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Petrochemistry of Metapsammitic Rocks from the Patom Highland: Reconstruction of the Protolith Composition

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Abstract—Precambrian psammitic rocks of the Patom Highland as constituents of metasedimentary groups belong to the quartz–polymictic family, which is divided in each group into the following five petrochemical types: (A) highly silicic quartz sandstones, (B) silicic quartz sandstones, (C) alkali silicic quartz sandstones, (D) Fe–Si polymictic sandstones, and (E) Fe–Al–Si polymictic sandstones. The mineralogic–petrographic classification elaborated by Shutov (1967) may be applied to the calculated quantitative mineral and component compositions of metasandstone protoliths. According to this classification, the petrochemical types A–E may be correlated with monomictic (A'), oligomictic (B'), and mesomictic (C') sandstones, feldspar–quartz graywacke (D') and graywacke proper (E'), respectively.

Quartz–polymictic sandstones make up the direct petrographic (mineralogic–petrographic) series A'–B'–C'–D'–E' and the almost mirror inverse series E'–D'–C'–B'. The direct series A'–E' represent the transgressive branches of sedimentary cycles that begin with the crustal redeposited products of chemical weathering, including high-Al schists and monomictic (A') and oligomictic (B') quartz sandstones. As the humid climate became arid, the sandstones gave way to the mesomictic sandstones C' and to the polymictic sandstones D' and E' in the middle sections of sedimentary cycles. The polymictic sandstones mark culminations of tectonic activity that led to the formation of high mountains. The inverse series E'–B' begin from the periods of mountainous topography and characterize regressive branches of sedimentary cycles that mark the decreasing tectonic activity. Polymictic sandstones E' and D' are replaced by oligomictic sandstones B' in these branches. Thus, petrographic or mineralogic–petrographic series reflect the compositional evolution of psammitic rocks between epochs of peneplanation. The termination of these epochs and resumption of orogenic movements are documented by deposition of the Teptorgo–Mama, Kadalikan, and Bodaibo sedimentary groups. The onset of tectonic events fell on the terminal Paleoproterozoic, Early Riphean, and the Middle–Late Riphean. The composition of sedimentary rocks underwent progressive changes during the tectonic evolution of the continental margin of the Siberian Craton and the concomitant variation of paleoclimate.

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INTRODUCTION

Proterozoic sedimentary rocks of the Patom Highland are separated from the Archean–Lower Proterozoic basement by redeposited products of deep chemical weathering (Purpul Formation). They make up a thick polycyclic sequence with hiatuses obliterated by regional metamorphism. Because of lack of reliable paleontological characteristics and the rejuvenation of isotopic ages, this sequence remains a 'mute' interval. The Proterozoic sequence comprises three large lithostratigraphic (terrigenous, terrigenous–carbonate, and terrigenous–volcaniclastic) subdivisions (from bottom to top). These subdivisions lack distinctly delineated boundaries. Therefore, the determination of their volumes, status (group or subgroup), and age was a subject of continuous debates. Salop (1964) and Kazakevich et al. (1971) considered that these sedimentary rocks make up the amagmatic Upper Proterozoic (Middle–Upper Riphean) Patom Group divided into the Ballaganakh, Kadalikan, and Bodaibo subgroups. According to (Velikoslavinskii, 1963), they were involved in the Caledonian tectonomagmatic reactivation. Korikovskii and Fedorovskii (1980) appreciably simplified the problem, assuming that the Patom Group in the central part of the highland represents the upper section of the Lower Proterozoic Tonod–Bodaibo Group.

Dol'nik (Dol'nik et al., 1986; Dol'nik, 2000) and Ivanov (Ivanov et al., 1995) supported the resolution of the All-Union Stratigraphic Conference (*Resheniya*…, 1983), but did not agree with such interpretation. They revised volumes of the Ballaganakh and especially Kadalikan subgroups recognized by Salop (1964) and divided the Proterozoic sequence in the central part of the highland into the Ballaganakh, Nygra, and Bodaibo groups. The Nygra Group corresponded to the upper part of the Kadalikan Subgroup. Together with the Ballganakh Subgroup, the lower part of the Kadalikan Subgroup was included into the Ballaganakh Group. The Bodaibo Group was reduced to the Bodaibo Subgroup.

The age of the polycyclic sequence was constrained by the Middle Riphean and Upper Riphean–Vendian at the bottom and top of the section, respectively.

The authors of these stratigraphic schemes paid little attention to the boundaries of lithostratigraphic subdivisions. Therefore, their schemes were unconvincing. Sharov et al. (2002) obtained new data that provided new insights into this issue. Based on the systematic study of metapelites in this region, we revealed a correlation between the evolution of their composition, their protoliths and the paleoclimate. This correlation gave impetus to a new approach to subdivision of the metasedimentary sequence into groups. In the proposed version of the stratigraphic chart supported by consistent isotopic (Sharov et al., 2002) and biostratigraphic determinations made by L.I. Narozhnykh (Kazakevich et al., 1971), the Middle Proterozoic Teptorgo Group and a larger part of the Upper Proterozoic Ballaganakh Subgroup (Salop, 1964) have been combined into the Lower Proterozoic Teptorgo–Mama Group. The Kadalikan and Bodaibo subgroups have been promoted (with some changes in volumes) into the Lower–Middle Riphean Kadalikan and Upper Riphean–Vendian Bodaibo groups.

In this paper, we consider the results of further petrochemical investigations aimed at specifying formation conditions of terrigenous rocks at the Patom Highland in the Early and Late Precambrian. We examined metasandstones associated with the previously studied metapelites.

METHODS

The psammitic rocks are well-known indicators of the formation conditions of sedimentary sequences. Petrochemical (Kossovskaya and Tuchkova, 1988; Trifonov, 1997) and, especially, mineralogic–petrographic attributes of these rocks (Shutov, 1967) bear a comprehensive information on their interrelations with the tectonic setting, climate, and provenance. However, the attempts to use metasandstones for these purposes are limited by difficulties related to the determination of quantitative proportions of lithic and mineral fragments. The mineral fragments are partly or completely recrystallized and disintegrated into small particles commensurable in size with minerals of matrix. In contrast to crystalline monolith minerals, the lithic clasts (mainly shales) are destroyed more rapidly during the transport from provenance, postsedimentary alterations, and intralayer displacements in the process of folding. In this regard, analytical methods of the calculation of mineralogic–petrographic and component compositions of protoliths attract certain interest.

