrochemical Systematics of Amphibolites from the Archean Section of the Kola Superdeep Borehole

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Abstract—This paper addresses the problem of the systematization of amphibolites from the Archean part of the section of the SG-3 Kola Superdeep Borehole. It was shown that a combined petrochemical and geochemical approach allows one to classify these rocks with high confidence and to distinguish supposedly Archean and Proterozoic varieties among them. It was found that Proterozoic rocks account for about 50–70% of basic rocks in the Archean section. Homologues of the basic metavolcanics of the Matert Formation were detected among the Proterozoic metaigneous rocks of the Archean section of the SG-3, which casts doubt on the conclusion of some authors on the allochthonous origin of the upper levels of the northern Pechenga section, including its productive horizons. This result has very important metallogenic implications.

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INTRODUCTION

The problem of the systematization of amphibolites from the Archean section has attracted the interest of researchers since the earliest period of the investigation of the SG-3 Kola Superdeep Borehole. As the terms para- and ortho-amphibolites can still be encountered in the literature, it should be emphasized from the beginning that we are adherents of the opinion of Predovskii [1] and some other researchers that there are no natural sedimentary rocks strictly corresponding to amphibolites in mineral and chemical compositions. The use of the misleading term para-amphibolite is probably explained by the fact that amphibole-bearing schists are assigned by some researchers to amphibolites. Such rocks may have in some cases a primary sedimentary or volcano-sedimentary origin, which is recorded in their chemical composition. Taking into account this fact, it should be pointed out that only those rocks are considered in this study that are composed of amphibole (occasionally with clinopyroxene or epidote) and plagioclase and correspond mineralogically to amphibolites in the conception of petrologists [2–4] and chemically to mafic and ultramafic igneous rocks.

The problem of amphibolite systematization in the SG-3 section was most comprehensively analyzed in the book of Kremenetskii and Ovchinnikov [5] and in the chapters of two monographs written by Yu.N. Yakovlev and A.K. Yakovleva [6] and Yu.P. Smirnov and V.A. Tyuremnov [7]. A subsequent detailed study of the composition of amphibolites led some authors to conclude that the Archean section of the SG-3 contains a variety of basic analogues to both Archean and Proterozoic metaigneous rocks. This was most convincingly demonstrated on the basis of isotopic data by Bayanova et al. [8] and Vetrin et al. [9].

In this context, the problem of the identification of amphibolites confined to the Proterozoic complex in the Archean section of the borehole became even more significant. Since the geochronological study of each sample is impracticable, new approaches should be sought to solve this problem. This challenge is addressed in this paper.

In this study, we used both new and previously published data on the composition of amphibolites from the Pechenga complex and Archean rock associations from the geologic environment of the SG-3 and the database on the chemical composition of amphibolites from the Archean section of the SG-3 kindly provided by the authorities of the Kol'skaya Sverkhglubokaya Research and Industrial Center. Overall, 293 silicate analyses of rocks from the SG-3 section and 1036 analyses of rocks from the Archean and Proterozoic complexes from the vicinity of the borehole were used.

METHODS

An important question for the problem considered here is where the homologues of the amphibolites recovered from the Archean part of the SG-3 section can be most probably encountered. Based on geological and petrogeochemical evidence, a territory north–northeast of the borehole, within the Jarfjord–Kola complex was previously chosen [10–12]. We have

