Cycles of Alkaline Magmatism

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Abstract—Geochronological data (~1800 dates) have been analyzed by the probabilistic statistical analysis of samplings of different subalkaline and alkaline rocks through the whole of geological time. The distribution of five groups of subalkaline and alkaline rocks within the Late Archean–Phanerozoic are strictly controlled by mantle cycles, which were distinguished from data on the upper mantle magmatic rocks. Since high alkali rocks are plume related, their universal participation in each of the revealed mantle cycles emphasizes the importance of this magmatism in the evolution of the crustal–mantle system. The initial Sr and Nd isotope ratios are subdivided into two groups: with mantle and crustal signatures. Mantle isotope ratios are typically observed throughout the entire geological interval of dated rocks, while the role of crustal isotope signatures increases from the Archean to Phanerozoic, reflecting the increasing the role of fluids and crustal rocks in the magmatic processes during the generation of mantle magmas and their consolidation in the crust. Since alkaline magmatic sources are formed during mantle metasomatism, which enriched the magma generation zones in incompatible elements, the repeated occurrence of this process in separate mantle zones may have lead to the anomalous accumulation of these elements, which should be reflected in the alkaline magmas.

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INTRODUCTION

Alkaline magmatism holds a special place among diverse endogenous processes defining the growth rate of continental crust, since its evolution most distinctly reflects the interaction between almost all of the Earth's shells.

Modern concepts suggest that alkaline magma generation is controlled primarily by the energetics of the core and lower mantle. This influence should change with the general cooling of the Earth's interior, reflected in the directed compositional evolution of alkaline magmas (the details reaming unstudied) and changes in the intensity of their generation. The latter have already been proved during the systematics of alkaline rock abundances in the geological time scale [1], which convincingly demonstrated an increase in alkaline magmatic activity from the Late Archean to Phanerozoic. Moreover, it was found [2] that alkaline magmatism evolved discretely with peaks at 1300–1000, ~550, 400, 250, 200–180, and 40–0 Ma, suggesting its relation with the cyclic formation of supercontinents and the generation of alkaline magmas at different mantle levels. Other works on the evolution in the abundance of various deep-seated plume magmas [3–6, etc.] (large igneous provinces of flood basalts, giant diabase dike swarms, carbonatites, and kimberlites) also have emphasized the discontinuous character of mantle activation, which increased during the existence of supercontinents and decreased during their breakup. However, different classifications of mantle events are very approximate and do not reflect the real scales and dynamics of plume activation.

At the same time, alkaline magmatism provides a unique example of mantle magmatism whose evolution is distinctly affected by external factors, such as the formation of free oxygen in the atmosphere and the supply of subduction-related oxidized material in the upper mantle. The change in the mantle oxygen fugacity caused a strong enrichment of the metasomatized mantle in the incompatible element (formation of enriched mantle reservoirs) and triggered the origin of alkaline magmas [1, 2]. This interpretation of the initial accumulation of incompatible and volatile components in the mantle seemed to be unambiguous. However, only a few of many hundreds of subalkaline and alkaline massifs show anomalously high enrichment (up to ore contents) in these elements. Hence, an additional argumentation is required.

For this purpose, we consider the evolution of alkaline magmatism over the geological time, with special emphasis put on the cycling and possible subsequent evolution of their mantle sources, which is controlled by discrete plume events.

INTENSITY OF SUBALKALINE AND ALKALINE MAGMATISM

To apply the probabilistic statistic analysis to the evolution of alkaline magmatism over geological time, all types of alkaline rocks were grouped in natural rock associations of increasing alkalinity according to the petrochemical and petrological classification [7, 8].
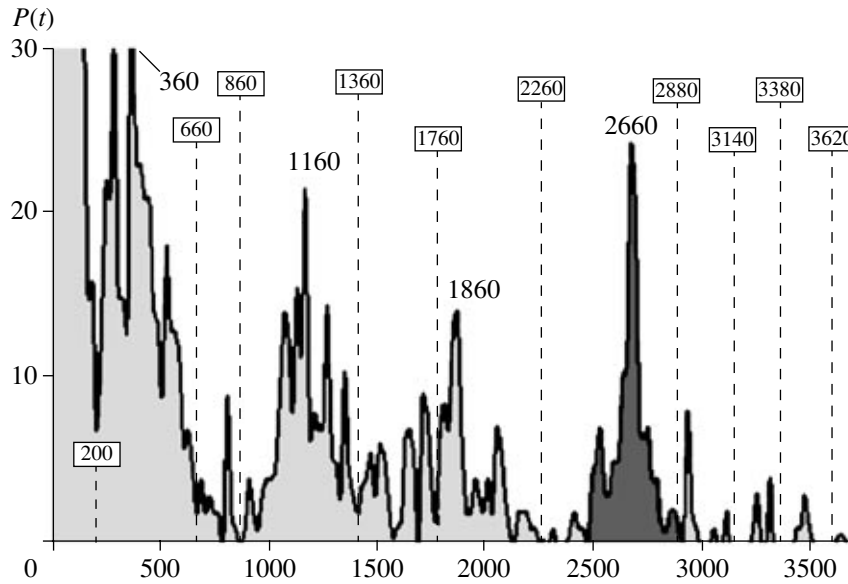
Fig. 1. Cycles of the total activation of subalkaline and alkaline magmatism, whose boundaries were constrained based on a sharp decrease in magmatic activity. Data were systematized using probabilistic statistics [6, 21], where $P(t) \approx N$ is the number of dates (averaging step is 20 Ma). Minima of mantle activation after [6, 21] are shown by dashed lines with the age in boxes.