Since we had a sufficient number of chemical analyses of metasandstones, our efforts were focused on the solution of this problem. This study is based on the determination of average chemical compositions of blastopsammitic metasandstones and their consecutive recalculation into the total quantitative mineral composition and the component composition. The total quantitative mineral composition was calculated by the method of balanced proportioning of typomorphic minerals of sedimentary rocks based on their compositions adopted from the literature (Grimm, 1956; Deer et al., 1962–1963; Kepezhinskas, 1965; Drits and Kossovskaya, 1991). Technique of the recalculation of chemical composition of metasedimentary rocks into mineral composition of primary sediments was worked out previously in application to metapelites of the Patom Highland (Sharov et al., 2002).

While passing from the total mineral composition to the component composition, we introduced a correction for the presence of nonsyngenetic quartz and feldspar fragments among their syngenetic (psammitic) counterparts. The nonsyngenetic fragments, which affect the component composition, are silty and clayey particles that made up the protolith. The quartz and feldspar particles are armored by psammitic clasts of the source rocks. In addition, they are dispersed in the sandstone cement, which is commonly a secondary material. Previously, Kossovskaya (1962) and Shutov et al. (1972) came to this conclusion, when they discussed the problem of matrix in sandy rocks. Based on the scrutinization of graywackes and analysis of materials presented in authoritative sources, they concluded that the true amount of matrix in the psammitic rocks is insufficient to affect the component composition. As a rule, the matrix is a pore–film and occasionally basal cement that occupies no more than 5% (10–15%, in rare cases).

The content of cement (clearly discernible under microscope) in the studied quartz sandstones is also insignificant (0.*n*–*n*%). Graywackes consist of shale fragments cemented with fine-grained and dispersed shaly mass, which is most likely a secondary material formed during and after the lithification of sediments. Thus, the silt–clay mass of nonsyngenetic quartz and feldspar may be neglected in the calculation of component composition. Since the content of quartz–feldspar admixture in shales associated with sandstones is known (Sharov et al., 2002), we can easily estimate its amount in the clastic clay mass of sandstones.

The mineralogic–petrographic classification elaborated by Shutov (1967) may be applied to the calculated component composition of the sandy protoliths. The Shutov classification fell into oblivion because of the necessity of time-consuming counting of crystal and lithic fragments under microscope. This classification is presented as table and ternary (clastic quartz–feldspar–lithic fragments) diagram. In the tabular version, the psammitic rocks are divided into quartz sandstones (100–50% quartz), arkosic sandstones (75–25% feldspar), and graywackes (100–25% lithic fragments). These series, in turn, are subdivided into types.

In this paper, we present average chemical compositions and statistical estimates of psammitic rocks in the entire Precambrian polycyclic sequence. Their calculations were based on 325 silicate analyses. Among them, 273 analyses (samples from the collection of Sharov) were performed at the Institute of the Earth Crust (T.A. Lukhneva, G.V. Bondareva, O.V Agalakova, A.I. Kurbatova, and N.V. Kuznetsova, analysts) and 52 analyses were taken from unpublished reports by N.A. L'vova (16 analyses of rocks from the Konkudera Formation), V.L. Tikhonov and E.N. Grigorov (12 analyses of the Ugokhan Formation and 18 analyses of the Marinin or Shusman Formation). The average chemical composition of sandstones from the Buzhuikhta Formation (6 samples) is was provided by B.V. Yablonovskii.

GEOLOGICAL POSITION AND COMPOSITION OF METASEDIMENTARY GROUPS

Lower and Upper Precambrian rocks of the Patom Highland make up a thick polycyclic sequence in the central (Bodaibo) and the marginal (Patom) troughs (Fig. 1). The Bodaibo Trough is transformed into a normal synclinorium; the Patom Foredeep, into a relatively simple synclinorium. They are separated by the Chuya–Tonoda–Nechera Uplift (Salop, 1964), which represents a ridge of Protogean–Neogean granite-gneiss domes (Sharov et al., 1978) rimmed by barriers of the early and late metamorphic zoning (Sharov, 1988). Together with sedimentary groups, these domes are indicators of the variation of tectonic settings at the continental margin. In accordance with the systematic variation in lithology of terrigenous rocks in the troughs, the metasedimentary groups are subdivided into the lower, middle, and upper subgroups (Fig. 2). In Fig. 1, the middle and upper subgroups of the Teptorgo–Mama and the Kadalikan groups are combined into a single unit. The upper subgroup of the Bodaibo Group is eroded. Its upper part is composed of polymictic sandstones of the Iligir Formation (Fig. 2, no. 16). Basal units of the groups consist of conglomerate and gravelstone of the Purpul Formation (1) in the Teptorgo–Mama Group and the Bugarikhta Formation (5) in the Kadalikan Group. The Bodaibo Group is underlain by quartz and quartz–sericite wackes of the terrigenous member in carbonate rocks of the Imnyakh Formation (11). This member has been separated from the uppermost section of the underlying Khomolkho Formation (Sharov et al., 2000). Boundaries between the subgroups are based on the appearance and predominance of polymictic sandstones (Fig. 2). Numbers inside boxes in this figure demonstrate that the boundaries are drawn at the base of the Khorlukhtakh (3), Buzhuikhta (8), and Anangra (14) formations. The base of groups is marked by the presence of redeposited crustal products of chemical weathering (mature and highly mature sediments transformed into quartzites, quartzitic sandstones, and high-Al metapelites). The Al_2O_3 content in metapelites reaches 20–25% or more. Such rock association is characteristic of the Purpul (1), Bugarikhta (5), Shusman (6), lower Imnyakh (11), and Aunakit and Vacha (13) formations. The immature (polymictic) sandstones and shales (up to 15–17% Al_2O_3) dominate in the middle sections of the metasedimentary groups. The association of insufficiently mature sandstones and shales is typical of the Khorlukhtakh (3), Buzhuikhta (8), Ugokhan (9), Anangra (14), Dogaldyn (15), and Iligir (16) formations. Quartz sandstones appear again in the upper parts of the Teptorgo–Mama Group and Kadalikan groups. The Al_2O_3 content in the associated shales increases to 18–21%.