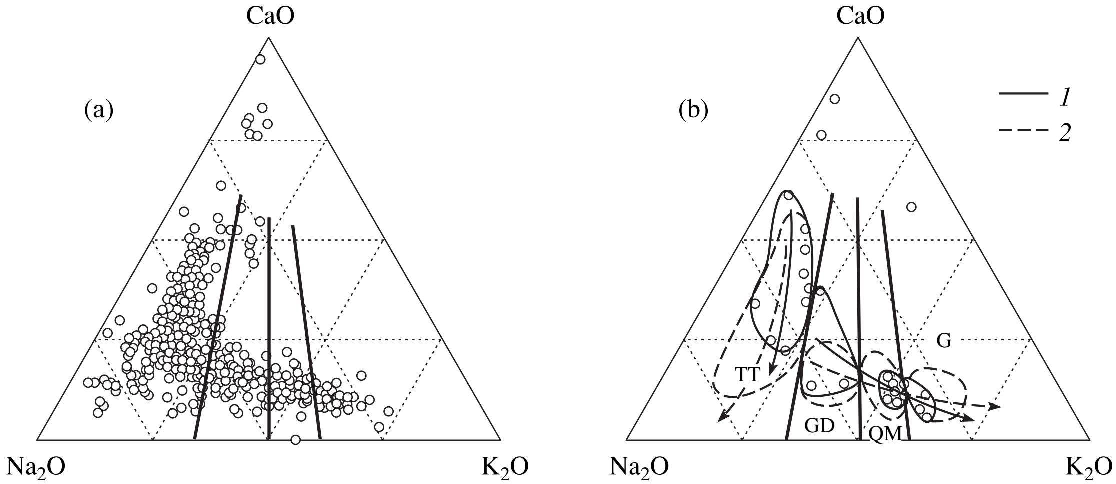

Fig. 1. Relations of components in the felsic rocks from (a) the Archean section of the SG-3 and (b) Jarfjord–Kola complex on the Condie (1983) diagram. Rock abbreviations: TT, tonalite–trondhjemites; GD, granodiorites; QM, quartz monzonites; and G, granites. Also shown are field boundaries and trends of compositional variations of (*1*) the rocks of the Jarfjord–Kola complex and (*2*) metamorphic rocks of the Archean section of the SG-3.

repeatedly justified this opinion using geological, petrogeochemical, and other arguments. However, this subject is still under discussion. In our opinion, it is of fundamental importance, because this region was used for the comparison of SG-3 amphibolites with the rocks of the geologic environment of SG-3, which is the focus of this paper.

The proposed method of the identification of homologues on the basis of petrogeochemical data was tested using the materials for the Proterozoic part of the SG-3 section. The available geological data allowed us to unequivocally solve the problem of homologues for this part of the section, which enabled a strict control of the results of comparisons. These investigations showed perfect agreement between the petrogeochemical and geological data, i.e., high reliability and plausibility of the method [11]. It was also shown that the conclusion on the probable occurrence of homologues of the rocks of the Archean section of the SG-3 within the Jarfjord–Kola complex is in agreement with geological, geochronological, and geophysical data.

However, one seemingly important argument of opponents of such a choice of a region for the search for homologues remains to be discussed. Tonalite–trondhjemite–gneiss associations are almost completely lacking within the complex but are widespread in the Archean section of the SG-3 [9]. In our opinion, this argument is unjustifiable [13]. In this case, we probably deal with a terminological confusion. Indeed, as was shown by our studies, biotite–amphibole gneisses and dioritic gneisses, corresponding in chemical composition to the classical tonalite–trondhjemite associations of Condie [14] and showing trends identical to those of the SG-3 granitoid associations (Figs. 1a, b) occur among the gneisses of the regions of L. Trifonoyarvi, Liinahamari, Malonemetskaya Bay, and in a number of test sites near the Luostari settlement, i.e., practically over the whole studied area of the Jarfjord–Kola complexes.

Biotite-amphibole gneisses (dioritic gneisses) were mapped by Yu.A. Morozov in the region of the Malonemetskaya Bay. The closed outlines of their outcrop suggests their intrusive origin ([15], Fig. 7, p. 24). On the other hand, in the eastern framing of the Pechenga structure, at the Luostari site (Fig. 2) and in an exposure along the Nickel–Murmansk highway, it is clearly seen that biotite gneisses of tonalite–trondhjemite compositions are either cut by compositionally variable (from tonalite–trondhjemite rocks to granites) biotite granitic gneisses or occur in the latter as xenoliths together with gneisses of different composition.

Good preservation of the orientation of planar elements was observed in the gneiss xenoliths, which appear as if impregnated by granitoids. Note also that the rocks that show intrusive (cross-cutting) contacts with the gneisses have no clearly defined geologic boundaries and compose separate patches in this region. The range of their composition is also very wide, from granite to tonalite.