Syenogranites, monzogranites, quartz syenites, monzonites and their volcanic counterparts (quartz trachytes and latites) compose the most primitive, subalkaline group, "granosyenite," which often forms an independent massifs (417 dates) in our database. Syenites, monzonites, and their foid-bearing analogues and volcanics were ascribed to the second subalkaline ("syenite") group, which forms derivatives in gabbrodiorite massifs, individual intrusions and volcanic edifices (246 dates). Foid-syenites, foid-monzonites, foidolites, and their volcanogenic analogues, as well as their melanocratic intrusive and volcanic varieties, lamprophyres and carbonatites, were combined into a group of Na-alkaline ("foidolite") rocks (840 dates). A separate group of alkaline rocks ("alkali granite") includes alkali granites, granosyenites, and their volcanogenic analogues (comendites, pantellerites), which occur as individual massifs approximating compositionally A-type granites or form derivatives of gabbroanorthosites, central-type foidolite intrusions, or ocean island alkali basalts (103 dates). Kimberlites, lamproites, and leucitic volcanic rocks were combined into a group of high-K rocks with $K_2O > Na_2O$ (233 dates).

Alkaline magmatism is typical of hot-spot oceanic islands and seamounts [1, 9–11, etc.], deep-seated faults in continental collisional zones, junction zone of ancient blocks of different age, continental rifts [1, 12–14, etc.], giant flood basalt provinces, and in the final stages of island-arc basaltic magmatism [15, 16, etc.]. Alkaline magmatism is generated at different mantle depths from the asthenosphere to the lower mantle–core boundary. There is, however, only rare evidence for their middle- and lower-mantle origin: isotope–geochemical anomalies (high $^3He/^4He$, $^{186}Os/^{188}Os$,