Sandstones make up fine (flyschoid) and coarse intercalations with siltstones, shales, and carbonate rocks. The psammitic and blastopsammitic textures are retained in zones of low-grade metamorphism. The rocks range from fine- and very fine-grained equigranular to medium- and coarse-grained inequigranular varieties. Depending on the amount of clayey–carbonaceous matter, the color of rocks changes from light gray (quartz sandstones) to greenish gray and black (polymictic sandstones). The clastic material is well sorted and rounded in quartz sandstones and poorly sorted in polymictic sandstones. Oligomictic sandstones dominate in both the lower and the upper sections of sedimentary groups. Monomictic equigranular (fine- and medium-grained) quartz sandstones occur largely at the base of the Teptorgo–Mama Group. Polymictic inequigranular sandstones contain lithic and mineral fragments up to 0.5–1.0 mm in size. The fragments are cemented with fine-flaky material (sericite and chlorite) and grains of carbonates, amphiboles, and ore minerals. In zones of high-grade metamorphism, quartz sandstones grade into quartzitic schists and quartzites, while polymictic sandstones are transformed into mica–garnet schists and amphibole- and garnet-bearing rocks.

RESULTS

Metasandstones of the studied series pertain to the quartz–polymictic family. In the mineralogic–petrographic diagram proposed by Kossovskaya and Tuchkova (1988), data points of these rocks occupy the fields of quartz (I), oligomictic (II), and polymictic (III) sandstones (Fig. 3). Figure 1 and Table 1 show that data points of polymictic sandstones of the Ugokhan (21) and Buzhuikhta (22) formations fall into the marginal part of the volcaniclastic sandstone field (IV). As can be seen from Table 1, the family of quartz–feldspar sandstones (quartz and sandstone series) is more diverse than their petrographic classification. For example, the group of quartz sandstones is divided into three (not two) types of highly silicic (A), silicic (B), and alkali silicic (C) sandstones. The group of polymictic sandstones includes the Fe–Si (D) and Fe–Al–Si (E) types. The average SiO_2 content in quartz sandstones ranges from 96.95 ± 0.78 to $82.40 \pm 3.20\%$ and reaches a maximum ($96.95 \pm 0.78\%$) in highly silicic type A of the Purpul (1) and Khorlukhtakh (3) formations. In silicic

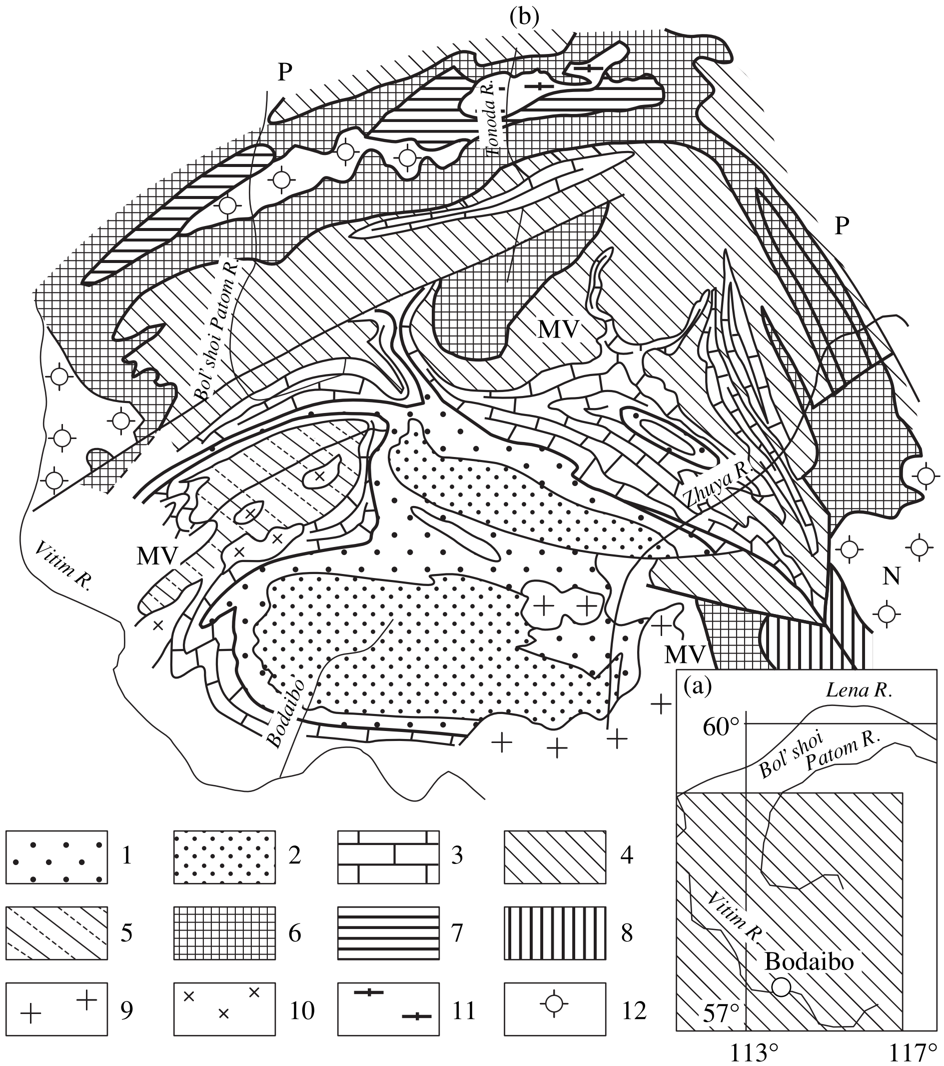

Fig. 1. (a) Index map and (b) simplified geological map of the Patom Highland. Based on the lithologic background of geological maps compiled by the Irkutskgeologiya Industrial Geological Association.