Taking into account all these facts, there are good reasons for believing that at least part of the tonalite–trondhjemite dioritic gneisses were formed by the palingenetic transformations of an ancient gneissic material rather than by the partial melting of a hypothetical metabasic source [9]. This is an important inference, because the hypothesis of partial melting was used by some researchers as a basis for the search for homologues, which resulted in that the Jarfjord–Kola region was erroneously excluded from the list of territories where surface exposures of rock complexes penetrated by the SG-3 could be found. It cannot be ruled out that, in addition to such complexes, older

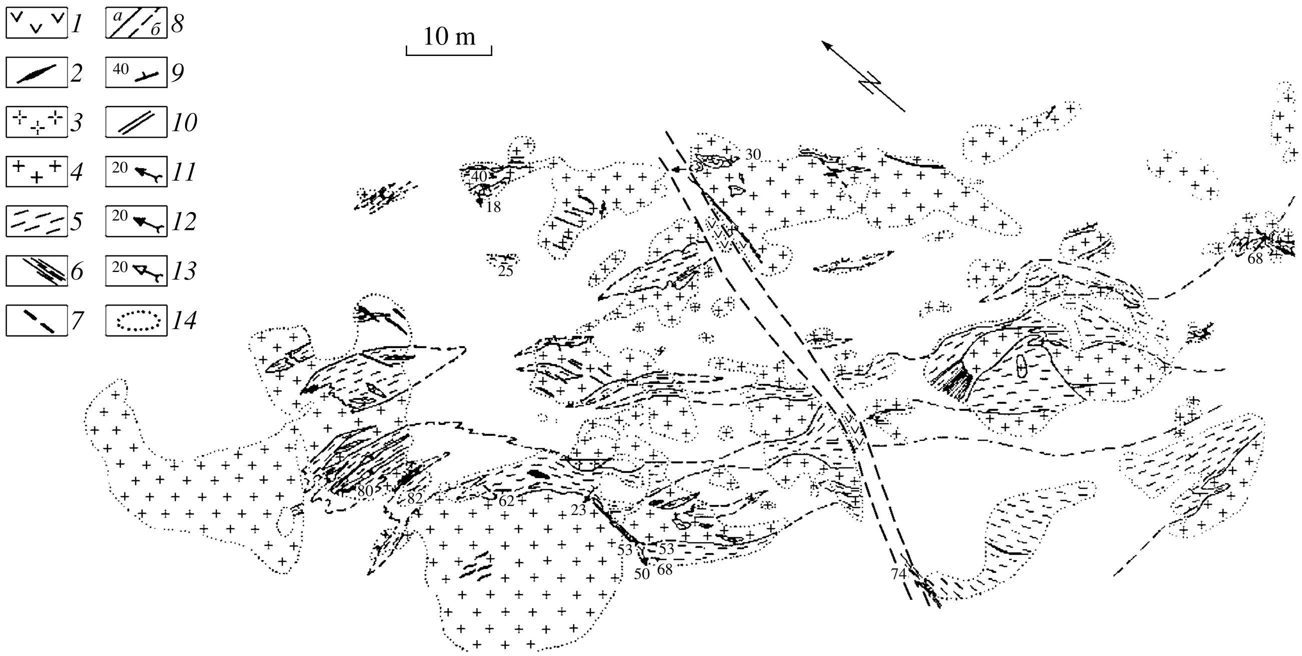

Fig. 2. Structural geological map of the Luostari prospect (compiled by N.E. Kozlova, A.V. Kolodkina, A.P. Filat'ev, and S.E. Tsarev). (*1*) Dolerite; (*2*) quartz vein; (*3*) pegmatite; (*4*) biotite granitic gneiss (varying in composition from tonalite–trondhjemite to granite); (*5*) biotite gneiss of tonalite–trondhjemite composition; (*6*) schistose zone; (*7*) fault; (*8*) identified boundaries; (*9*) azimuth of SCPS dip; (*10*) azimuth of SCPS strike; (*11*) hinges of late folds in the quartz–chlorite fault zones of Proterozoic age; (*12*) hinges of late plastic slip folds of Archean age; (*13*) hinges of relict folds; and (*14*) outlines of outcrops.

