ISSN 0869-5938, Stratigraphy and Geological Correlation, 2006, Vol. 14, No. 3, pp. 225–239. © MAIK "Nauka/Interperiodica" (Russia), 2006.
Original Russian Text © A.V. Samsonov, Yu.O. Larionova, 2006, published in Stratigrafiya. Geologicheskaya Korrelyatsiya, 2006, Vol. 14, No. 3, pp. 3–18.

Geochemical Evolution of Magmatism in Archean Granite-Greenstone Terrains

A. V. Samsonov[a] **and Yu. O. Larionova**[b]

[a] *Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, Moscow, Russia*

[b] *Moscow State University, Moscow, Russia*

Received January 12, 2005; in final form, April 28, 2005

Abstract—Evolution of Archean magmatism is one of the key problems concerning the early formation stages of the Earth crust and biosphere, because that evolution exactly controlled variable concentrations of chemical elements in the World Ocean, which are important for metabolism. Geochemical evolution of magmatism between 3.5 and 2.7 Ga is considered based on database characterizing volcanic and intrusive rock complexes of granite-greenstone terrains (GGT) studied most comprehensively in the Karelian (2.9–2.7 Ga) and Kaapvaal (3.5–2.9 Ga) cratons and in the Pilbara block (3.5–2.9 Ga). Trends of magmatic geochemical evolution in the mentioned GGTs were similar in general. At the early stage of their development, tholeiitic magmas were considerably enriched in chalcophile and siderophile elements Fe_2O_3, MgO, Cr, Ni, Co, V, Cu, and Zn. At the next stage, calc-alkaline volcanics of greenstone belts and syntectonic TTG granitoids were enriched in lithophile elements Rb, Cs, Ba, Th, U, Pb, Nb, La, Sr, Be and others. Elevated concentrations of both the "crustal" and "mantle-derived" elements represented a distinctive feature of predominantly intrusive rocks of granitoid composition, which were characteristic of the terminal stage of continental crust formation in the GGTs, because older silicic rocks and lithospheric mantle were jointly involved into processes of magma generation. On the other hand, the GGTs different in age reveal specific trends in geochemical evolution of rock associations close in composition and geological position. First, the geochemical cycle of GGT evolution was of a longer duration in the Paleoarchean than in the Meso- and Neoarchean. Second, the Paleoarche an tholeiitic associations had higher concentrations of LREE and HFSE (Zr, Ti, Th, Nb, Ta, Hf) than their Meso- and Neoarchean counterparts. Third, the Y and Yb concentrations in Paleoarchean calc-alkaline rock associations are systematically higher than in Neoarchean rocks of the same type, while their La/Yb ratios are in contrast lower than in the latter. These distinctions are likely caused by evolution of mantle magmatic reservoirs and by changes in formation mechanisms of silicic volcanics and TTG granitoids. The first of these factors was likely responsible for appearance of sanukitoid magmatic rocks in the Late Mesoarchean. Representative database considered in the work includes ca. 500 precision analyses of Archean magmatic rocks.

DOI: 10.1134/S0869593806030014

Key words: granite-greenstone terrains, geochemistry, magmatism, tholeiitic and calc-alkaline associations, sanukitoid series, crust, lithospheric mantle, Paleo-, Meso- and Neoarchean.

Geochemical and petrological evolution of magmatism that was of variable intensity in the Archean Eon is of key significance for understanding the early development of the Earth crust and biosphere. Exactly this evolution controlled concentrations of chemical elements (including those important for metabolic and fermentative microbial activity) transported by mantle flux and continental runoff into the World Ocean at different stages of its pre-Proterozoic history. Significance of the last factor is doubtless, because magmatic rocks (intrusive and volcanic) dominated in Archean provenances.

Among elements, which migrated by magmatism in outer shells of the Earth, metals were of prime importance owing to their high catalytic ability for the life activity of microorganisms. Suffice it to say that nearly three fourth of natural ferments known at present contain metal ions as components of active centers, and a relatively high concentration of many these metals in seawater of the early Earth was one of the factors, which controlled the life origin and evolution (Fedonkin, 2003, 2004). In addition to variable geochemistry of magmatic rocks, seawater composition depended on the other factors. Mineral traps, which appeared on evolving continents, removed a mass of chemical elements from the recycling system and thus reduced mobility of many metals, their availability for biogenic reactions. Tectonic movements in provenances changed proportions of rocks exposed to weathering, intensity of which depended on compositional evolution of the atmosphere. All these factors and oxygenation of biosphere had a decisive impact on the early biota evolution (Fedonkin, 2004, and references therein).

Problems of the Archean magmatism evolution are therefore of prime importance for understanding the early biosphere. Granite-greenstone terrains (GGT) represent the main source of information about Archean magmatic rocks. Being known in all the Precambrian cratons, they evolved during the greater period of the documented geological history beginning from the Paleoarchean.[1] Large volumes of magmatic rocks of ultrabasic to silicic compositions created the GGT juvenile crust composed of greenstone and granite-gneiss complexes tightly associated with each other in space and similar over the Earth in their general structure and composition. The greenstone complex includes sedimentary-volcanogenic successions, which are of a relatively low metamorphic grade and occur in greenstone belts of synform or monocline forms, while granite-gneiss complexes are represented by diverse metamorphic rocks, migmatites, and granitoids confined to large blocks between greenstone belts. Original geological and structural relations, petrographic and geochemical characteristics of rock associations are well preserved in the GGTs, which are more informative than Archean areas with high-grade metamorphic rocks, where initial features of rock complexes are greatly changed by tectonics and metamorphism.

We analyzed geochemical evolution of Archean magmatic complexes using as examples three large and best studied GGTs, which evolved from 3.5 to 2.7 Ga, i.e., almost throughout the Archean Eon. These are the GGTs of basement in the Kaapvaal (South Africa) and Pilbara (Australia) cratons, which are 3.5 to 2.7 Ga old, and the younger Karelian GGT (Baltic Shield), where the main volume of juvenile crust was formed 2.9–2.7 Ga ago. The considered database includes most representative geochemical data characterizing successive magmatic complexes. We selected data obtained by the most precise analytical methods of XRF spectrometry, ICPA spectrometry, and isotope dilution technique for those samples, which contain magmatic zircons dated by the U–Pb age method. When U–Pb zircon dates were unavailable, we used results of the Sm–Nd isochron dating for whole-rock samples of basic and ultrabasic rocks despite a considerable uncertainty of age determination by this method. We excluded from consideration the Sm–Nd isotopic systematics of rocks, because geochemical and isotopic data characterizing the same samples are reported in different publications and often it is not possible to combine the whole information together.

In the each GGT, we divided rocks into four groups. The first group comprises volcanics of the earliest tholeiitic association (metamorphic equivalents of tholeiitic basalts and andesites, komatiites, boninites), which prevail in lower parts of sections of greenstone belts. Association of calc-alkaline volcanics (metamorphosed basalts, andesites, dacites, and rhyolites of subvolcanic, lava and tuff facies) dominant in upper parts of the sections is attributed to the second group. The third group includes TTG granitoids frequently confined to flanks of greenstone belts and comagmatic with volcanic rocks of the latter. The fourth group is represented by late tectonic intrusive rocks, i.e., by prevailing K–Na and K granites and by subordinate Mg granitoids (sanukitoids) and associated syenites, gabbro, and lamprophyres. Data on oldest gneisses predating greenstone belts have not been included in the database. Being represented fragmentarily in each GGT, these gneisses are close in geochemical parameters to syntectonic TTG granitoids, and data points characterizing them in the age–element diagrams add nothing to information about compositional evolution of magmatic rocks in Archean GGTs.

As a result, database characterizes concentrations of major, trace and rare-earth elements and their indicative ratios (60 parameters in total) in nearly 500 samples of magmatic rocks. All major oxides are recalculated to equal 100% of dry rock. Data are processed by means of plotting the diagrams of the paired age–element correlation, and significance of correlation links is estimated using statistic programs. This approach is applied to examine the summary populations of magmatic rocks in each GGT under consideration, in each of four rock groups discriminated in the GGTs different in age, and in database as a whole to determine general variation trends from 3.5 to 2.7 Ga ago. The principal attention is paid to the Karelian GGT, which we studied personally analyzing the confidently dated samples in the same laboratories. That is why we consider data below in the reversed order from this younger GGT to older ones.

GEOCHEMICAL EVOLUTION OF MAGMATIC ASSOCIATIONS DURING FORMATION OF MESO–NEOARCHEAN GGT (KARELIAN CRATON)

The Karelian GGT in the southeast of Baltic Shield (Fig. 1) is bounded at the northeast by the Belomorian mobile belt that was formed during the Paleoproterozoic reworking of Archean complexes by tectonic and metamorphic events (Bibikova et al., 1999a, 1999b). Western and southwestern flanks of the GGT correspond to the boundary of Svecofennides with Paleoproterozoic juvenile crust, and at east, the GGT is overlain by Phanerozoic platform cover. Archean rocks of the Karelian GGT, the main objects of current consideration, originated in majority 3.02–2.69 Ga ago in the formation period of greenstone belts and during subsequent tectono-magmatic events (Bibikova et al., 2003, and references therein). Older gneisses and granitoids

---

[1] In this work, we accept following Gradstein et al. (2004) the Archean division into the Eoarchean (>3.6 Ga), Paleoarchean (3.6–3.2 Ga), Mesoarchean (3.2–2.8 Ga), and Neoarchean (2.8–2.5 Ga).