(1, 2) Terrigenous and volcaniclastic rocks of the Bodaibo Group: (1) shales and sandstones of the Anangra, Dogaldyn, and Iligir formations; (2) quartzitic sandstones, high-Al schists, limestones, and marlstones of the Imnyakh, Aunakit, and Vacha formations; (3–5) carbonate and terrigenous rocks of the Kadalikan Group: (3) marbles, limestones, shales, polymictic and mesomictic sandstones of the Buzhuikhta, Ugokhan, and Khomolkho formations; interlayers of quartzitic sandstones and high-Al schists of the Shusman Formation at the base of sequence; (4, 5) quartzitic sandstones and high-Al schists of the Bugarikhta, Khaiverga, and Khorlukhtakh formations; (6) coarse terrigenous and terrigenous rocks of the Teptorgo–Mama Group: quartzite and high-Al schists of the Purpul Formation at the base, boulder and pebble polymictic conglomerates and sandstones of the Medvezhevsky and Kharlukhtakh formations in the middle part of the group, and schists of the Khaiverga Formation in the upper part of the group; (7) Lower Proterozoic Chuya Sequence (Group) of shales and sandstones; (8) crystalline schists of the Archean Chara Group (Korikovskii and Fedorovskii, 1980); (9, 10) granites and pegmatites of the Paleozoic (9) Konkudera–Mamakan and (10) Mama–Oron complexes; (11) Riphean–Lower Proterozoic Amandrak granite; (12) Lower Proterozoic Chuya–Kadar Granite; (Ch, T, N) Protogean–Neogean granite-gneiss domes of the Chuya–Tonoda–Nechera Uplift; (MV) Mama–Vitim Zone of granite-gneiss domes of the Bodaibo Synclinorium; (P) inner wall of the Patom Syncline superimposed on foredeep.

type B, the SiO_2 content drops from 95.40 ± 1.79 to 88.70 ± 2.40%; in alkali silicic type C, from 89.4 ± 1.38% to 82.40 ± 3.20%. The Al_2O_3 content simultaneously increases from 0.50 ± 0.28 % in type A to 4.00 ± 2.24 and 5.85 ± 0.51% in B and from 6.50 ± 1.60 to 8.70 ± 0.47% in C. Table 1 shows that the total iron oxide content (1.45 ± 0.41%) in highly silicic type A reaches 2.40 ± 1.28% in silicic type B and 2.95 ± 1.48% in alkali silicic type C (5.40 ± 1.79% in no. 7). The CaO content is low (<0.45 ± 0.36%) and increases to 1.17 ± 0.81 and 2.80 ± 2.14% in calcareous varieties (nos. 10 and 12, respectively). The total alkali content is extremely low (0.6%) in highly silicic type A, ~1% in silicic type B, and approaches 2% in alkali silicic type C (3.3% in no. 11).

Polymictic sandstones are distinguished by lower average SiO_2 contents and high contents of other chemical elements. The SiO_2 content decreases from 79.35 ±

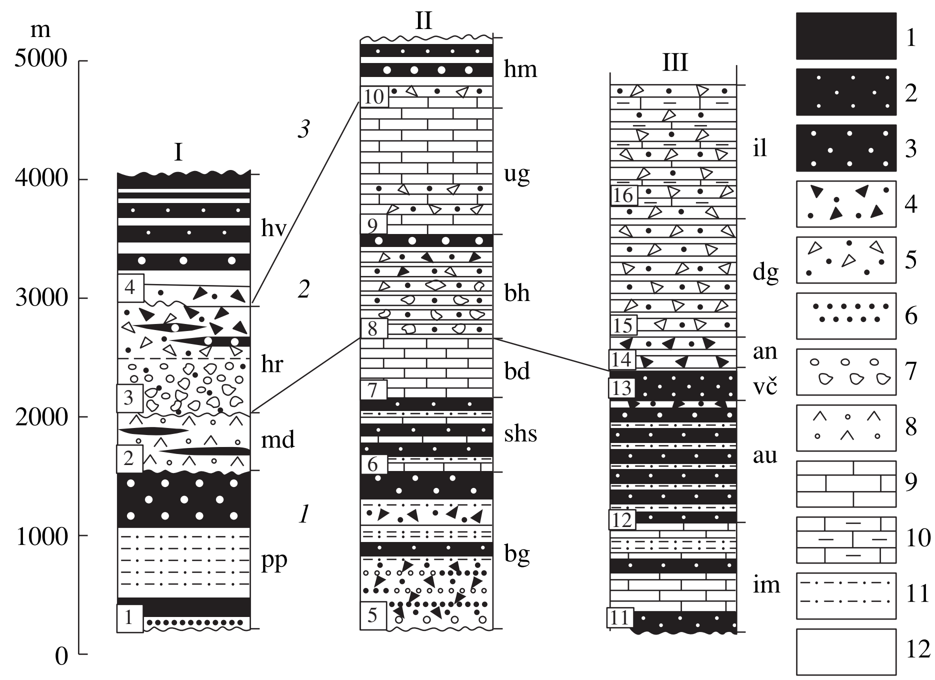

Fig. 2. Distribution of sandy rocks in (I) Teptorgo–Mama, (II) Kadalikan, and (III) Bodaibo metasedimentary groups. (1–3) Quartz sandstones: (1) monomictic, (2) oligomictic, (3) mesomictic; (4, 5) polymictic sandstones: (4) feldspar–quartz graywacke, (5) quartz–feldspar graywacke; (6) gravelstone; (7) boulder and pebble conglomerates; (8) sequence of conglomerates and dolerites; (9) marbles and limestones; (10) calcareous schists; (11) high-Al schists; (12) shales and siltstones; subcycles (subgroups) of sedimentary cycles (groups): (*1*) lower, (*2*) middle, (*3*) upper. Formations: (pp) Purpul, (md) Medvezhevsky, (hr) Khorluktakh, (hv) Khaiverga, (bg) Bugarikhta, (shs) Shusman (Konkudera), (bd) Bodaibo, (bh) Buzhuikhta, (ug) Ugokhan, (hm) Khomolkho, (im) Imnyakh, (au) Aunakit, (vč) Vacha, (an) Anangra, (dg) Dogaldyn, il, (Iligir). The formations are also designated by the corresponding numbers (1–16 inside the boxes).