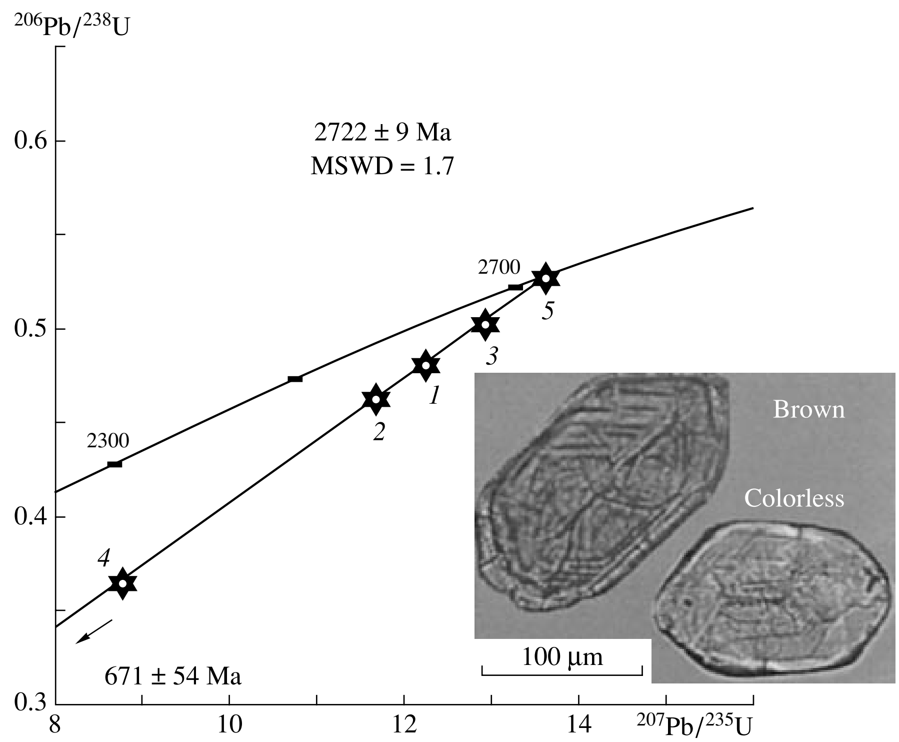

Fig. 3. U–Pb concordia diagram for the dioritic gneisses of the Malonemetskaya Bay prospect.

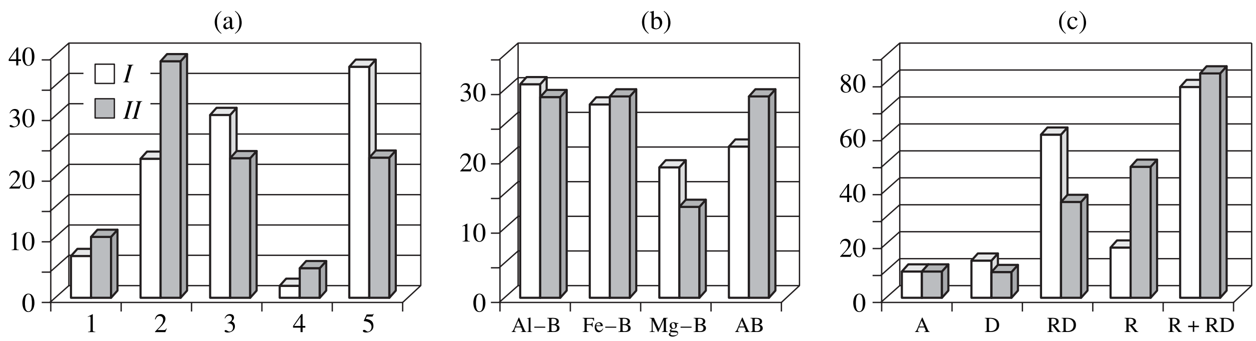

Fig. 4. Relative abundances of the types of metamorphosed igneous rocks (a) in the Archean section of the (*I*) SG-3 and (*II*) Jarfjord–Kola complex and for the groups of (b) basic and (c) felsic metamorphosed volcanic rocks. 1, Metatuffites; 2, metasedimentary rocks; 3, basic metavolcanics; 4, felsic metavolcanics; and 5, rocks of unidentified primary nature. Abbreviations: Al-B, Fe-B, and Mg-B, aluminous, iron-rich, and magnesian metabasic rocks, respectively; AB, basaltic metaandesites; A, metaandesites; D, metadacites; RD, metarhyodacites; and R, metarhyolites.

tonalite–trondhjemite assemblages of another origin can be found in the Archean section of the SG-3; however, their discrimination from the described palingenetic rocks is hardly possible. Therefore, the use of this hypothesis for the selection of areas promising for the search of the possible homologues of metamorphic rocks from the SG-3 section is not reasonable for the particular region.