$^{187}Os/^{188}Os$ ratios; elevated $^{87}Sr/^{86}Sr$, and low $^{143}Nd/^{144}Nd$ as compared to those of oceanic basalts), which are supposedly typical of the lower mantle or outer core [10, 11, 16–18, etc.]; relict mantle textures in ancient kimberlite phenocrysts [19, 20, etc.]; the existence of a slow S-wave velocity anomaly at a depth of 500 km below the hot spot surface, which is traced based on tomographic evidence and on the presence of elongated chains or ridges of alkaline volcanoes [10]. Among the subalkaline series, only the syenite group exhibits distinct evidence for mantle genesis, whereas the granosyenite group typically exhibits only fluid mantle influences. However, the total distribution of subalkaline and alkaline (SALK) rocks (more than 1800 dates) shows distinct cyclicity (Fig. 1), whose boundaries were marked by episodes of minimum mantle activation. The ages of these episodes coincide with the boundaries of mantle cycles, which were determined from changes in the upper mantle endogenous events [21]. Similar cycling is traced individually for subalkaline and alkaline series (Fig. 2). This indicates that SALK magmatism is an inherent component of the cyclical activation of the upper mantle within at least 0–3.5 Ga. Since alkaline magmatism is considered to be the deepest seated mantle magmatism, its evolution reflects the pulsed introduction of energy and material from different mantle levels [22]. Based on the total statistics on the subalkaline and alkaline series, we distinguished several maximum ("megacyclical") peaks (2660, 1860, 1160 for the Precambrian and, in more details, for the Phanerozoic: 520, 360, 280, 120, 80, and 0–10 Ma), which are traced with insignificant variations individually for each SALK series (Fig. 2). This information is consistent, within ±20 Ma, with previous
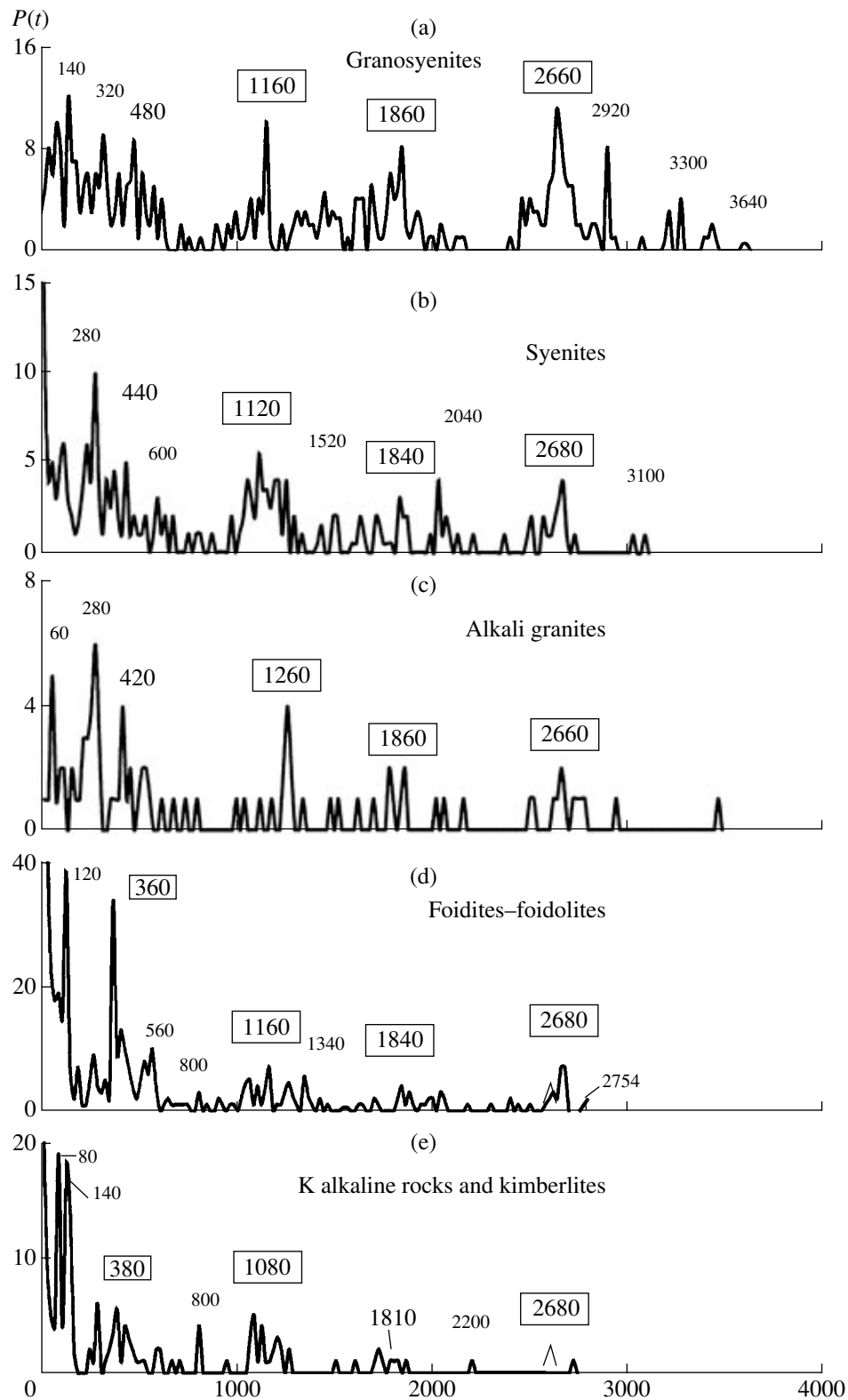
Fig. 2. Detailed evolution of subalkaline and alkaline magmatism for different rock associations. Consistent ages of the maximum plume peaks in the evolution of each series are shown in boxes. Averaging step is 20 Ma.