2.74 to 66.10 ± 2.33% in the Fe–Si type D and reaches a minimum of 63.49% in Fe–Al–Si type E of polymictic sandstones. The Al_2O_3 content increases from 10.20 ± 2.05% to 15.20 ± 1.68% in type D and from 18.00 ± 1.24 to 20.10% in type E. In this group, the total Fe content increases from 3.9 ± 1.1 to 7.65 ± 0.92% and 10.40 ± 2.46 (Table 1, no. 20). The MgO content in rocks of this group varies from 1.20 ± 0.44% to 3.50 ± 0.77%; the CaO content, from 0.70 ± 0.55 to 3.20 ± 1.18%, respectively. The total alkali content ranges from 3.58 to 5.25%.

The average chemical compositions of metasandstones (Table 1) were recalculated to the total quantitative mineral compositions of their protoliths (Table 2), i.e., the compositions of rocks with lithic fragments containing an admixture of nonsyngenetic quartz and feldspar. As was mentioned above, the amount of matrix in sandy rocks is insignificant. Therefore, the results obtained for metasandstones at this stage may be subdivided based on the classification proposed by Shutov (1967). For this purpose, we can use the amounts of quartz, feldspar, and the clay–chlorite mass (Table 3, columns 3–6).

Table 2 shows that proportions of quartz, feldspar, and clay–chlorite mass show that the highly silicic quartz metasandstones of type A (94.4% quartz, 1.5% feldspar, and 3.2% clay mass) correspond to monomic-

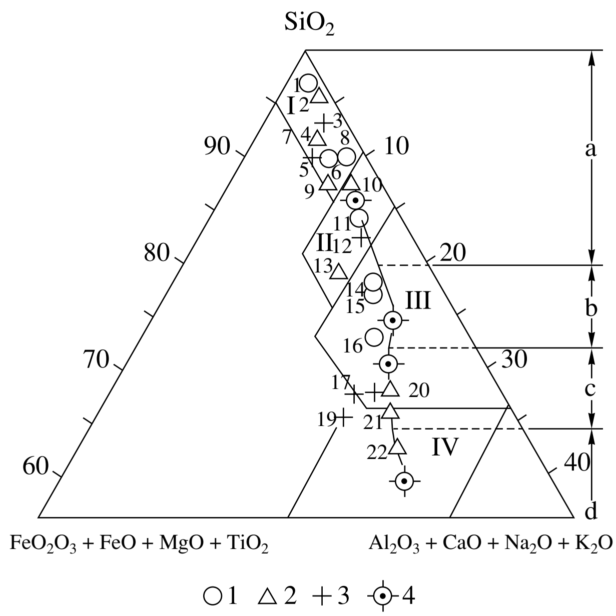

Fig. 3. Metasandstone compositions in the petrochemical diagram (Kossovskaya and Tuchkova, 1988). (1–3) Metasandstones of (1) Teptorgo–Mama, (2) Kadalikan, and (3) Bodaibo groups; (4) psammitic rocks from (a) passive and (b) active continental margins, (c) marginal oceanic and (d) intraoceanic arcs, after Bhatia (1983); (I–IV) sandstone fields: (I) quartz; (II) oligomictic, (III) polymictic, (IV) volcaniclastic.

Table 1. Average chemical compositions of metasandstones, %

Petrochemical types	Ord. no.	Formation no.	SiO_2	TiO_2	Al_2O_3	FeO + Fe_2O_3	MgO	CaO	Na_2O	K_2O	*n*
A	1	1, 3	96.95/0.78	0.10/0.10	0.50/0.28	1.45/0.41	0.20/0.12	0.45/0.36	0.15/0.09	0.20/0.10	13
B	2	6	95.40/1.79	0.70/0.11	1.15/0.31	1.45/0.30	0.60/0.30	0.70/0.41	–	–	18
	3	13	92.85/3.17	0.25/0.12	4.00/2.24	1.45/0.40	0.35/0.26	0.15/0.07	0.25/0.13	0.70/0.55	16
	4	5, 10	92.0/2.8	0.25/0.28	4.10/1.80	2.0/1.34	0.30/0.19	0.30/0.30	0.45/0.39	0.60/0.22	3
	5	12	90.65/2.95	0.35/0.21	4.70/1.20	2.40/1.50	0.35/0.22	0.40/0.37	0.45/0.32	0.70/0.25	13
	6	3, 10	89.75/1.95	0.20/0.10	5.85/0.51	2.40/1.28	0.22/0.20	0.10/0.06	0.18/0.14	1.30/0.37	4
	7	1	88.70/2.40	0.28/0.17	4.55/1.87	5.40/1.79	0.40/0.18	0.27/0.21	0.20/0.25	0.20/0.13	17
C	8	3, 4	89.40/1.38	0.10/0.10	5.75/0.85	1.60/0.52	0.30/0.06	0.45/0.68	1.40/0.53	1.0/0.77	5
	9	8, 10	86.75/3.71	0.50/0.18	6.50/1.60	2.90/1.44	1.00/1.25	0.40/0.29	1.25/0.36	0.70/0.35	14
	10	5	86.36/3.25	0.35/0.17	7.15/2.20	2.20/0.75	0.60/0.90	1.17/0.81	1.55/0.50	0.62/0.20	17
	11	4	84.0/1.36	0.40/0.13	8.70/0.47	2.75/0.58	0.55/0.16	0.30/0.14	2.15/0.31	1.15/0.21	10
	12	12	82.40/3.20	0.45/0.17	7.30/2.55	2.95/1.48	1.25/0.95	2.80/2.14	1.80/0.32	1.05/0.33	4
D	13	10, 12	79.35/2.74	0.65/0.19	10.20/2.05	4.60/1.80	1.55/0.68	0.80/0.95	1.20/0.79	1.65/0.54	24
	14	5	77.56/2.71	0.61/0.17	10.85/2.26	3.90/1.10	1.25/0.42	2.25/1.53	2.00/1.86	1.58/0.76	21
	15	4	77.06/3.67	0.65/0.28	11.50/2.26	4.80/1.99	1.20/0.44	0.70/0.55	2.10/0.68	2.0/0.72	11
	16	3	74.10/3.85	0.50/0.12	13.25/1.25	4.80/1.48	1.90/0.66	1.10/0.60	3.10/0.54	1.25/0.60	24
	17	14	67.65/2.44	0.95/0.11	15.20/1.68	7.65/0.92	2.20/1.45	1.95/1.89	2.70/0.67	1.70/0.65	18
	18	15	67.55/2.13	0.90/0.10	14.40/1.20	6.60/0.90	3.50/0.77	2.90/1.14	2.30/0.80	1.85/0.56	39
	19	6	66.40/3.53	0.75/0.14	15.00/1.72	6.30/1.16	3.10/0.87	3.20/1.18	2.20/0.69	3.05/0.47	22
	20	16	66.10/2.33	0.85/0.12	13.90/0.67	10.40/2.46	3.15/1.31	1.70/1.09	2.30/0.83	1.60/0.48	10
E	21	9	66.85/2.61	1.05/0.17	18.00/1.24	5.92/1.28	2.76/0.64	0.80/0.56	1.92/0.43	2.70/0.58	16
	22	8	63.49	0.85	20.10	7.25	2.48	0.75	2.39	2.69	6