In our opinion, the conclusion on the possible occurrence of the homologues of rocks from the Archean section of the SG-3 in the Jarfjord–Kola complex is consistent with the data of geochronological investigations. Samples 9802 and 9821 from the dioritic gneiss massif of the Malonemetskaya Bay region were studied. The U–Pb analysis of zircon was carried out using conventional isotopic dilution techniques [16] on an MI-1201T mass spectrometer at the Laboratory of Geochronology and Isotope Geochemistry of the Geological Institute, Kola Research Center, Russian Academy of Sciences. The analytical results are shown in Table 1 and Fig. 3.

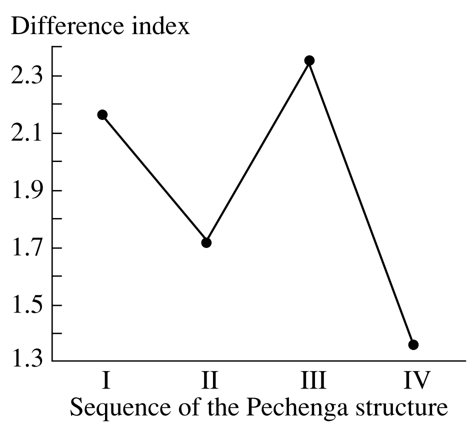

Fig. 5. Degree of difference between group 7 amphibolites and metavolcanic rocks from various sequences of the Pechenga zone. The lower the difference index, the greater is the similarity between the compared rocks. Numbers on the diagram show the values of the Puri–Sen–Tamura criterion for the distance from sequence IV (Matert Formation) to other sequences. The difference between the compared sequences is significant at a level of 5 or 2%, if this criterion is higher than 3.8 and 6.6, respectively.

Zircon separated from the diorite-gneisses (sample 9802) is represented by 90% of transparent colorless short prismatic crystals showing a transition from the zircon type ({110} prism and {111} bipyramid) to the hyacinth type ({100} prism and {111} bipyramid) and 10% of light brown short prismatic zircon crystals with prism $\{100\} \gg \{110\}$ and bipyramid faces $\{111\} > \{311\}$. The tips and edges of crystals are smoothed. The grains are 75–300 μm in size. The occurrence of a fine zoning and similar isotopic compositions allowed us to assign all the zircon types to a magmatic generation, and the diversity of morphological types can be related to various stages of the evolution of the crystallizing melt. According to the systematization of Pupin [17], the presence and development of prisms is controlled mainly by the temperature conditions of crystallization. Using Pupin's [17] diagram, it can be suggested that the zircons of the dioritic gneisses crystallized within the cooling interval from 900 to 600°C.

The brown zircon could be formed during the final stages of crystallization at high concentrations of trace elements or owing to spatial heterogeneities in the chemical composition of melt in a magma chamber. The age of both zircon types is 2724 ± 27 Ma and is interpreted as the age of magmatic crystallization. The second sample of diorite-gneisses (sample 9820) contained mainly colorless zircon of the first type and the same age, 2721 ± 3 Ma (Fig. 3, point 5). The age of magmatic crystallization of the diorites was estimated as 2722 ± 9 Ma (Fig. 3) using five analyses from the both samples. Amphibolite-facies metamorphism was imprinted in the formation of thin rims of newly formed zircon, which often impart rounded outlines to prismatic zircon grains. In order to remove the metamorphic rims, coarse zircon fractions were abraded, and

Table 1. U–Pb data for zircon from the diorite gneisses of the Malonemetskaya Bay area

Fraction no.	Fraction, μm	Weight, mg	Pb rad ppm	U ppm	Measured ratios			Corrected ratios*		Age, Ma
					$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{206}Pb}{^{207}Pb}$	$\frac{^{206}Pb}{^{208}Pb}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{206}Pb}$
(Sample 9802)										
1	>100. brown	0.4	130.9	261	1169	5.1360	11.7419	12.2244	0.4807	2693 ± 2
2	75–100. brown	0.6	144.1	295	1000	5.1418	14.0158	11.6889	0.4643	2676 ± 12
3	>150. colorless, abraded	1.0	39.2	68	804	4.9560	11.4360	12.9120	0.5010	2715 ± 9
4	75–100. colorless	0.5	93.2	240	1904	5.5700	10.8189	8.7569	0.3664	2590 ± 11
(Sample 9820)										
5	150–200. colorless, abraded	0.8	51.0	84	1179	5.0652	13.6155	13.5755	0.5250	2721 ± 3

Note: Fraction numbers correspond to point numbers in the concordia diagram.