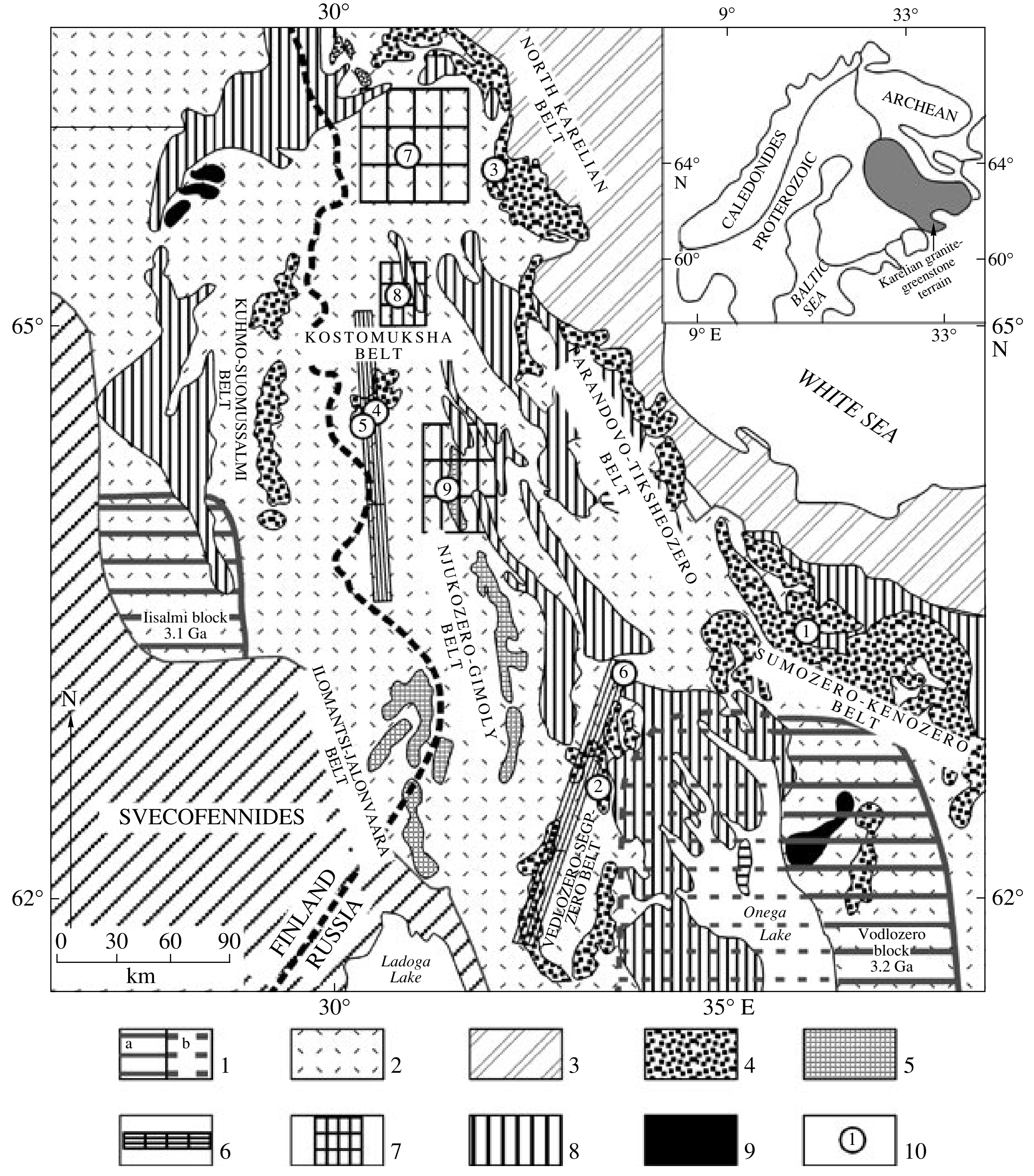

Fig. 1. Schematic geological map of the Karelian granite-greenstone terrain (*Volcanism…*, 1981, with additions): (1) ancient blocks of "pre-greenstone" crust observable (a) and presumable (b); (2) syn- and post-greenstone granitoids undivided; (3) Belomorian Complex, gneisses and amphibolites; (4) TTG-greenstone belts with supracrustal rocks and flanking granitoids 2.94–2.78 Ga old; (5) volcanogenic-sedimentary rocks 2.74–2.73 Ga old; (6–7) distribution areas of post-greenstone intrusions associated with greenstone belts (6) and fragments of composite batholith (7); (8) Paleoproterozoic volcanogenic-sedimentary complexes; (9) Paleoproterozoic mafic–ultramafic massifs; (10) sampling areas or rocks included in geochemical database (see numeration meaning in the text).

(3.5–3.1 Ga) predating in origin this period and occurring in two highly reworked blocks of the East Karelia and East Finland zones are excluded from consideration.

The time span from 3.02 to 2.78 Ga corresponded to accumulation period of supracrustal successions in greenstone belts and to emplacement of TTG granitoids. Metamorphosed volcanogenic-sedimentary rocks are localized in linear chains of small structures (*Volcanism…*, 1981) belonging to the Sumozero–Kenozero, Parandovo–Tikshozero, North Karelian, Vedlozero–Segozero and other greenstone belts (Fig. 1). In all the belts, there are distinguished two main associations of metamorphosed supracrustal rocks. The first tholeiitic association is represented by metavolcanic rocks of basic to ultrabasic composition and by associated carbonaceous slates and jaspilites. The second calc-alkaline association includes lavas tuffs and tuffites of predominantly silicic composition with massive sulfide deposits and associated carbonaceous and flinty slates, jaspilites, and siliciclastic metasediments. Based on the U–Pb dating of zircons from silicic rocks of calc-alkaline association, two separate periods of volcanism in greenstone belts are established: one lasted from 3.02 to 2.85 Ga in the eastern part of the Karelian GGT; the other one from 2.80 to 2.78 in the western part.

The post-greenstone evolutionary stage of the Karelian GGT was marked by immense endogenic activity that resulted 2.75–2.69 Ga ago in emplacement of intrusive, predominantly granitoid bodied of diverse composition (Lobach-Zhuchenko et al., 2000; Samsonov et al., 2001; Bibikova et al., 2005). In addition to geochronological constraints of this stage, it is evident from geological observations that an episode of deformations with associated metamorphism, perhaps, separates everywhere rock associations of the TTG-greenstone and post-greenstone complexes. Magmatic rocks of the post-greenstone complex are irregularly distributed in the Karelian GGT (Fig. 1). Near TTG-greenstone belts, this complex is represented by spaced small massifs of subalkaline high-Mg granitoids (analogs of granitoids of sanukitoid series in Canadian Shield; Shirey and Hanson, 1984; Chekulaev, 1999) and by basic lamprophyre dikes (Lobach-Zhuchenko et al., 2000) and granites. Besides, in granite-gneiss fields of the Karelian GGT there are several areas dominated by magmatic rocks of the post-greenstone complex that includes prevalent granitoids of sanukitoid series, lamprophyres, granites, gabbroids, and syenites. Clusters of these intrusions occupying areas up to several thousands square kilometers in size are traceable for a distance of 400 km at least from northern to central and, probably, to southern Karelia; they can be regarded as intrusive bodies of a complex batholithic belt. In central and southern segments of the belt, there are narrow graben-like structures of the Njukozero–Gimoly greenstone belt. Volcanogenic-sedimentary complexes of the latter accumulated 2730 ± 5 Ma ago (Samsonov et al., 2001) concurrently with emplacement of sanukitoid intrusions.

Database for the Karelian GGT includes 134 analyses of volcanic and plutonic rocks of the greenstone complex formed 2916–2780 Ma ago and 80 analyses of younger magmatic rocks ranging in age from 2740 to 2690 Ma. Sampling sites of rocks included in the database are shown in the map (Fig. 1).

Volcanics and syntectonic granitoids of the greenstone complex have been sampled in separate structures of four TTG-greenstone belts. Volcanic rocks of the Kamennoe Ozero structure (area 1) in the Sumozero–Kenozero belt correspond to basalts and komatiites of the early tholeiitic association (Sm–Nd isochron age 2916 ± 117 Ma; Puchtel et al., 1999) and to basalts, andesites, dacites, and rhyolites of the late calc-alkaline association (U–Pb zircon ages 2875 ± 2 and 2876 ± 5 Ma; Puchtel et al., 1999). Among volcanics of the Koikary structure (area 2), the Vedlozero–Segozero belt, we selected andesites, dacites, and rhyolites of the late calc-alkaline association (U–Pb zircon ages 2859 ± 15 and 2876 ± 5 Ma of dacites and rhyolites, respectively) and basalts and komatiites of the early tholeiitic association. The latter rocks have not been dated directly, but they could be formed ca. 2900 Ma ago by analogy with rocks of the Kamennoe Ozero structure. Data on volcanic rocks and TTG granitoids of the Khizovaara structure (area 3), the North Karelian belt, characterize tholeiites, Fe-Ti basalts and andesites of the early association (age of metamorphism 2780 ± 5 Ma and age of magmatic events not less than 2820 Ma; Bibikova et al., 2003), calc-alkaline volcanics of the late association (2780–2796 Ma), and TTG granitoids 2800 to 2820 Ma old (Bibikova et al., 2003). Rocks of the Kostomuksha structure (area 4) in synonymous belt are represented in database by supracrustal tholeiitic basalts, andesites, and komatiites of the early association (Sm–Nd isochron age 2843 ± 39 Ma; Puchtel et al., 1998) and by volcanics (2790–2792 Ma) and syntectonic TTG granitoids (2786–2790 Ma) of the late calc-alkaline association (Samsonov et al., 2001; Bibikova et al., 2005).

Volcanic rocks, gabbroids, sanukitoids, lamprophyres, syenites, and granites of the post-greenstone complex are well studied in geochemical aspect in separate areas of structural-tectonic zones of the Karelian GGT, which are of different structure, age, and composition. In the West Karelian zone, these are differentiated diorite–granodiorite massifs of sanukitoid type (U–Pb zircon age 2715 ± 10 Ma; Samsonov et al., 2004), lamprophyre dikes, and granite intrusions of the Kostomuksha region (area 5). Data on the East Karelian zone characterize differentiated diorite–granodiorite–granite (sanukitoid) massifs (U–Pb zircon age ca. 2740 Ma; Levchenkov et al., 1989; Chekulaev et al., 1994) and lamprophyres of the Bergaul region (area 6). For the Central Karelian batholithic belt, we selected data on volcanics, sanukitoids, lamprophyres, syenites, gabbroids, and granites from its northern area 7 (U–Pb zircon age of sanukitoids 2724 ± 8 Ma; Bibikova and Slabunov, 1997) and from two areas in central part (area 8, U–Pb zircon age of a late lamprophyre dike 2696 ± 10 Ma, and area 9, U–Pb zircon age of rhyolite 2730 ± 15 Ma; Samsonov et al., 2001). Sanukitoids 2706 ± 5 Ma old (Bibikova et al., 2005) are also included in the data base. Secular geochemical variations of magmatic rocks in the Karelian GGT are illustrated in diagrams of the paired age–element correlation (Fig. 2).