Note: (A) Highly silicic, (B) silicic, and (C) alkali silicic quartz sandstones; (D) Fe–Si and (E) Fe–Al–Si polymictic sandstones. Formation and sequence numbers are as in Fig. 2; (*n*) number of samples. Average and dispersion values are shown in the numerator and denominator, respectively. (–) Absent.

Table 2. Average quantitative mineral compositions of primary rocks in different formations, %

Mineralogic–petrographic type	Ord. no.	Forma-tion no.	Quartz	Feldspar	Kaolinite	Hydromica	Smectite, glauconite	Chlorite	Amphibole	Calcite, dolomite	Ore minerals
1	2	3	4	5	6	7	8	9	10	11	12
A'	1	1, 3	94.4	1.5	0.7	–	2.5	–	–	0.4	0.5
B'	2	6	93.9	–	–	–	–	4.5	–	0.8	0.8
	3	13	84.9	1.8	3.5	8.4	0.7	0.7	–	–	–
	4	5, 10	84.9	3.7	2.3	5.2	1.3	2.5	–	–	–
	5	12	79.2	4.6	2.0	6.4	6.0	0.9	–	–	0.7
	6	3, 10	79.3	2.4	–	13.4	2.1	2.9	–	–	–
	7	1	79.0	0.9	2.0	–	12.7	3.6	–	–	1.8
C'	8	3, 4	73.3	13.4	–	9.4	1.7	1.9	–	0.3	
	9	8, 10	71.1	10.7	–	8.1	4.0	5.3	–	0.1	0.7
	10	5	68.7	14.9	–	5.7	4.9	4.9	–	0.9	–
	11	4	60.0	20.2	–	12.5	4.6	2.7	–	–	–
	12	12	61.9	14.7	–	11.3	4.0	4.5		2.9	0.7
D'	13	10, 12	53.4	13.7	–	11.3	16.3	4.7	–	–	0.6
	14	5	51.0	18.4	–	17.6	5.6	5.9		1.3	0.2
	15	4	47.0	21.6	–	14.7	11.5	4.7	–	0.5	–
	16	3	38.4	24.2	–	14.2	17.3	5.1	–	0.6	0.2
	17	14	33.3	20.7	–	17.6	9.5	11.8	4.7	1.5	0.9
	18	15	32.5	23.0	–	17.5	9.5	12.0	4.6	0.9	–
	19	6	30.0	18.4	–	29.5	9.8	9.7	–	2.1	0.5
	20	16	26.6	17.0	–	34.1	–	10.8	11.5	–	–
E'	21	9	25.5	19.8	–	37.5	8.4	7.9	–	–	0.9
	22	8	16.6	24.4	–	38.8	10.2	9.2	–	0.1	0.7

Note: Quartz sandstones: (A') monomictic; (B') oligomictic, (C') mesomictic; polymictic sandstones: (D') feldspar–quartz, (E') quartz–feldspar (?) graywackes. (–) Absent.

tic quartz sandstones in the Shutov (1967) classification (>90% quartz, <5% feldspar, and <5% lithic clasts). Silicic quartz metasandstones of type B (84.9–79.0% quartz, 0.9–3.7% feldspar, and 11.3–18.4% clay–chlorite mass) correspond to oligomictic quartz sandstones (95–65% quartz, 25–5% feldspar, and 25–5% lithic clasts). Alkali silicic quartz metasandstones (73.3–60.0% quartz, 10.7–20.2% feldspar, and 13.4–19.8% clay–chlorite mass) correspond to mesomictic quartz sandstones (60–50% quartz, 25–10% feldspar, and 25–10% lithic clasts).

Fe–Si metasandstones of type D (53.4–26.6% quartz, 13.7–23.0% feldspar, and 29.1–49.0% clay–chlorite mass) correspond to feldspar–quartz graywackes (75–25% lithic fragments, <10% feldspar and ≥10% quartz). Fe–Al–Si metasandstones of type E (54.1–57.9% clay–chlorite mass, 25.5–16.6% quartz, and 19.8–24.4% feldspar) correspond to quartz–feldspar graywackes (75–25% lithic fragments, 10% quartz, and ≥10% feldspar).

To specify the component composition, the contents of nonsyngenetic quartz and feldspar were subtracted from the total amounts of these minerals (Table 2). Table 3 reflects the calculation procedure (columns 4–7) and results (columns 8–10). Contents of the main components are plotted on the Shutov (1967) ternary diagram. Data points of psammitic rocks classified above based on their total mineral composition as monomictic, oligomictic, and mesomictic quartz sandstones and feldspar–quartz graywackes are plotted in their specific fields (Fig. 4); i.e., the refined component compositions and total mineral compositions occupy the same fields, except for the Fe–Al–Si polymictic sandstones. This type of metasandstones characterized by the highest content of the clay–chlorite mass is enriched in the nonsyngenetic quartz and feldspar to the greatest extent. The clay–chlorite mass accounts for

Table 3. Calculation of corrections for nonsyngenetic quartz and feldspar, and component compositions of primary sandstones in different formations