generalized estimates for intervals and peaks of alkaline magmatism [2]. Moreover, as is seen from Figs. 1 and 2, all the series with the exception of the "granosyenite" subalkaline one, show increasing intensity from the Archean to Phanerozoic. This conclusion is consistent with those in [1, 2, and others]. It should be added that only the trend in the intensity of alkaline magmatism is presumably related to an increase in the lithospheric thickness during the Earth's cooling and, as a result, a displacement of magma generation areas to deeper seated upper mantle levels and the formation of plume-related magmatic chambers in the middle and lower mantle. Such a trend is observed, for example for the deepest seated kimberlite diamondiferous melts, which typically entrap diverse mantle peridotite xenoliths and xenocrysts. In particular [19, 20, 23], peridotite xenoliths from the Premier pipe, South Africa, have an age of 1202 ± 72 Ma [24] and were formed at 58 kbar (about 185 km), those from the Udachnaya pipe, Yakutia, have an age of 360 ± 10 Ma [25] and were generated at 80 kbar (about 250 km), while baddeleyite xenocryst from the Mbuji–Mayi kimberlite, South Africa, has an age of 70 Ma [19, 20] and bares evidence of its lower-mantle origin. The second factor is the subsequent introduction of oxidized crustal products, together with volatiles, into the mantle during polycyclic subduction events, which continued in the Late Archean, Proterozoic, and Phanerozoic. This defines the significant expansion of the network of incompatible element-enriched mantle zones [1] and an increase in the mantle geochemical heterogeneity, which is expressed by an increase in alkaline magmatic activity toward the Phanerozoic.

The time of the first appearance of different SALK series is different (Fig. 2). The oldest rocks are represented by scarce findings of primitive subalkaline rocks (quartz monzonites and monzogranites) in Western Australia (Pilbara block, 3200–3630 Ma) [26]. Alkaline granites first appeared at 3466 ± 2 Ma, with scarce Late Archean dates at 2946 ± 6 and 2762 ± 4 Ma. However, late alterations superimposed on some varieties of these rocks [26] complicate an accurate diagnostics of the oldest "alkaline" granites. Other series began to form in the Late Archean. The second subalkaline group is represented in this case by the oldest varieties: syenites of Barberton (3105 ± 10 Ma) [27] and trachyte tuffs (3048 ± 19 Ma) in the Pilbara block [26]. Na and K alkali series first appeared at ~2700 Ma. Ultrapotassic rocks (pyroxenites, syenites, and shoshonites) of the Ukduska Massif, Aldan Shield, have a similar age (2719 ± 14 Ma) [28]. Kimberlites and lamproites formed much later. The oldest kimberlites (≈ 2200 Ma) and lamproites (1815 ± 14 Ma) were dated in Australia [29, 30].

The review of all the data indicates that the first significant ("megacyclical") magmatic peak occurred at 2680–2660 Ma (Fig. 1), as has already been mentioned in [22 e.a.]. This peak generated numerous stocks and intrusions of monzodiorites, monzonites, syenites,
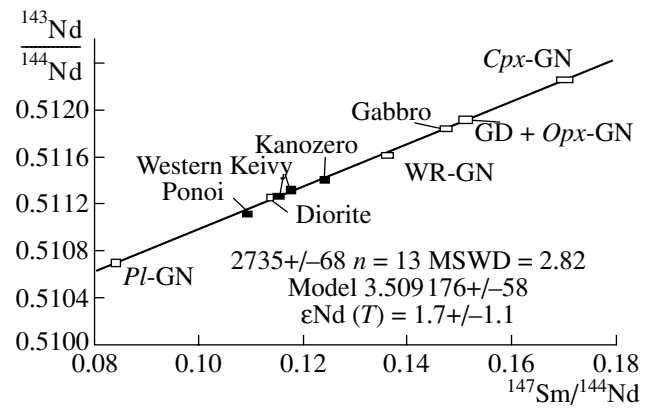

Fig. 3. Sm–Nd isochron on alkali granites (black boxes) and gabbro and gabbronorites xenoliths (white boxes) found in alkali granites.