* The values were corrected for mass fractionation (0.18 ± 0.06 a.m.u. for Pb), blank contamination (0.2–0.5 ng for Pb and 0.05 ng for U), and common lead (using the Stacey–Kramers model).

fine fractions were handpicked in a water–alcohol mixture, which usually allowed us to separate zircons without rims or with minimum rim widths.

Our age estimate is identical to the previous value obtained in the same laboratory for the amphibole–biotite tonalitic and trondhjemitic gneissic granites from the lower part of the SG-3 section: 2746 ± 65 and 2740 ± 10 [6, 18]. There is also an older age estimate for the tonalitic gneisses, 2832 ± 6 Ma [7, 18]. Since this value was obtained not only for individual grains but also for fractions composed of several grains, most of which were preliminarily abraded, it cannot be excluded that this value characterizes the age of an older material, the palingenesis of which could produce part of the tonalite–trondhjemite rock associations. It is suggested that a similar investigation of metamorphic rocks from the Nemetskaya Bay region will probably resolve the apparent controversy.

The similarity of rocks from the SG-3 section to those from the Jarfjord–Kola region is additionally supported by the proportions of reconstructed primary rock varieties, both in general (Fig. 4a) and for the groups of basic (Fig. 4b) and felsic (Fig. 4c) metamorphosed igneous rocks. Note that hereafter the evaluation of variations in rock varieties in the SG-3 section was based on the method of the determination of the abundances of rocks associations from the number of samples in various real sets [19].

Some comments should be made here. For instance, in Fig. 4a, the metamorphic rocks corresponding to a rather compact petrochemical group of primary felsic or intermediate tuffites [1] were assigned to the group of metatuffites, and the rocks corresponding, according to the same classification, to graywackes and subgraywackes were included into the group of metasedimentary rocks.

Figure 4b shows all the samples of basic metamorphic rocks from both the borehole and the geologic environment of the SG-3 that were collected within the fields of Archean complexes and, according to geological data, cannot be unequivocally assigned to the younger Proterozoic complex. In the context of the problem discussed in this paper, such an approach to this rock group is certainly rather arbitrary, because, as will be shown below, many basic rocks from the Archean part of the SG-3 section have Proterozoic ages. We do not exclude a similar situation for the complex of the SG-3 environment. It is possible that the similarity in the proportion of rock types in Fig. 4 illustrates, among other things, this situation.

In general, all the data, both reported in this paper and published by us previously, allow us to suggest with high confidence that the Jarfjord–Kola region contains the associations of rocks homologous to the rocks from the Archean section of the SG-3. This conclusion was used as a starting point for the present investigation. During the comparative investigation of amphibolites, we assumed that comagmates of the Pechenga volcanic sequences, Mount General'skaya intrusion, and metavolcanics of the Archean complexes of the Jarfjord–Kola region can be encountered in the Archean section of the SG-3. Because of this, mafic rocks from these complexes were used as reference samples for a comparison with the amphibolites of the Archean part of the SG-3 section.

In this study the systematization of amphibolites was based on the classification of Predovskii [1], which takes into account many compositional parameters, including such important indicators as the basicity and total alkalinity of metamorphic rocks, whereas the classification proposed by Kremenetskii and Ovchinnikov [5] relies on the contents of particular elements only. Nonetheless, we used their classification for the solution of particular problems, for instance, for a more detailed classification of basic rocks and picrobasalts of normal alkalinity.

The grouping of SG-3 amphibolites was considered as the first step in the sequence of successive operations on their systematization. The final stage included a comparison of the groups with the reference sets of basic rocks occurring in the geologic environment of the SG-3 using the method of E.V. Martynov, which was described elsewhere [11, 12, 15]. To this end, the reference groups composed of rocks from the geologic environment of the SG-3 were also preliminarily classified in the same way as the rocks of the SG-3 section.

DISCUSSION

The preliminary petrogeochemical classification of amphibolites from the Archean part of the SG-3 section showed that instead of six groups described by Kremenetskii and Ovchinnikov [5], 14 groups can be distinguished (Table 2). Data on the abundance of TiO_2 in the rocks were also employed for the classification of Fe-rich basic rocks of low and normal alkalinity and picrobasalts of normal alkalinity (Table 2; groups 6, 7, 10, 11, 13, and 14). The use of the terms high-titanium and low-titanium in the names of groups is conditional to a certain degree. We wished to point out that some groups distinguished on the basis of the universally accepted classification may comprise varieties showing significantly different TiO_2 contents, which is described in the notes of Table 2.