Petrochemical type	No.	Clay–chlorite mass in sandstones, %	Fine-clastic fractions of quartz and feldspar, %				Calculated component composition, %		
			in clay–chlorite mass of sandstones		in sandstones				
			quartz	feldspar	quartz	feldspar	quartz	feldspar	rock
1	2	3	4	5	6	7	8	9	10
A	1	3.2	2.8	3.4	0.1	0.1	94.3	1.4	4.3
B	2	5	10.0	–	0.5	–	93.4	–	6.6
	3	13.3	6.5	5	0.9	0.7	84.0	1.1	14.9
	4	11.3	6.5	5	0.7	0.6	83.9	3.0	13.1
	5	15.3	6.5	5	1.0	0.8	78.4	3.8	17.8
	6	18.4	6.5	5	1.9	0.9	78.1	1.5	20.4
	7	18.3	6.5	5	1.2	0.9	77.8	–	22.2
C	8	13.0	10.0	5.6	1.3	0.7	72.0	12.7	15.3
	9	17.4	10.0	5.6	1.7	1.0	69.8	9.7	20.5
	10	15.5	10.0	5.6	1.5	1.0	67.2	13.9	18.9
	11	19.8	10.0	5.6	2.0	1.1	58.0	19.1	22.9
	12	19.8	10.0	5.6	2.0	1.1	59.9	13.6	26.5
D	13	32.8	27.6	9.0	8.9	3.0	44.4	9.9	45.7
	14	29.1	22.5	12.0	6.5	3.5	44.8	15.2	40.0
	15	30.9	22.5	12.0	7.0	3.7	40.3	18.1	41.6
	16	36.6	22.5	12.0	8.3	4.4	30.1	19.8	50.1
	17	43.6	22.5	12.0	9.8	5.2	24.0	15.5	60.5
	18	43.7	22.5	12.0	9.8	5.2	22.7	17.8	59.5
	19	49.0	22.5	12.0	11.0	5.9	19.0	12.5	68.5
	20	44.9	22.5	12.0	10.0	5.4	16.6	11.6	64.3
E	21	54.1	25.5	16.0	13.8	8.7	13.0	11.1	75.9
	22	57.9	25.5	16.0	14.7	9.3	1.9	15.1	83.0

Note: Contents of fine-clastic fractions in high-Al metapelites (columns 4 and 5) are taken from (Sharov et al., 2002). Column 10 indicates the total content of clastic clay mass and film–pore cement including fragments of tuffaceous rocks (Table 1, nos. 17–19) and dusty particles of ore and carbonate minerals. (–) Absent.

54.1–57.0% of the total mineral composition (Table 3, column 3, nos. 21, 22), while nonsyngenetic quartz and feldspar account for 14.7–19.8% (column 6) and 8.7–9.3% (column 7), respectively. As the result of appreciable enrichment of Fe–Al–Si polymictic metasandstones in nonsyngenetic quartz and feldspar, the total mineral compositions and the refined component compositions show different classification properties. The total mineral composition fits the quartz–feldspar graywacke; the component composition, the graywacke proper. Owing to the excess mass of nonsyngenetic quartz and feldspars, the graywackes are transferred in the preliminary version of the ternary diagram (Fig. 4) from field X to the margin of field IX.

According to the summary Table 4, the average contents of quartz, feldspar, and lithic fragments are distributed in the following way with respect to mineralogic–petrographic types. In the group of quartz sandstones, the amount of quartz decreases from 94.3% in monomictic sandstones to 82.6% in oligomictic sandstones, 65.4% in mesomictic sandstones, 32% in feldspar–quartz graywackes, and 7.4% in graywackes proper. The amount of lithic clasts mainly composed of shales increases from 4.6% in monomictic quartz sandstones to 15.8% in oligomictic quartz sandstones, 20.8% in mesomictic quartz sandstones, 53.7% in feldspar–quartz graywackes, and 79.5% in graywackes proper. The feldspar content increases from 1.4% (type A') to 1.6 (type B'), 13.8 (type C'), and 15.3% (type D').

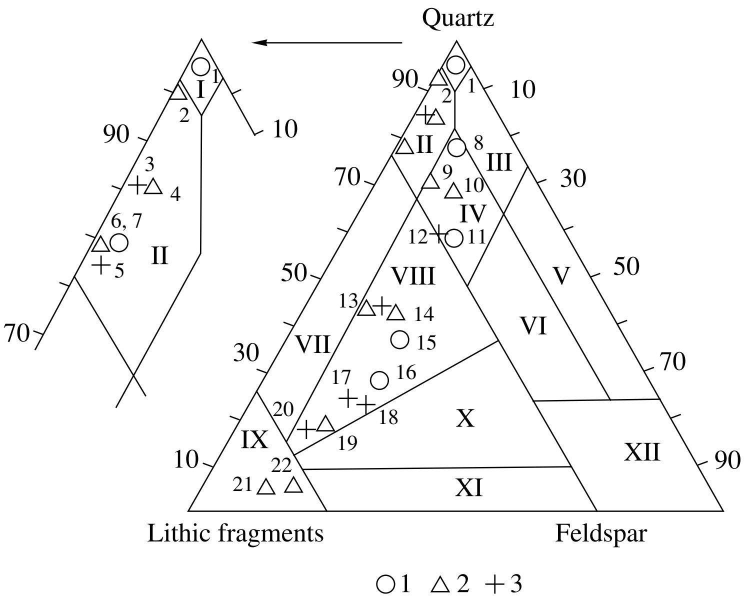

Fig. 4. Component composition of psammitic rocks plotted in the Shutov classification diagram (Shutov, 1967). (I–IV) quartz sandstones: (I) monomictic, (II) siliciclastic quartz, (III) feldspar–quartz, (IV) mesomictic; (V, VI) arkosic sandstones: (V) arkosic proper, (VI) arkosic graywacke, (VII–XI) graywackes: (VII) quartz, (VIII) feldspar–quartz, (IX) graywacke proper, (X) quartz–feldspar graywacke, (XI) feldspar graywacke, (XII) crystal tuff. See Fig. 1 for legend.

The feldspar content is slightly lower (13.1%) in graywackes proper (type E').