Volcanic rocks of the tholeiitic association, which are represented by komatiites, boninites, tholeiitic

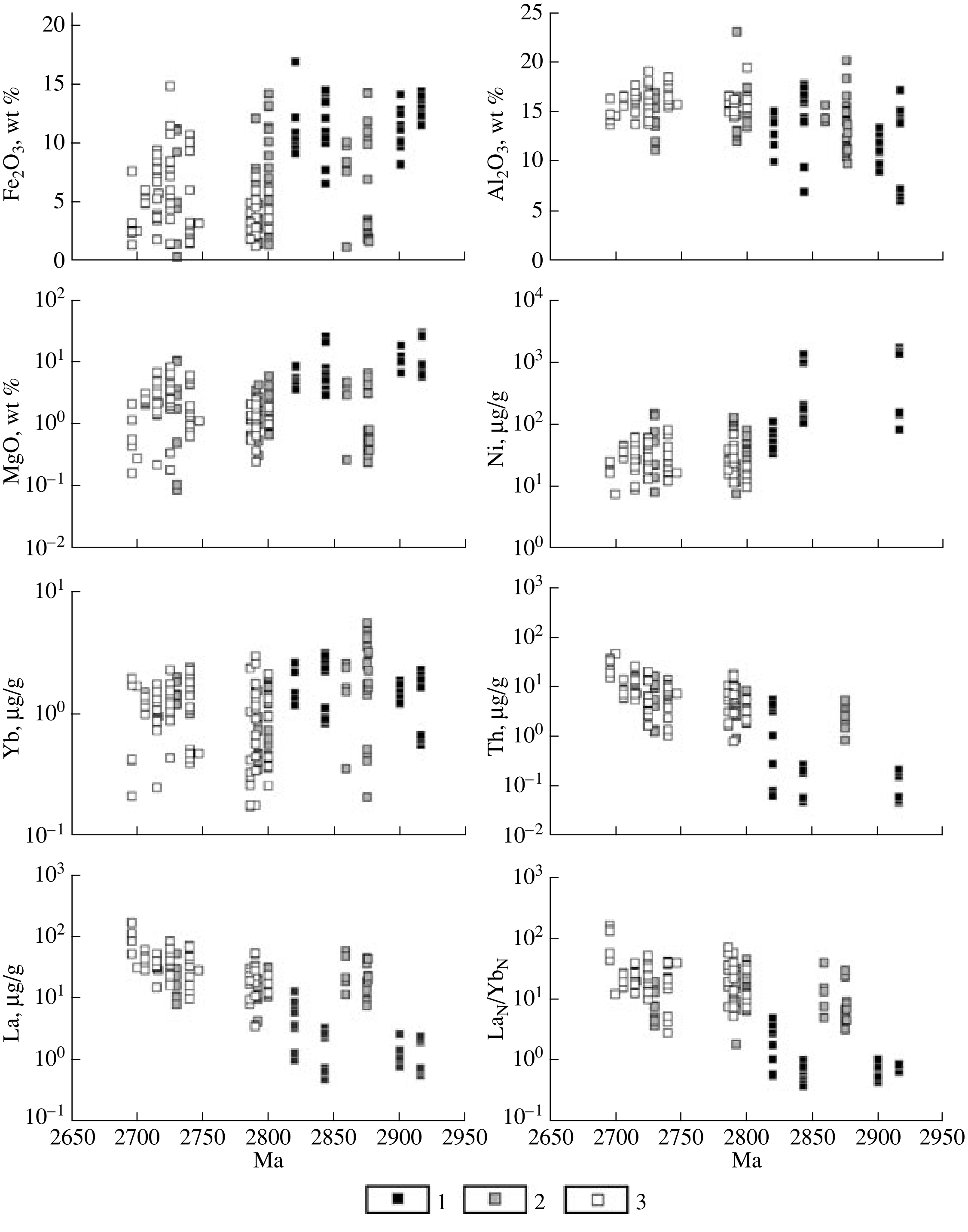

Fig. 2. Secular changes of major and trace element concentrations in rocks of tholeiitic (1) and calc-alkaline (2) volcanic associations and granitoids (3) of the Karelian granite-greenstone terrain.

basalts and andesites, reveal distinct trends of changes in concentrations of many elements, when the rock ages decrease from 2916 to 2820 Ma, i.e., the growing trend of SiO$_2$, Al$_2$O$_3$, Ba, Th, U, Pb, Nb, La, Yb, Y, and Sr contents in contrast to declining abundance of MgO, Cr, Ni, Co and decrease of Mg differentiation index. Trends of changes in abundance of some major and trace elements (Fe$_2$O$_3$, MnO, V, Zn, Cu, Sc) or in Th/U and La/Yb ratios are indistinct. The established trends of secular geochemical variations characterizing tholeiitic volcanics can be interrelated with two factors of petrogenesis at least.

The most simple explanation is a growing contribution of sialic components to mantle-derived magmas.

This could be first the crustal growth that enlarged contamination of magmas by sialic material at the development time of the TTG-greenstone belts. On the other hand, the lithospheric mantle beneath the Karelian GGT could be enriched in lithophile elements during subduction episodes at different stages of evolution of the TTG-greenstone complexes (Mints, 1998; Bibikova et al., 2003; Samsonov et al., 2005). According to isotopic-geochemical data, the contaminating material could be derived from two sources: one corresponding to crustal blocks composed of Mesoarchean (>3.0 Ga) TTG granitoids, and the other one to the juvenile silicic material segregated in the Neoarchean time from depleted mantle. This is evident from great variations of Nd isotopic composition in volcanics of the tholeiitic association: εNd(T) from +2.3 to +3.1 in komatiites and tholeiitic basalts of the Kamennoe Ozero and Kostomuksha structures (Puchtel et al., 1998, 1999); from –1.7 to +2.2 in the same rocks of the Koikary structure (Samsonov et al., 1997; Svetov and Huhma, 1999); from +1.10 to +2.48 in boninites and low-Ti tholeiitic basalts of the Khizovaara structure (Shchipansky et al., 2004). However, the idea of contamination by sialic material does not explain secular variations in concentrations of compatible elements (MgO, Cr, Ni, Co), which noticeably decrease with time. This trend and, to some extent, growing concentrations of incompatible elements could be related to a lesser degree of melting in the mantle source of tholeiitic magmas because of the secular mantle cooling. The latter could be caused by the heat dissipation in mid-ocean ridges, by relatively cold oceanic plates sinking into mantle, and by a higher degree of metasomatic reworking of mantle material above subduction zones. Thus, time-dependent changes in geochemical characteristics of tholeiitic volcanics from greenstone belts of the Karelian GGT were possibly controlled by the lowering degree of melting in the mantle subjected besides to intensifying metasomatic reworking and by growing contamination of magmas by crustal components.

Volcanic rocks of calc-alkaline association from greenstone belts of the Karelian GGT are represented by basalts, andesites, dacites, and rhyolites. As compared to underlying rocks of the tholeiitic association, they are sharply depleted in MgO, Cr, Ni and Co, being simultaneously enriched in LJLE and HFSE. When the rock ages decrease from 2887 to 2780 Ma, distinct geochemical trends can be established for a few elements only. In this case, we detected the directional growth of petrogenic, rare alkalies, Th, U, Pb, Sr concentrations as well as La/Yb and Sr/Y ratios, on the one hand, and decreasing concentrations of Yb and Y, on the other. At the same time, older rocks of calc-alkaline association from the Kamennoe Ozero and Koikary structures, where they range in age from 2887 to 2850 Ma, exhibit very wide geochemical variations and bimodal distribution of element concentrations in most cases. By transition to younger (2800–2780 Ma) calc-alkaline rocks of the Kostomuksha and Khizovaara structures, diapason of variations is getting much narrower (Fig. 2).

Wide concentration ranges and irregular distribution of many major and trace elements in volcanic rocks under consideration suggest heterogeneity of magmatic reservoirs, which originated in basites and crustal rocks according to isotopic criteria (εNd(T) from + 4.5 to –6.5; Puchtel et al., 1998, 1999; Samsonov et al. 2001, 2005; Bibikova et al., 1999, 2005), and a variable degree of subsequent magmatic differentiation. On the other hand, the established trends of Th, U, and Pb concentrations growing with time in calc-alkaline volcanics may reflect increasing contribution of sedimentary components related to crustal growth. At the same time, successive rise of Sr, Yb, Y concentrations and La/Yb and Sr/Y ratios may be indicative of either a greater depth of basic rocks melting in subducting slabs, or a higher extent of lithospheric mantle reworking above subduction zones by fluids and adakitic melts.

Granitoids of the TTG series ranging in age from 2826 to 2786 Ma are comparable in all geochemical characteristics with concurrent calc-alkaline volcanics in adjoining greenstone belts (Fig. 2). This is an important indication of comagmatic origin of two igneous complexes.

The late tectonic granitoids and volcanics, which originated 2.74–2.69 Ga ago, have wider compositional variations as compared to rocks of the previous magmatic stage (Fig. 2), because melting in magma sources involved, as we believe, a greater diversity of materials contrasting in composition. Different horizons of continental crust formed prior to that time and dominated by TTG granitoids represented sources of granitic magmas with diverse geochemical characteristics (Chekulaev et al., 1997; Samsonov et al., 2001). At the same time, melting in the lithospheric mantle subjected earlier to intense subduction-related metasomatism gave rise to origin of sanukitoid magmatic rocks (Samsonov et al., 2004; Kovalenko et al., 2005). Exactly these rocks determine specific geochemistry of magmatism at the terminal stages of the Karelian GGT evolution. Displaying growth of Mg differentiation index, they are enriched in elements typical of both the crustal and mantle reservoirs, i.e., in MgO, Al_2O_3, Ba, Cr, Ni, Co, V, Mo, W, Zn, Cu, Th, U, Pb, La, Sc, Sr, and alkalies (Fig. 2).

GEOCHEMICAL EVOLUTION OF MAGMATIC ASSOCIATIONS DURING DEVELOPMENT OF PALEO–MESOARCHEAN GGT (PILBARA AND KAAPVAAL CRATONS)

The Pilbara and Kaapvaal cratons having similar geological history were formed in the same period of geologic time (de Wit, 1998). Their igneous rocks complementing geochemical characteristics of relevant magmatism originated in the Paleo- and Mesoarchean.