A further comparison of the distinguished groups with the reference sets of metamorphic rocks from the geologic environment of the SG-3 showed that none of them is similar to the rocks of Mount General'skaya. During the selection between reference samples of the Pechenga structure and Archean rock associations, a similarity with particular rocks from the geologic environment of the SG-3 was established with a rather high confidence (at least 90%) for 8 groups of 14, which included 82% of the samples (Table 2). The high degree of similarity of group 9 to the Archean rocks (with a probability of more than 99%) and groups 7 and 10 to the Proterozoic rock associations (with a probability of no less that 95%) deserves special attention. This result is in agreement with geochronological data obtained for some samples of these groups [8, 9]. The isotopic model ages obtained for groups 5, 7, 9, and 12 do not contradict the results of our investigations.

Note also that our previous conclusions [20] on the confinement of specific rock associations to certain age levels of the Kola region (for instance, aluminous basic rocks are widespread in the Archean complexes and absent in the Proterozoic) also support the Archean age of the metamagmatic rocks of group 9.

Overall, among the identified metamorphic rocks from the Archean part of the SG-3 section, 48% of basic rocks were assigned to the Archean, and 52%, to the Proterozoic. Even assuming that all the unidentified groups of amphibolites are of Proterozoic age, the fraction of Proterozoic rocks in the Archean part of the SG-3 section will be no higher than 67%, which is somewhat lower than the previous estimate of ≥80% [9].

Amphibolites from the intervals 7638–7656 and 10098–10120 m were previously geochronologically studied [8], i.e., analyzed probably as group samples, and their model ages were estimated as 2499 and 2434 Ma, respectively. According to our data, they are represented in the aforementioned interval by rocks of different petrogeochemical groups (Table 2; groups 4 and 11 in the former case; groups 2 and 12 in the latter case). This is probably why the age of the protolith of group 2, which was identified by us as Archean, was estimated in [8] as Proterozoic.

Interesting results were obtained by a comparison of amphibolites of group 7, the protolith of which, according to our data and the results of geochronological investigations, is most likely of Proterozoic age, with the rocks of various sequences of the Pechenga structure (Fig. 5). This group is correlated (with a probability of 95%) with the rocks of sequence IV of Pechenga, i.e., with the volcanics of the Matert Formation. Thus, it can be stated that many of the amphibolites of the Archean part of the SG-3 section (about 25% of samples identified as Proterozoic and about 8% of the whole set of amphibolite sample) are homologues of the upper metavolcanic levels of the Pechenga section and their magma conduits. These data cast doubt on the suggestion of N.P. Vinogradova and V.A. Melezhik (2002, final Meeting of Project No. 408 of the IPGC, UNESCO, Zapolyarnyi, personal communication) on the absence of such rocks in the Archean part of the SG-3 section and, correspondingly, possible allochthonous origin of the productive formation of Pechenga and the overlying Matert Formation.

In this paper, we did not address the distribution of the distinguished amphibolite groups in the SG-3 section, which will be the subject of a special investigation and discussion. Note only that all the groups, without exception, of supposedly Archean and Proterozoic ages contain rocks recovered from the SG-3 section, including sequences I (groups 1, 2, 4–6, 10, 12–14) and II (groups 3, 7–9, 11). This indicates later formation of the protoliths of both Proterozoic (which is obvious) and Archean basic rocks compared with the majority of gneiss sequences penetrated by the borehole (only group 8 and 9 rocks can theoretically be older than the gneisses of sequence I of the SG-3 section).