DISCUSSION

The results obtained show that the association of psammitic rocks involved in the formation of a thick polycyclic sequence since the end of the Early Proterozoic until the Vendian is represented by the quartz–polymictic family that is surprisingly similar in all sedimentary groups. Rocks of this family is divided into five petrochemical types (A–D, see Table 1) and five mineralogic–petrographic types (A' –D', see Tables 2, 3). In Shutov's classification diagrams (Table 4), these types fall into the fields of monomictic (A'), oligomictic (B'), and mesomictic (C') quartz sandstones, as well as feldspar–quartz graywacke (D') and graywacke proper (E').

The mineralogic–petrographic types make up direct (A'–B'–C'–D'–E') and inverse (E'–D'–C'–B') continuous petrographic (mineralogic–petrographic) series. The direct series comprise the transgressive branches of sedimentary cycles (groups), whereas the inverse series correspond to the regressive branches. In the Teptorgo–Mama and Kadalikan sedimentary groups, the petrographic series of sandy rocks are almost symmetrical. They begin with quartz sandstones (A'–B–C') that grade into polymictic varieties (D'–E'). Polymictic sandstones in regressive branches again give way to quartz sandstones (Tables 1–3). The Bodaibo Group (only the lower part of this group is retained to date) only consists of the transgressive branch (A'–B'–C'–D'–E'). Gradation of mineralogic–petrographic types from A' to E' and from E' to B' reflects decrease in the degree of maturity of psammitic rocks from the bottom and roof of sedimentary groups toward their middle sections. Metapelites behave similarly in the sedimentary groups (Sharov et al., 2002).

Tables 2 and 3 allow us trace the compositional evolution of sandy rocks in petrographic series. In all

Table 4. Component composition of sandy rocks in different mineralogic–petrographic types

Mineralogic–petrographic type	Component composition, %			Number of samples
	quartz	feldspar	rock	
Monomictic quartz sandstone A'	94.3	1.4	4.6	13
Oligomictic quartz sandstone B'	82.6	1.6	15.8	71
Mesomictic quartz sandstone C'	65.4	13.8	20.8	50
Feldspar–quartz graywacke D'	31.0	15.3	53.7	169
Graywacke proper E'	7.4	13.1	79.5	22

series, the formation of transgressive branches begins with the deposition of monomictic and/or the most mature (most enriched in quartz) oligomictic sandstones. The total quartz content diminishes from 94.4 in quartz sandstones to 25.1–16.0% in feldspar–quartz graywackes and graywackes proper; the amount of feldspar, from 1.5 to 24.4%; and the content of clay–chlorite mass, from 3.2 to 57.9% (Table 3, column 3). These variations are clearly expressed in the component composition. According to the averaged data (Table 4), the amount of quartz fragments in these rocks is reduced from 94.3% to 7.4%, whereas the amount of feldspar fragments increases from 1.4 to 15.3%. The content of lithic fragments and their fine-grained mass, which makes up the secondary (postsedimentary) cement, rises from 4.6 to 79.5%.

In the regressive branches with the terminal members represented by oligomictic sandstones of the Khomolkho Formation (Table 3, nos. 4, 6) and mesomictic sandstones of the Khaiverga Formation (Table 3, nos. 8, 11), the content of quartz fragments is 78.1–83.9 and 58.0–72.0%, respectively, whereas the content of feldspar fragments is 1.5–3.0 and 12.7–19.1%, respectively. The amount of lithic fragments is 13.2–20.4% and 15.3–22.9%, respectively.

Thus, the studied Precambrian psammitic rocks of different ages make up similar petrochemical and petrographic (mineralogic–petrographic) series. The change of petrochemical and mineralogic–petrographic series was controlled by the evolution of paleoclimate, the systematic variation in rock lithology, and the degree of maturity of terrigenous rocks. As a result, mature quartz sandstones, which begin the transgressive series, grade into immature polymictic sandstones. Further, polymictic sandstones are replaced by mesomictic and oligomictic mature sandstones in the regressive series. The cause of wavelike change of sandstone compositions is obvious. Correlation of chemical compositions of these rocks plotted on the diagram of Kossovskaya and Tuchkova (1988) together with average chemical compositions of rocks from sedimentary basins of various genetic types (Bhatia, 1980) shows that the variation was induced by the cyclic alternation of geodynamic regimes during the Early Proterozoic, Riphean, and Vendian (Fig. 3). This process was also responsible for the repeated formation of passive continental margin in the southern part Siberian Craton and its periodic involvement in mountain building. The cyclic character of events is recorded in the regular compositional variation of terrigenous rocks. Deposition of sediments started from the scouring of peneplain and the accumulation of mature and highly mature clastic material at the base of sedimentary groups. This material subsequently transformed into quartzites, quartzitic sandstones, and associated high-Al metapelites. Culminations of tectonic activity were accompanied by the formation of high mountains at continental margins, the compensated deposition of tilloids at foothills, and the filling of the Bodaibo Trough with polymictic sandstones.

CONCLUSIONS

Results of the petrochemical study of metasandstones of the Patom Highland with relict blastopsammitic textures and the reconstruction of their quantitative mineral and component compositions indicate that the mineralogical–petrographic classification of psammitic rocks elaborated by Shutov (1967) has retained important genetic implications and can successfully be applied for the reconstruction of metasandstones of the Patom Highland. These investigations have made it possible to establish the petrochemical and mineralogic–petrographic types of polymictic quartz sandstones and to recognize their primary sedimentary nature. These rocks are related to transgressive and regressive branches of sedimentary cycles. The transgressive branch evolves from quartz to polymictic sandstones, whereas the regressive branch is characterized by an inverse succession from polymictic to quartz sandstones. The main tectonic events and related climatic changes are recorded in sandstone compositions. Quartz sandstones and associated high-alumina schists are typical of the humid climate. They are most developed at the initial stage of the Teptorgo–Mama, Kadalikan and Bodaibo periods. Their role is subordinate at the final stage of these periods.

Polymictic sandstones mark the middle parts of sedimentary cycles, which coincided with mountain building and aridization of the humid climate. Such environment promoted the input of tilloids and polymictic sandstones to the sedimentary sequences. Tilloids accumulated at foothills of geoanticlinal uplifts, whereas polymictic sandstones filled the inner Bodaibo Trough. Quartz and polymictic sandstones, which make up similar series in sequences of different ages, bear the most complete information on the tectonic evolution of the main provenance represented by the southern continental margin of the Siberian Craton.

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