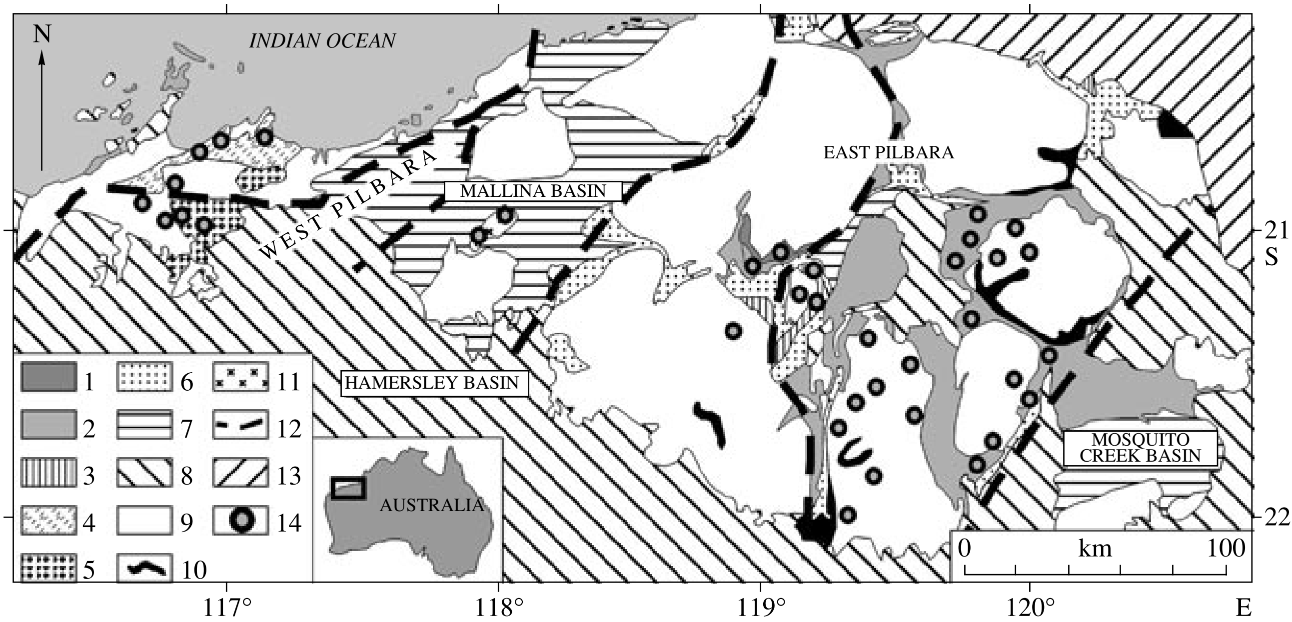

Fig. 3. Simplified geological map of the Pilbara granite-greenstone terrain (after Kloppenburg et al., 2001; Van Kranendonk et al., 2002; Smithies and Champion, 2000). Volcanogenic-sedimentary rocks of greenstone belts: (1) Coonterunah Group, 3.52–3.49 Ga, (2) Warrawoona Group, 3.49–3.31 Ga, (3) Sulfur Spring Group, 3.28–3.24 Ga, (4) Roebourne Group, 3.28–3.25 Ga, (5) Whundo Group, 3.13–3.12 Ga, (6) Gorge Creek Group, 3.24–3.05 Ga; (7) De Grey Group, 3.02–2.94 Ga, and (8) Mount Bruce Group, 2.77–2.49 Ga, in sedimentary rift basins; (9–11) granitoids 3.48 to 2.85 Ga old: (9) undivided, predominantly TTG granitoids, (10) granites and granodiorites, (11) high-Mg granitoids of sanukitoid type; (12) main tectonic zones; (13) Phanerozoic cover; (14) sites of rocks included in database.

The Pilbara craton is a large Archean block situated in northwestern Australia. Archean complexes of the block are overlain by Neoarchean (2.77–2.49 Ga) deposits of the Hamersley Basin in the south and southeast (Arndt et al., 1991) and by Phanerozoic sedimentary rocks in the northeast (Barley, 1997). The East (3.52–3.20 Ga) and West Pilbara (3.28–2.94 Ga) GGTs distinguished in the craton structure (Fig. 3) are separated by the large Mallina rift basin (3016–2940 Ma), which is filled with siliciclastic turbidite-like sediments containing rare intercalations of basic and silicic volcanics (Van Kranendonk et al., 2002).

In geological structure of the East Pilbara GGT, large granite-gneiss domes are closely associated with greenstone belts representing a system of conjugate synclinal and monoclinal volcanogenic-sedimentary structures (Fig. 3), which developed almost throughout the Paleoarchean from 3.52 to 3.20 Ga. The older rocks (3.72–3.54 Ga) occurring here are represented by granitoids of negligible volume (ca. 1%) known in the Warrawagine granite-gneiss dome, the northeast of the terrain, and by gabbro-anorthosites of the Shaw batholith (Van Kranendonk et al., 2002).

In the recent regional stratigraphic scheme, the volcanogenic-sedimentary succession of the East Pilbara greenstone belts is divided, being up to 30 km thick in total, into five groups (Barley, 1997; Van Kranendonk et al., 2002). The oldest Coonterunah Group (3515–3498 Ma) confidently discriminated in central area only is composed of tholeiitic basalts associated with much less abundant volcanics of intermediate and silicic composition. The overlying Warrawoona Group (3490–3308 Ma) is dominant in the succession, enclosing thick (up to 18 km) sequences of tholeiitic and komatiitic lavas associated with calc-alkaline volcanics ranging in composition from andesites to ultra-silicic rhyolites. Subordinate sedimentary rocks of the group are represented by stromatolitic carbonate and sulfate sediments, jaspilites, sandstones, and shales. The Sulfur Spring Group (3280–3235 Ma) well exposed in the west of the East Pilbara GGT includes komatiites and magnesian basalts underlying the thick upper sequence of calc-alkaline volcanics (basalt–andesite–dacite–rhyolite series) with associated massive sulfide deposits. The next Gorge Creek and De Grey groups, which accumulated respectively 3235–3050 and 3050–2940 Ma ago, are terminal in the supracrustal succession of the East Pilbara greenstone belts. They are composed predominantly of siliciclastic metasediments and jaspilites; subordinate metavolcanics of basic composition are represented in the upper part of the Gorge Creek Group (Van Kranendonk et al., 2002). Spacious granite-gneiss domes (3.48–2.85 Ga) of the East Pilbara GGT are composed mostly of the Paleoarchean (3.5–3.3 Ga) TTG granitoids. Granodiorites and granites about 2.93 Ga old are main rock types of the Yule batholith situated in the extreme southwest of the GGT.

Three volcanogenic-sedimentary groups of the West Pilbara greenstone belts are closely associated in space with concurrent granitoid complexes (Van Kranendonk et al., 2002). The oldest Roebourne Group (3280–3250 Ma) is composed of komatiites, basalts, and subordinate flinty slates. The middle Whundo Group (3125–3115 Ma) is represented by tholeiitic basalts in the lower part and by silicic lavas, tuffs, and tuffites in the upper one. The upper Gorge Creek Group includes siliciclastic metasediments, carbonaceous and ferruginate slates, which are estimated to be from 3018 ± 3 to 3014 ± 6 Ma old based on U–Pb dating of clastic zircons from metasediments and magmatic zircons from diorite-porphyry bodies crosscutting the latter. Among three groups of granitoids of the West Pilbara GGT, the oldest one (3260–3270 Ma) is represented by rocks of the TTG series. Subalkaline to alkaline granites are dominant rocks of two later groups of plutonic rocks emplaced 3160–3060 and 3015–2940 Ma ago (Van Kranendonk et al., 2002). Diverse igneous rocks, the age analogs of youngest granitoids of the West Pilbara GGT intruded deposits of the Mallina basin; of prime importance among them are granitoids of sanukitoid series about 2950 Ma old (Smithies and Champion, 2000).

The database considered here includes results of geochemical analyses of 179 samples characterizing volcanic and plutonic rocks from different areas of the Pilbara craton. Among these rocks, there are volcanics of the tholeiitic association from the Coonterunah (3515 Ma; Green et al., 2000) and Warrawoona groups (3490–3475 Ma; Kato and Nakamura, 2003; Green et al., 2000), and calc-alkaline volcanics from the latter (3490–3320 Ma; Jahn et al., 1981; Bickle et al., 1983; Barley et al., 1998) and Sulfur Spring groups (ca. 3250 Ma; Vearncomble and Kerrich, 1999) of the East Pilbara GGT. Analytical data on tholeiitic volcanics from the Roebourne Group (3280 Ma; Ohta et al., 1996) characterize relevant magmatism of the West Pilbara GGT. Intrusive complexes of the craton are represented by samples of granitoids ranging in age from 3493 to 2930 Ma (Jahn et al., 1981; Bickle et al., 1983; Barley and Pickard, 1999; Green et al., 2000; Smith et al., 1998; Smith, 2003) and by sanukitoids intruding supracrustal formations of the Mallina basin (Smithies and Champion, 2000).

The Kaapvaal craton, a large block of Archean crust in South Africa, is bounded by Mesozoic sediments of the Lebombo monocline in the east and by the Namakwa–Natal belt of Proterozoic rocks in the south and west. The block northern boundary corresponds to axial zone of the Limpopo mobile belt that developed during the Archean and Paleoproterozoic (Brandl and de Wit, 1997). In the craton structure, there are discriminated several domains of different age and composition (Poujol et al., 2003), the oldest East Domain studied in detail including (Fig. 4A). Crust of the latter was largely formed 3.5–3.1 Ga ago, when accumulation of volcanics and sediments in greenstone belts was accompanied by emplacement of granitoids different in composition. The older gneiss complex of Swaziland (3.7–3.6 Ga) predating formation of greenstone belts is known in central area of the East Domain (Hunter et al., 1978; Kroner and Tegtmeyer, 1994; Poujol et al., 2003).