Table 2. Systematization of amphibolites from the Archean section of the SG-3

Group (number of samples)	Group distinguished after [1] accounting for data of [5]	Amphibolite group after [5] with our modifications*	Age based on comparison of Archean and Proterozoic complexes	Model Sm–Nd age, Ma
1(8)	Picrites[2*] of normal alkalinity	Fe-a, FM-a	?	–
2(17)	Subalkaline picrites and basic–intermediate rocks	Fe-a, FM-a	Archean (0.1)[6*]	2434
3(6)	Subalkaline and normal basic–intermediate rocks	Fe-a, Si-a	?	–
4(10)	Fe-rich basic–intermediate rocks of low and normal alkalinity	Fe-a, FM-a	?	2499
5(39)	Low-alkali basic–intermediate and basic rocks	Si-a, SM-a	Archean (0.1)	2648
6(42)	Low-alkali low-Ti Fe-rich basic rocks[3*]	Fe-a	?	–
7(24)	Low-alkali high-Ti Fe-rich basic rocks[3*]	Fe-a	Proterozoic (0.01)	2160
8(7)	Low-alkali Mg–Fe basic rocks	FM-a	Archean?[7*]	–
9(33)	Aluminous basic rocks	Fe-a, Si-a, M-a, SM-a, AM-a, M-a	Archean (0.001)	2702
10(40)	Low-Ti Fe-rich basic rocks of normal alkalinity[4*]		Proterozoic (0.05)	–
11(16)	High-Ti Fe-rich basic rocks of normal alkalinity[4*]	Fe-a	?	2499
12(23)	Fe–Mg basic rocks of normal alkalinity	FM-a	Proterozoic (0.1)	2434
13(15)	Low-Ti picrobasalts of normal alkalinity[5*]	FM-a, TA-s, Ac-s, M-a	Proterozoic (0.1)	–
14(13)	High-Ti picrobasalts of normal alkalinity[5*]	FM-a, Fe-a	?	–

* FM-a are amphibolites with $SiO_2 < 53\%$; $Fe_2O_3 + FeO > 10\%$, and $MgO > 7\%$; Fe-a – $SiO_2 < 53\%$; $Fe_2O_3 + FeO > 10\%$, and $MgO < 7\%$; AM-a – $SiO_2 < 53\%$; $Al_2O_3 > 16\%$, and $MgO > 7\%$; Ac-s – $SiO_2 < 53\%$; $CaO > 10\%$, and $MgO > 10\%$; M-a (introduced by us) – $SiO_2 < 53\%$; $Al_2O_3 \leq 16\%$; $Fe_2O_3 + FeO < 10\%$, and $MgO \geq 7\%$; Si-a – $55\% > SiO_2 > 53\%$, and $MgO < 7\%$; TA-s – $55\% > SiO_2 > 53\%$; $MgO > 20\%$; SM-a (introduced by us) – $55\% > SiO_2 > 53\%$; $20\% > MgO \geq 7\%$;

2* Hereafter, the names of groups are given according to the classification of Predovskii [1].

3* Group 6 – $TiO_2 < 1.9\%$ and group 7 – $TiO_2 > 1.9\%$;

4* Group 10 – $TiO_2 < 1.9\%$ and group 11 – $TiO_2 > 1.9\%$;

5* Group 13 – $TiO_2 < 1\%$ and group 14 – $TiO_2 > 1.5\%$;

6* The significance level is no lower than the given value.

7* The significance level is lower than 0.1; however, most rocks (six of seven samples) are more similar in composition to Archean rocks.

Finally, it should be noted that our amphibolite groups do not correspond in volume and composition to the groups previously distinguished by several authors on the basis of mineral composition [6, 7]. Since their classification was developed on a considerable factual basis and invoked mineralogical and other quantitative criteria, this information can be used in further studies. This challenge is beyond the scope of this study. The same applies to the systematization of Kremenetskii and Ovchinnikov [5].

CONCLUSIONS

(1) Based on the comprehensive analysis of petrochemical characteristics, the amphibolites of the Archean section of the SG-3 were classified into 14 groups, which is different from the number of groups distinguished previously using mineralogical and geochemical data.

(2) Taking into account the published geochronological data and compositional characteristics, four of the 14 groups can be identified with confidence as Archean complexes, four groups represent Proterozoic complexes, and six groups cannot yet be assigned to either of these eons. Proterozoic amphibolites account for about 50–70% of basic rocks in the Archean section of the SG-3.

(3) The finding of metavolcanic homologues of the Matert Formation among the Proterozoic metaigneous rocks of the Archean part of the SG-3 section cast doubt on the supposed allochthonous origin of the upper parts

of the northern Pechenga section, including its productive horizons.

(4) The amphibolites that were previously geochronologically studied as group samples collected from the intervals 7638–7656 and 10098–10120 m have ages of 2499 and 2434 Ma, respectively, and are probably represented by different petrogeochemical groups. Therefore, the age estimates obtained for them must be further refined.

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