The best studied Barberton greenstone belt in the domain central zone (Fig. 4B) is composed of volcanogenic and sedimentary rocks, which are metamorphosed under conditions of amphibolite and greenstone facies being divided into three successive groups (Brandl and de Wit, 1997). The oldest Onverwacht Group (3.49–3.40 Ga) is composed predominantly of basic to ultrabasic volcanic rocks with subordinate intercalations of metasediments and silicic volcanics. The Fig Tree Group (3.26–3.22 Ga) that accumulated after a considerable hiatus includes prevailing sediments (graywackes, sandstone, slates, and jaspilites) and less abundant dacitic and rhyolitic volcanics of the calc-alkaline association (Kohler and Anhaeusser, 2002). The Moodies Group (3.22–3.10 Ga) is dominated by siliciclastic rocks (conglomerates, quartzites, slates) and jaspilites associated with subordinate volcanic rocks of diverse composition. The groups were intruded 3.44–3.11 Ga ago by large massifs of granitoids different in composition. The early syntectonic plutons (3.44–3.22 Ga) are represented by TTG granitoids, while granodiorites and granites ranging in age from 3.20 to 3.11 Ga prevail in the late and post-tectonic massifs (Poujol et al., 2003; Kleinhanns et al., 2003). In the Nondweni greenstone belt situated in the south of East Domain, age and lithologic analogs of the Onverwacht Group are also divided into three groups (Riganti and Wilson, 1995). The oldest Magongolozi Group is dominated by metavolcanics (3406 ± 3 Ma) of ultrabasic, basic and intermediate composition. Silicic lavas, tuffs and tuffites with associated massive sulfide deposits are attributed to the overlying Toggekry Group. The Witkop Group crowning rock succession of the Nondweni belt is composed of basic to silicic volcanics, which contain conglomerate, stromatolitic dolostone, chert, and evaporite interlayers in the upper interval (Riganti and Wilson, 1995).

We included in database geochemical data on 95 samples of volcanic rocks from the Nondweni and Barberton greenstone belts and of granitoids flanking the latter (areas 3.1 and 3.2 in Fig. 4A; dots in Fig. 4B). Selected samples characterize the following rocks: (1) basalts and komatiites of tholeiitic association from the Barberton (Onverwacht Group, Komati Formation, 3490 Ma, Parman et al., 1997, 2003) and Nondweni belts (Magongolozi Formation, 3406 Ma, Riganti and Wilson, 1995); (2) silicic calc-alkaline volcanics from the Barberton belt (Onverwacht Group, Theespruit Formation, 3453 Ma; Fig Tree Group, Bien Venue and Shoongezicht formations, 3256–3259 Ma, Kohler and Anhaeusser, 2002); (3) diverse granitoids (3437–3105 Ma) flanking the Barberton belt (Kleinhanns et al., 2003).

As one can see from Fig. 5, secular variation trends of geochemical characteristics, which are depicted for three rock associations of the Kaapvaal and Pilbara cra-

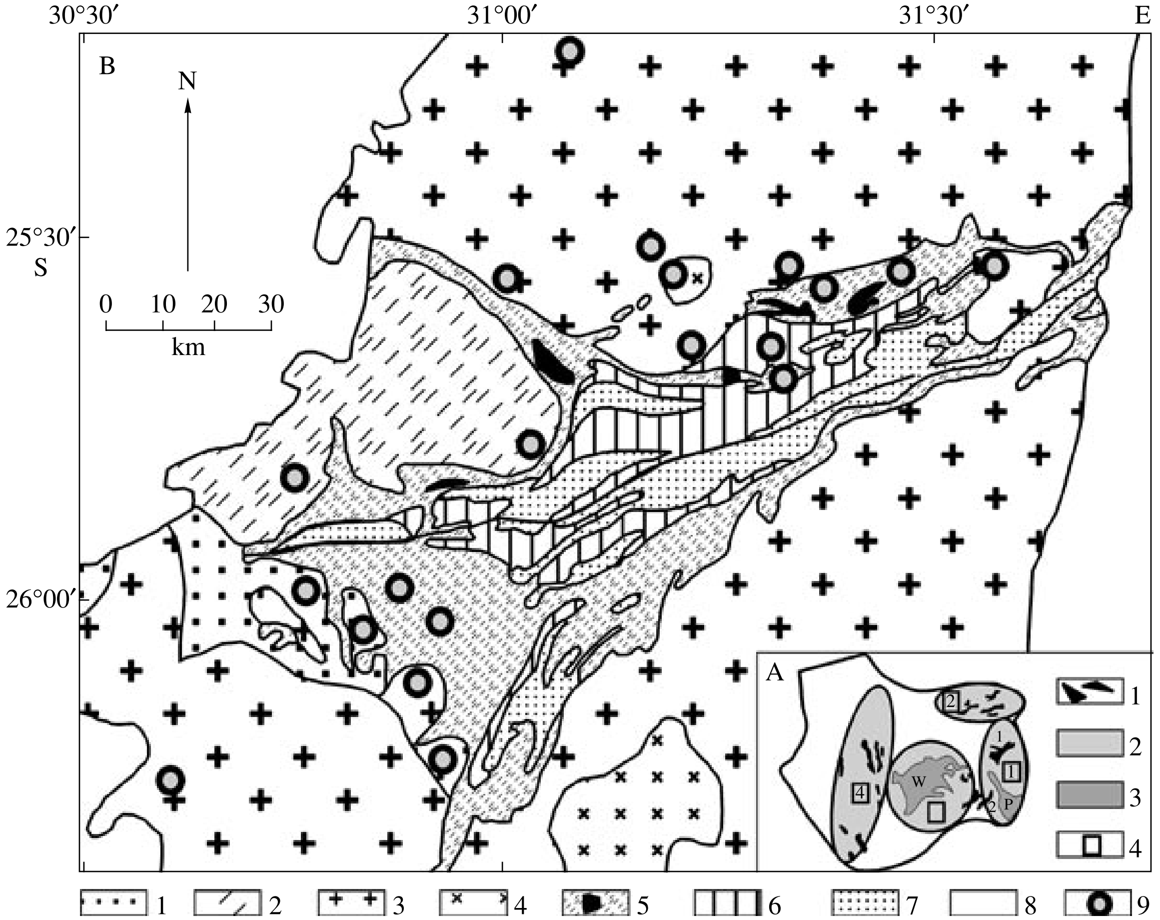

Fig. 4. (A) Structural elements of the Kaapvaal craton (after Poujol et al., 2003): (1) greenstone belts Barberton (*1*) and Nondweni (*2*); (2) granite-gneiss terrains; (3) sedimentary basins Witwatersrand (W) and Pongola (P); (4) principal domains by numbers: (1) East Domain, 3.60–3.10 Ga, (2) North Domain, 3.25–3.00 Ga, (3) Central Domain, 3.25–2.70 Ga, (4) West Domain, 3.00–2.70 Ga. (B) Simplified geological map of the Barberton greenstone belt and flanking granite-gneisses (after Poujol et al., 2003): (1) early trondhjemite plutons, 3.5–3.4 Ga; (2) late tonalite–trondhjemite plutons, 3.2 Ga; (3) granodiorite–adamellite batholiths and plutons, 3.2–3.1 Ga; (4) granodiorite–granite plutons, 2.7 Ga; (5) Onverwacht Group, 3.50–3.26 Ga, and associated ultramafic intrusions; (6) Fig Tree Group, 3.26–3.22 Ga; (7) Moodies Group, 3.22–3.10 Ga; (8) platform cover; (9) sites of rocks included in database.

tons, are practically identical, emphasizing similar geological evolution of two cratons during comparable periods of geologic time (de Wit, 1998).

Volcanics of tholeiitic association from the Pilbara craton range in age from 3515 to 3280 Ma. Relatively older basalts and komatiites of the East Pilbara from the Coonterunah (3515) and Warrawoona (3475 Ma) groups, which have similar, though broadly variable concentrations of major and trace elements, are noticeably enriched in LREE ($La_N/Yb_N \geq 1$). Younger (3280) tholeiitic basalts of the West Pilbara with non-fractionated REE spectra (La_N/Yb_N close to 1) reveal narrow compositional variations and decreased Th, Nb, and REE concentrations, being similar to older rocks in concentrations of other elements (Fig. 5). Geochemical distinctions between the above rock complexes of different age likely reflect different degree of contamination by crustal material. Certainly, contamination by old (3.58–3.72 Ga) crustal material is admissible for tholeiitic volcanics of East Pilbara based on presence of relict zircons in siliciclastic metasediments of relevant greenstone belts and in granite-gneiss batholiths, being consistent in addition with the results of Sm–Nd isotopic systematics (Green et al., 2000, and references therein). In contrast, primitive depleted tholeiitic volcanics of the West Pilbara are lacking such a contribution (Ohta et al., 1996).

In komatiites and komatiitic basalts of the Komati Group (3490 Ma) from the Barberton belt, which are comparable in age with komatiitic basalts of the Warrawoona Group, East Pilbara, concentrations of MgO, Cr and Ni are relatively higher, while concentrations of many lithophile elements (La, Nb, Th, etc.) are lowered. This is likely a consequence of a different degree and/or depth of melting in mantle reservoirs with close geochemical parameters. In distinction from the East Pilbara case, the relative enrichment of Barberton komatiites in LREE ($La_N/Yb_N \geq 1$) was likely caused by

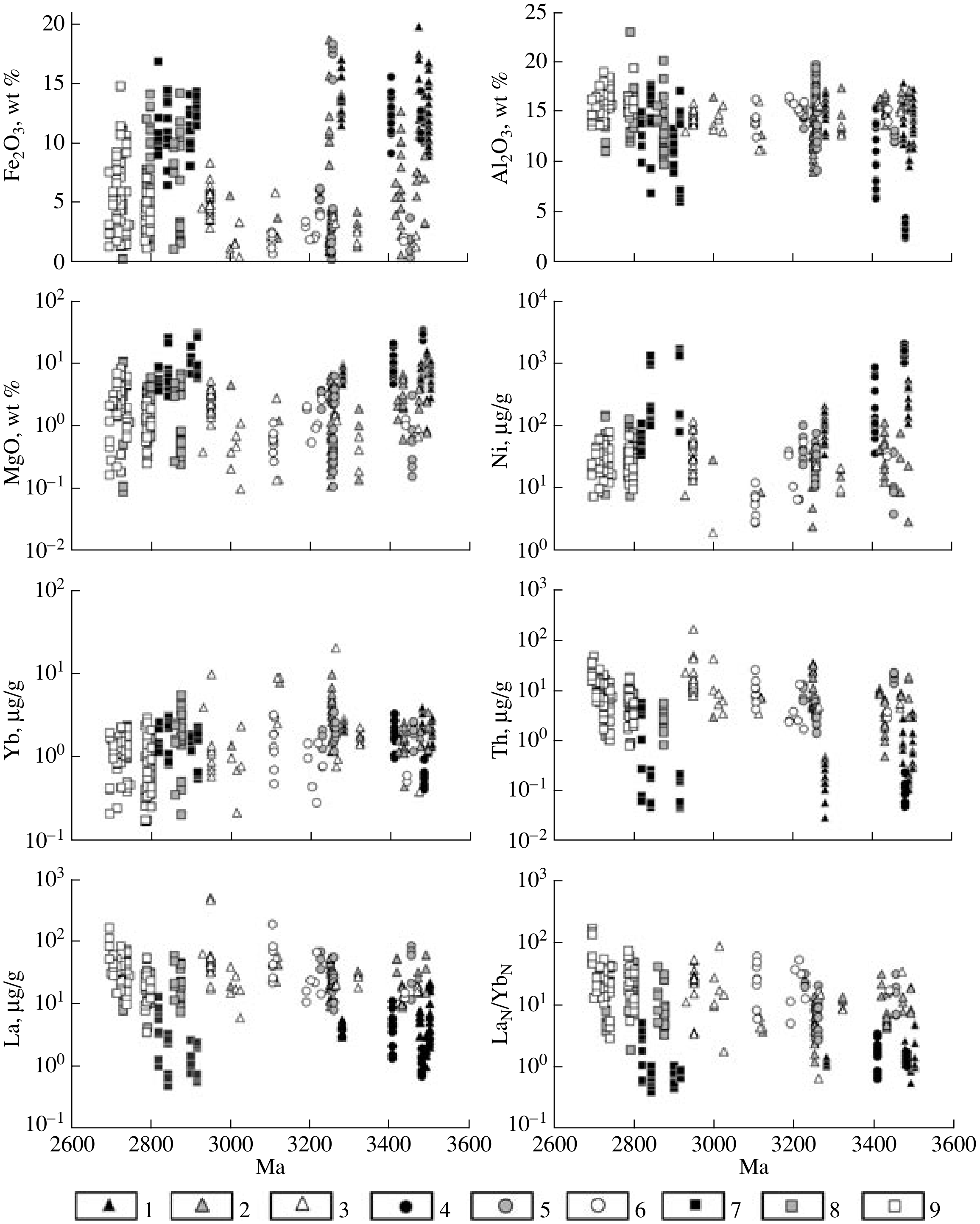

Fig. 5. Secular changes of major and trace element concentrations in igneous rocks of the Pilbara, Kaapvaal, and Karelian granite-greenstone terrains (GGT): (1) tholeiitic, (2) calc-alkaline volcanics and (3) granitoids of the Pilbara GGT; (4) tholeiitic, (5) calc-alkaline volcanics and (6) granitoids of the Kaapvaal GGT; (7) tholeiitic, (8) calc-alkaline volcanics and (9) granitoids of the Karelian GGT;

the subduction-related LREE addition to depleted mantle source of magmas rather than by the crustal contamination (Parman et al., 2003). By transition from magnesian volcanics of the Barberton belt to younger (3406 Ma) komatiites and tholeiitic basalts of the Nondweni belt, we observe lowering MgO, Cr and Ni concentrations, increasing abundance of many lithophile elements, and a higher extent of relative enrichment in LREE (Fig. 5) that is explained by crustal contamination of juvenile magmas (Riganti and Wilson, 1995).

Thus, one of the factors, which controlled secular variations in geochemical characteristics of Paleoarchean tholeiitic volcanic rocks, was crustal contamination of mantle melts that became relatively enriched in lithophile elements. In the Pilbara craton, influence of this factor is recorded in older tholeiitic volcanics of the eastern zone (Coonterunah and Warrawoona groups), whereas younger tholeiitic basalts of the West Pilbara (Roebourne Group) are lacking indications of this influence. In contrast, contamination of tholeiitic magmas by crustal material increases in the East Domain of Kaapvaal craton by transition from older volcanics of the Komati Formation of the Barberton belt to younger volcanic rocks of the Magongolozi Formation of the Nondweni belt. Besides the crustal contamination that influenced geochemistry of tholeiitic magmas, the decreasing degree of melting in response to successive cooling of mantle under cratons could be responsible for the general depletion of tholeiitic associations with time in the characteristic "mantle" components, such as MgO, Cr, Ni and Co.

Volcanics of calc-alkaline association from the East Pilbara greenstone belts represent different horizons of the Warrawoona (3490–3320 Ma) and Sulfur Spring (3250 Ma) groups. They reveal the following trends of changes in their geochemical characteristics with time: successively increasing concentrations of Y, Yb, Th, Nb, U, Ba and SiO_2; decreasing contents of Al_2O_3, Cr, V, Sr, Ti and lowering La/Yb and Sr/Y ratios; relatively constant concentrations of La, Ni, Mg, Fe and some other elements. Despite the less representative amount of geochemical data for rocks of the Kaapvaal craton, it is evident (Fig. 5) that calc-alkaline volcanics from the Onverwacht (3453 Ma) and Fig Tree (3256–3259 Ma) groups repeat in general the secular geochemical trends characterizing this rock association in the Pilbara craton. Two interrelated factors could be controlling geochemical trends of calc-alkaline volcanics under consideration. First, it could be the decreasing depth of silicic magma generation and associated lower proportion of garnet but higher proportion of plagioclase in restite (cumulative) mineral associations at the corresponding levels. Second, abundance of silicic crustal material could be getting higher in magma sources. According to tectonic reconstructions (Vearncombe and Kerrich, 1999), the observable geochemical trends could be caused by changes in the thermal state of mantle and, consequently, by the modified geometry of Archean subduction zones with interrelated adjustment of petrogenetic processes. If these assumptions are correct, then the early silicic volcanics of the Warrawoona Group can be regarded as eruption products of magmas, which originated by melting of metabasites of subducting oceanic crust, whereas younger silicic volcanics of the Sulfur Spring Group can be interpreted as differentiates of magmas generated in a mantle wedge above subduction zone.

Granitoids of the Kaapvaal and Pilbara cratons originated from 3.47 to 2.95 Ga demonstrate systematic changes in concentrations of many elements by transition from the early syntectonic TTG granitoids to the late and post-tectonic calc-alkaline intrusive rocks. In general, "mantle" chalcophile and siderophile elements (Fe_2O_3, MgO, Cr, Ni, V, Sc, Cu) tend to decline in abundance, when concentrations of crustal lithophile elements, HFSE and LREE (Ba, Sr, U, Pb, Nb, Th, La, etc.) increase in granitoids ranging in age from 3.47 to 3.00 Ga. This tendency reflects, as we believe, the successive geochemical differentiation of evolving continental crust. The maximum enrichment in "crustal" elements and simultaneous step-wise growth of concentrations of "mantle" elements are established in granitoids of sanukitoid series of the Pilbara craton, which are ca. 2.95 Ga old (Smithies and Champion, 2000). This is likely a result of magma generation in the enriched lithospheric mantle with subsequent crustal contamination of derived sanukitoid magmas.

CONCLUSIONS

Geochemical trends similar in general are characteristic of the Paleoarchean to Neoarchean evolution of magmatism in the considered GGTs. At the early magmatic stages in heterochronous GGTs, volcanics of tholeiitic associations, the products of magma generation at various levels of asthenospheric and lithospheric mantle, transported up to the crust simatic material enriched in chalcophile and siderophile elements Fe_2O_3, MgO, Cr, Ni, Co, V, Cu, and Zn. The next stage of magmatism corresponded to eruption of calc-alkaline volcanics and to emplacement of syntectonic TTG granitoids. This stage was interrelated with partial melting of tholeiitic metavolcanics either in lower horizons of thickened mafic crust of the oceanic plateau type (Hoffman and Ranalli, 1988; de Wit, 1998; Zegers and van Keken, 2001), or by subduction of oceanic crust (Martin, 1999; Kusky and Polat, 1999; Samsonov et al., 2005). This led to the crust enrichment in lithophile elements (Rb, Cs, Ba, Th, U, Pb, Nb, La, Sr, Be, etc.). Terminal stages of the crust formation in all GGTs were marked by emplacement of granitoid intrusions with elevated concentrations of crustal and "mantle" components (MgO, Al_2O_3, Ba, Cr, Ni, Co, V, Mo, W, Zn, Cu, Th, U, Pb, La, Sc, Sr). At this stage, silicic rocks of earlier stages and lithospheric mantle that experienced metasomatic alterations during past subduction episodes were jointly involved in processes of magma generation. The outlined geochemical trends characterize complete cycle of the GGT evolution with resultant formation of Archean juvenile crust. The GGT development with corresponding geochemical cycles of crust formation was characteristic of the terminal Paleoarchean, Mesoarchean, and Neoarchean.

Besides these general trends of geochemical evolution, magmatism of GGTs different in age had some specific aspects. First, cycle of geochemical evolution was much longer in the Paleo- to Mesoarchean GGTs than in the Meso- to Neoarchean GGTs. Second, being similar in composition and geological position magmatic rocks of the GGTs differing in age show geochemical distinctions.

Volcanics of tholeiitic association from the Paleoarchean Kaapvaal and Pilbara cratons, being compared with Neoarchean analogs from the Karelian GGT, which have close Mg, Cr and Ni concentrations, reveal wider variation ranges and higher concentrations of elements incompatible with mantle restites, such as Fe, V, Cu, Zn, Ti, La, Yb, Nb, U, Th and other LILE, HFSE, and REE (Fig. 5). These distinctions in geochemistry of heterochronous tholeiitic volcanics could be explained by a more significant contribution of sialic material to mantle-derived Paleoarchean magmas as compared to those of the Neoarchean time. However, this explanation seems paradoxical and improbable, because continental crust progressively grew throughout the Archean Eon, and crustal influence on composition of mantle-derived melts should be greater in the Neoarchean than in the Paleoarchean. The more plausible explanation is that secular changes in geochemistry of Archean tholeiitic magmas reflect general geochemical evolution of mantle reservoirs they were derived from, since successive events of partial melting led to depletion of mantle material in incompatible elements, which accumulated in upper shells of the Earth, i.e., in the crust and lithospheric mantle.

Calc-alkaline volcanics and granitoids of Paleoarchean GGT show higher Y and Yb concentrations and less fractionated REE spectra ($La_N/Yb_N < 10$) than the same rock associations of the Neoarchean time (Fig. 5). These geochemical parameters are controlled in magmatic systems primarily by garnet (Rollinson, 1993), and consequently, by pressure at the levels of generation and/or differentiation of magmatic melts (Rapp et al., 1991; Rapp and Watson, 1995), and their decrease with time suggests the increasing depth of calc-alkaline magma generation during the Archean. This could be interrelated with changes in geometry of subduction zones, e.g., with the oceanic plates subduction under steeper angles, because their thickness and temperature decreased in response to the Earth cooling (Martin, 1999; Martin and Moyen, 2003). It should be noted also that many researchers consider the Late Mesoarchean and Neoarchean calc-alkaline volcanics and TTG granitoids younger than 3.0 Ga as related in origin to convergent plate boundaries (de Wit, 1998; Kusky and Polat, 1999; Shchipansky et al., 1999, 2001: Polat and Kerrich, 1999, 2001, 2002). In contrast, origin of the same Paleoarchean rocks is interpreted either in terms of partial melting of greatly thickened crust of oceanic plateaus, which are thought to be formed either above large mantle plumes (Shchipansky and Podladchikov, 1991; Samsonov and Bogatikov, 1999; Zegers and van Keken, 2001), or by tectonic imbrication of gently dipping oceanic plates (Hoffman and Rinalli, 1988). An additional argument in favor of tectonic factors, which could control development of calc-alkaline volcanism and emplacement of TTG granitoids, when mechanism of plate tectonics was triggered in the Late Mesoarchean, is appearance at that time (about 2.95 Ga ago) of sanukitoid magmatic rocks, the derivates of magmas, which originated in lithospheric mantle greatly altered by subduction-related metasomatic processes.

ACKNOWLEDGMENTS

M.A. Semikhatov stimulated this work aimed at understanding of geochemical factors in evolution of the early biosphere on the Earth. His comments to our results and conclusions and constructive remarks of V.A. Glebovitskii were used to improve the final version of manuscript. The work was supported by the priority programs nos. 25 and 5 of Presidium and Earth-science Division of Russian Academy of Sciences, and by the Russian Foundation for Basic Research, project no. 04-05-64628.

Reviewers V.A. Glebovitskii and M.A. Semikhatov

REFERENCES

1. N. T. Arndt, D. R. Nelson, W. Compston, et al., "The Age of the Fortescue Group, Hamersley Basin, Western Australia, from Ion Microprobe Zircon U–Pb results," Australian J. Earth Sci. **38**, 261–281 (1991).
2. M. E. Barley, "The Pilbara Craton," in *Greenstone Belts,* Ed. by de Wit, M.J. and Ashwal, L. (Clarendon, Oxford, 1997) 657–664.
3. M. E. Barley, S. E. Loader, and N. J. McNaughton, "3430 to 3417 Ma Calc-Alkaline Volcanism in the McPhee Dome and Kelly Belt, and Growth of the Eastern Pilbara Craton," Precambrian Res. **88**, 3–23 (1998).
4. M.E. Barley and A. L. Pickard, "An Extensive, Crustally-Derived, 3325 to 3310 Ma Silicic Volcanoplutonic Suite in the Eastern Pilbara Craton: Evidence from the Kelly Belt, McPhee Dome and Corunna Downs Batholith," Precambrian Res. **96**, 41–62 (1999).
5. E. V. Bibikova and A. I. Slabunov, "U-Pb Geochronology and Major-Element Chemistry of a Diorite-Plagiogranitic Batholith in Northern Karelia," Geokhimiya, No. 11, 1154–1160 (1997) [Geochem. Int. **35**, 1021–1028 (1997)].
6. E. V. Bibikova, A. V. Samsonov, A.Yu. Petrova, and T. I. Kirnozova, "The Archean Geochronology of Western Karelia," Stratigr. Geol. Korrelyatsiya, No. 5, 3–20 (2005) [Stratigr. Geol. Correlation **13**, 459–475 (2005)].
7. E. V. Bibikova, A. V. Samsonov, A. A. Shchipansky, et al., "The Hizovaara Structure in the Northern Karelian Greenstone Belt as a Late Archean Accreted Island Arc: Isotopic Geochronological and Petrological Evidence," Petrologiya **11** (3), 289–320 (2003) [Petrology **11**, 261–290].
8. E. V. Bibikova, A. I. Slabunov, S. V. Bogdanova, et al., "Early Precambrian Tectono-Thermal Evolution of the Earth Crust in the Karelian and Belomorian Provinces of

the Baltic Shield: U-Pb Isotopic Evidence from Sphene and Rutile," Geokhimiya, No. 8, 842–857 (1999a) [Geochem. Int. **37**, 750–764 (1999a)].

9. E. V. Bibikova, A. I. Slabunov, S. V. Bogdanova, et al., "Early Magmatism of the Belomorian Mobile Belt, Baltic Shield: Lateral Zoning and Isotopic Age," Petrologiya **7** (2), 115–140 (1999) [Petrology **7** (2), 123–146 (1999)].
10. M. J. Bickle, L. F. Betteney, M. E. Barley, et al., "A 3500 Ma Plutonic and Volcanic Calc-Alkaline Province in the East Pilbara Block," Contrib. Mineral. Petrol. **84**, 25–35 (1983).
11. G. Brandl and M. J. de Wit, "The Kaapvaal Craton," in *Greenstone Belts*, Ed. by de Wit, M. J. and Ashwal, L. (Clarendon, Oxford, 1997), pp. 581–607.
12. V. P. Chekulaev, "Archean 'Sanukitoids' on the Baltic Shield," Dokl. Akad. Nauk **368** (5), 230–235 (1999) [Dokl. Earth Sci. **369** (8), 1137–1139 (1999)].
13. V. P. Chekulaev, O. A. Levchenkov, S. B. Lobach-Zhuchenko, et al., "New Determinations of Age Limits for Archean Complexes in Karelia," in *General Problems and Principles of Subdividing the Precambrian*, Ed. by Glebovitskii, V.A and Shemyakin, V.M (Nauka, St. Petersburg, 1994), pp. 69–86 [in Russian].
14. V. P. Chekulaev, S. B. Lobach-Zhuchenko, and L. K. Levskii, "Archean Granites in Karelia as Indicators of the Composition and Age of the Local Continental Crust," Geokhimiya, No. 8, 805–816 (1997) [Geochem. Int. **35**, 704–715 (1997)].
15. M. A. Fedonkin, "Geochemical Impoverishment and Eukaryotization of the Biosphere: A Causal Link," Paleontol. Zh., No. 6, 33–40 (2003) [Paleontol. J. **37** (6), 592–599 (2003)].
16. M. A. Fedonkin, "Declining Availability of Metals by Eukaryotization of Precambrian Biosphere," in *Current Problems of Geology* (Nauka, Moscow, 2004), pp. 426–447 [in Russian].
17. F. M. Gradstein, J. G. Ogg, A. G. Smith, et al., "A New Geological Time Scale, with Special Reference to Precambrian and Neogene," Episodes **27** (2), 83–100 (2004).
18. M. G. Green, P. J. Sylvester, and R. Buick, "Growth and Recycling of Early Archaean Continental Crust: Geochemical Evidence from the Coonterunah and Warrawoona Groups, Pilbara Craton, Australia," J. South Am. Earth Sci. **322**, 69–88 (2000).
19. P.F. Hoffman and G. Rinalli, "Archean Oceanic Flake Tectonics," Geophys. Res. Lett. **15**, 1077–1080 (1988).
20. D. R. Hunter, F. Barker, and H. T. Millard, "The Geochemical Nature of the Ancient Gneiss Complex and Granodiorite Suite, Swaziland: a Preliminary Study," Precambrian Res. **7**, 105–127 (1978).
21. B-M. Jahn, A. Y. Glikson, J. J. Peucat, et al., "REE Geochemistry and Isotopic Data of Archean Volcanics and Granitoids from the Pilbara Block, Western Australia: Implications for the Early Crustal Evolution," Geochim. Cosmochim. Acta **45**, 1633–1652 (1981).
22. Y. Kato and K. Nakamura, "Origin and Global Tectonic Significance of Early Archean Cherts from the Marble Bar Greenstone Belt, Pilbara Craton, Western Australia," Precambrian Res. **125**, 191–243 (2003).
23. I. C. Kleinhanns, J. D. Kramers, and B. S. Kamber, "Importance of Water for Archaean Granitoid Petrology: a Comparative Study of TTG and Potassic Granitoids from Barberton Mountain Land, South Africa," Contrib. Mineral. Petrol. **145**, 377–389 (2003).
24. A. Kloppenburg, S. H. White, and T. E. Zegers, "Structural Evolution of the Warrawoona Greenstone Belt and Adjoining Granitoid Complexes, Pilbara Craton, Australia: Implications for Archaean Tectonic Processes," Precambrian Res. **112**, 107-147 (2001).
25. E. A. Kohler and C. R. Anhaeusser, "Geology and Geodynamic Setting of Archaean Silicic Metavolcanic Rocks of the Bien Venue Formation, Fig Tree Group, Northeast Barberton Greenstone Belt, South Africa," Precambrian Res. **116**, 199–235 (2002).
26. A. Kovalenko, J. D. Clemens, and V. Savatenkov, "Petrogenetic Constraints for the Genesis of Archaean Sanukitoid Suites: Geochemistry and Isotopic Evidence from Karelia, Baltic Shield," Lithos. **79**, 147–160 (2005).
27. A. Kroner and A. Tegtmeyer, "Gneiss-Greenstone Relationships in the Ancient Gneiss Complex of Southwestern Swaziland, Southern Africa, and Implications for Early Crustal Evolution," Precambrian Res. **67**, 109–139 (1994).
28. T. M. Kusky. and A. Polat, "Growth of Granite-Greenstone Terranes at Convergent Margins, and Stabilization of Archean Cratons," Tectonophysics **305**, 43–73 (1999).
29. O. A. Levchenkov, S. B. Lobach-Zhuchenko, and S. A. Sergeev, "Geochronology of Karelian Granite-Greenstone Terrain," *Isotopic Geochronology of the Precambrian*, Ed. by Levskii, L. K. and Levchenkov, O. A. (Nauka, Leningrad, 1989), pp. 63–72 [in Russian].
30. S. B. Lobach-Zhuchenko, V. P. Chekulaev, V. V. Ivanikov, et al., "Late Archean High-Mg and Subalkaline Granitoids and Lamprophyres as Indicators of Gold Mineralization in Karelia (Baltic Shield), Russia," in *Ore-Bearing Granites of Russia and Adjacent Countries*, Ed. by A. Kremenetsky, B. Lehmann, and R. Seltmann, (IMGRE, Moscow, 2000), pp. 193–211.
31. S. B. Lobach-Zhuchenko, V. P. Chekulaev, and I. N. Krylov, "Lamprophyres of Western Karelia," Dokl. Akad. Nauk **370** (3), 357–359 (2000) [Dokl. Earth. Sci. **370** (1), 43–45 (2000)].
32. H. Martin, "Adakitic Magmas: Modern Analogues of Archaean granitoids," Lithos. **46**, 411-429 (1999).
33. H. Martin and J.-F. Moyen, "Secular Changes in TTG Composition: Comparison with Modern Adakites," Geophys. Res. Abstracts **5** (02673) (2003).
34. M. V. Mints, "Archean Miniplate Tectonics," Geotektonika, No. 6, 2–22 (1998) [Geotectonics **32** (6), 427–443].
35. H. Ohta, S. Maruyama, E. Takahashi, et al., "Field Occurrence, Geochemistry and Petrogenesis of the Archean Mid-Oceanic Ridge Basalts (AMORBs) of the Cleaverville Area, Pilbara Craton, Western Australia," Lithos **37**, 199–221 (1996).
36. S. W. Parman, J. C. Dann, T. L. Grove, et al., "Emplacement Conditions of Komatiite Magmas from the 3.49 Ga

Komati Formation, Barberton Greenstone Belt, South Africa," Earth Planet. Sci. Lett. **150**, 303–323 (1997).

37. S. W. Parman, N. Shimizu, T. L. Grove, et al., "Constraints on the Pre-Metamorphic Trace Element Composition of Barberton Komatiites from Ion Probe Analyses of Preserved Clinopyroxene," Contrib. Mineral. Petrol. **144**, 383–396 (2003).
38. A. Polat and R. Kerrich, "Formation of an Archean Tectonic Melange in the Schreiber-Helmo Greenstone Belt, Superior Province, Canada: Implications for Archean Subduction-Accretion Process," Tectonics **18**, 733–755 (1999).
39. A. Polat and R. Kerrich, "Magnesian Andesites, Nb-Enriched Basalt-Andesites, and Adakites from Late Archean 2.7 Ga Wawa Greenstone Belts, Superior Province, Canada: Implications for Late Archean Subduction Zone Petrogenetic Processes," Contrib. Mineral. Petrol. **141**, 36–52 (2001).
40. A. Polat and R. Kerrich, "Nd-Isotope Systematics of ~2.7 Ga Adakites, Magnesian Andesites, and Arc Basalts, Superior Province: Evidence for Shallow Crustal Recycling at Archean Subduction Zones," Earth Planet. Sci. Lett. **202**, 345–360 (2002).
41. H. N. Pollack, "Thermal Characteristics of the Archaean," in *Greenstone belts*, Ed. by M. J. de Wit and L. Ashwal (Clarendon, Oxford, 1997), pp. 223–232.
42. M. Poujol, J. Robb, C. R. Anhaeusser, et al., "A Review of the Geochronological Constraints on the Evolution of the Kaapvaal Craton, South Africa," Precambrian Res. **127**, 181–213 (2003).
43. I. S. Puchtel, A. W. Hofmann, K. Mezger, et al., "Oceanic Plateau Model for Continental Crustal Growth in the Archaean: A Case Study from the Kostomuksha Greenstone Belt, NW Baltic Shield," Earth Planet. Sci. Lett. **155**, 57–74 (1998).
44. I. S. Puchtel, A. W. Hofmann, Yu. V. Amelin, et al., "Combined Mantle Plume - Island Arc Model for the Formation of the 2.9 Ga Sumozero-Kenozero Greenstone Belt, SE Baltic Shield: Isotope and Trace Element Constraints," Geochim. Cosmochim. Acta **63** (21), 3579–3595 (1999).
45. R. P. Rapp and E.B. Watson, "Dehydration Melting of Metabasalt at 8-32 kbars: Implications for Continental Growth and Crust-Mantle Recycling," J. Petrology **36**, 891-931 (1995).
46. R. P. Rapp, E. B. Watson, and C. F. Miller, "Partial Melting of Amphibolite/Eclogite and the Origin of Archean Trondhjemites and Tonalities," Precambrian Res. **51**, 1–25 (1991).
47. A. Riganti and A. H. Wilson, "Geochemistry of the Mafic/Ultramafic Volcanic Associations of the Nondweni Greenstone Belt, South Africa, and Constraints on Their Petrogenesis," Lithos **34**, 235–252 (1995).
48. H. Rollinson, *Using Geochemical Data: Evaluation, Presentation, Interpretation* (Longman, London, 1993).
49. A. V. Samsonov, I. S. Puchtel, A.A. Shchipansky, et al., "Isotope-Geochemical Variations between Felsic Volcanic Rocks from Karelian Greenstone Belts and Some Tectonic Implications," in *Proceedings of the 9 European Union of Geosciences Conference, France, 1997*, p. 363.
50. A. V. Samsonov and O. A. Bogatikov, "Petrogenesis and Tectonic Setting of Formation of the Middle Dnieper Gneiss-Greenstone Terrain, the Ukrainian Shield," in *Problems of Geology and Petrology*, Ed. by O. Z. Dudauri (GIN AN Gruzii, Tbilisi, 1999), pp. 26–46 [in Russian].
51. A. V. Samsonov, E. V. Bibikova, M. M. Bogina, et al., "The Relationship Between Adakitic and Calc-Alkaline Volcanic Rocks and TTGs in the Karelian Greenstone Belts," Lithos **79**, 83–106 (2005).
52. A. V. Samsonov, E. V. Bibikova, Yu. O. Larionova, et al., "Magnesian Granitoids (Sanukitoids) of the Kostomuksha Area, Western Karelia: Petrology, Geochronology, and Tectonic Environment of Formation," Petrologiya **12** (5), 495–529 (2004) [Petrology **12** (5), 437–468 (2004)].
53. A. V. Samsonov, R. G. Berzin, N. G. Zamozhnyaya, et al., "Formation of Early Precambrian Crust in NW Karelia, Baltic Shield. Results of Geologic and Petrologic Study and of Deep Seismic Sounding (Profile 4B)," in *Deep Structure of the Earth Crust along Profile 4B Kem'-Kalevala*, Ed. by R. G. Berzin, A. K. Suleimanov, and N. Zamozhnyaya (Karel. NTs RAN, Petrozavodsk, 2001), pp. 109–143 [in Russian].
54. A. A. Shchipansky and Yu. Yu. Podladchikov, "Clustering Batholiths as Indicators of the Early Archean Thick Crust of the Oceanic Type," Dokl. Akad. Nauk SSSR **320** (5), 1212–1216 (1991).
55. A. A. Shchipansky, I. I. Babarina, K. A. Krylov, et al., "The Oldest Ophiolites: The Late Archean Suprasubduction Zone Complex of the Iringora Structure, North Karelian Greenstone Belt," Dokl. Akad. Nauk **377** (3), 376–380 (2001) [Dokl. Earth Sci. **377A** (3), 283–287 (2001)].
56. A. A. Shchipansky, A. V. Samsonov, E. V. Bibikova, et al., "2.8 Ga Boninite-Hosting partial Subduction Zone Ophiolite Sequences from the North Karelian Greenstone Belt, NE Baltic Shield, Russia," in *Precambrian Ophiolites and Related Rocks*, Ed. by T. M. Kusky (Elsevier, Amsterdam, 2004), pp. 424–486.
57. A. A. Shchipansky, A. V. Samsonov, M. M. Bogina, et al., "High-Mg, Low-Ti Quartz Amphibolites of the Khizovaara Greenstone Belt, Northern Karelia: Archean Metamorphosed Boninites?" Dokl. Akad. Nauk **365** (6), 817–820 (1999) [Dokl. Earth Sci. **365A** (3), 422–425 (1999)].
58. S. B. Shirey and G.N. Hanson, "Mantle-Derived Archaean Monzodiorites and Trachyandesites," Nature **310**, 222–224 (1984).
59. J. B. Smith, M. E. Barley, D. I. Groves, et al., "The Sholl Shear Zone, West Pilbara: Evidence for a Domain Boundary Structure from Integrated Tectonostratigraphic Analyses, SHRIMP U–Pb Dating and Geochemical Data of Granitoids," Precambrian Res. **88**, 143–171 (1998).
60. J. B. Smith, "The Episodic Development of Intermediate to Silicic Volcano-Plutonic Suites in the Archaean West Pilbara, Australia," Chem. Geol. **194**, 275–295 (2003).
61. R.H Smithies. and D.C. Champion, "The Archaean High-Mg Diorite Suite: Links to Tonalite-Trondhjemite-Granodiorite Magmatism and Implications for Early

Archaean Crustal Growth," J. Petrology **41**, 1653–1671 (2000).

62. S. A. Svetov and H. Huhma, "Geochemistry and Sm-Nd Systematics of the Archean Komatiitic-Tholeiitic Associations of the Vedlozero-Segozero Greenstone Belt, Central Karelia," Dokl. Akad. Nauk **369** (2), 261–263 (1999) [Dokl. Earth Sci. **369** (8), 1204–1206 (1999)].
63. Y. Tatsumi, "Origin of High-Magnesian Andesites in the Setouchi Volcanic Belt, Southwest Japan. II. Melting Experiments at High Pressure," Earth Planet. Sci. Lett. **60**, 305–317 (1982).
64. M. J. Van Kranendonk, A.H. Hickman, R. Smithies, et al., "Geology and Tectonic Evolution of the Archean North Pilbara Terrain, Pilbara Craton, Western Australia," Econ. Geology **97**, 695–732 (2002).
65. S. Vearncombe and R. Kerrich, "Geochemistry and Geodynamic Setting of Volcanic and Plutonic Rocks Associated with Early Archaean Volcanogenic Massive Sulphide Mineralization, Pilbara Craton," Precambrian Res. **98**, 243–270 (1999).
66. *Volcanism of Archean Greenstone Belts*, Ed. by V.A. Sokolov (Nauka, Leningrad, 1981) [in Russian].
67. T. E. Zegers and P. E. van Keken, "Middle Archean Continent Formation by Crustal Delamination," Geology **29**, 1083–1086 (2001).
68. M.J. de Wit, "On Archean Granites, Greenstones, Cratons and Tectonics: Does the Evidence Demand a Verdict?" Precambrian Res. **91**, 181–226 (1998).