nepheline syenites, carbonatites, lamprophyre dikes, as well as trachyte and leucite volcanic rocks. These rocks are mainly confined to the southern part of the Canadian Shield (Ontario–Quebec), southern Greenland, and Western Australia [12, 13, 31, and others]. Within the Baltic Shield, SALK massifs coeval to Canadian and rocks of Greenland were found in the central and eastern parts of the Kola peninsula: quartz monzodiorites of Pyatnjarv with ages from 2715 ± 8 to 2650 ± 15 Ma [32], monzonite–latites from the Mariiok River with an age of 2657 ± 8.4 Ma [32], monzonites of the Tsaga anorthosite massif with an age of 2662 ± 10 Ma [33], alkaline syenites from the Sakhariiok Massif with an age of 2682 ± 10 Ma [34], and lamprophyres of the Porosozero Massif with an age of 2680 ± 10 Ma [35]. The most sensational data were obtained on the giant alkali granite and granosyenite province in the Keivy domain of the central Kola block. These rocks were formed from 2674 ± 6 to 2654 ± 5 Ma [34] and crop out over an area of 2500 km^2 (at an average thickness of 500–700 m), which approximately corresponds to the total volume of the coeval SALK series in other regions. The question arises as to whether the alkali granites of the Kola Peninsula and SALK rocks of other regions were generated by plume activity. In the Canadian Shield, subalkaline and alkaline massifs and volcanic rocks (>27 of them are dated) are mainly confined to the wide Ontario–Quebec boundary zone and are considered to be related to collision (2690–2660 Ma), which terminated the evolution of 2740–2710-Ma-old greenstone belts southwest of the Abitibi subprovince [12]. Thus, alkaline rocks of this region demonstrate a significant shift towards younger ages, suggesting their relation with the activation of underlying asthenosphere in the Abitibi collisional zone [36]. Syenites, carbonatites, monzonites, and foidolites of the Skjoldungen large alkaline igneous province in southeastern Greenland are dated within a narrow range of 2698–2664 Ma and can also be regarded as derivatives of common plume magmatism. What is the origin of the Kola alkali
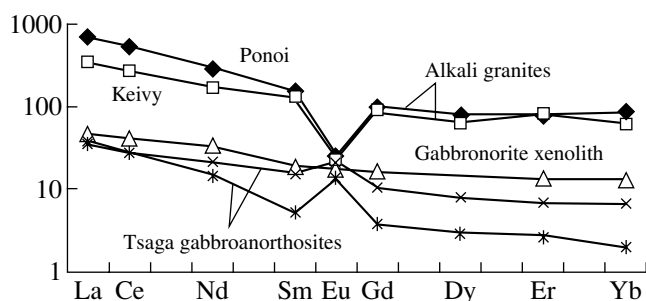
Fig. 4. Complementary REE distribution patterns for early gabbro anorthosites and late alkali granites relative to the average REE content in gabbronorite. The REE distribution patterns in the Ponoi granite and gabbronorite are taken from [37], those in Keivy, from [39], and those in gabbronorites were determined by isotope dissolution in the Geological Institute of Kola Scientific Center, analyst I.V. Sharkov.

granites? First, granites contain gabbro and gabbronorite xenoliths (Ponoi Massif) having a similar age of 2740 ± 59 Ma [37]. The data points of these xenoliths, and the least altered alkali granites [37, 38], define a Sm–Nd isochron with an age of 2735 ± 68 Ma (Fig. 3), which approximates, within the accuracy, the most accurate U–Pb data on the formation time of alkali granites (2674–2654 Ma). The positive initial $\varepsilon Nd(T) = +1.7 \pm 1.1$ suggests the derivation of the gabbro xenoliths and alkali granites from a slightly depleted source. Elevated $La_n/Yb_n = 2.8–3.5$ and Ti, Ni, V, Cr, and Co contents [37] in xenoliths suggest their affiliation to subalkaline varieties of mantle continental magmas. Hence, the source of alkali granites was related to subalkaline basaltic magma. The strong differentiation of alkali granites (sharp negative Eu anomaly $Eu/Eu^* = 0.2$, high $La_n/Yb_n = 8.21–5.45$ (Fig. 4)) suggests the existence of early differentiation products, which selectively accumulated Pl and, respectively, Eu. It is therefore necessary to search for such rocks in the Keivy and adjacent areas. Given the giant volume of alkali granites, the early derivatives must form large massifs. In addition, alkali granites contain large and small gabbroanorthosite xenoliths, which represent relicts of spatially and temporally associated (2678–2659 Ma) large massifs [40, 34 *etc.*]. The REE distribution pattern of gabbro-anorthosites (Fig. 4) shows a positive Eu anomaly, which is complementary to the negative anomaly in the alkali granites. Moreover, late Archean gabbroanorthosite massifs of the Keivy domain show petrographic and petrochemical evidence of deep differentiation [high b values, up to 75–80, in the Zavaritskii vector diagrams [41] as compared to their Proterozoic analogues (<42–48)] [42]. In the same diagrams, the Archean massifs show high contents of alkali aluminosilicates. In addition, the same massifs host sulfide-associated Ti–magnetite magmatic mineralization, whose scales significantly exceed those of similar mineralization of the Proterozoic analogues. Thus, the par-

ent magmas of the Archean massifs were higher in Ti and Na contents relative to the Proterozoic analogues ($TiO_2 = 1.09–0.87$ and 0.3–0.25 and $Na_2O = 2.52–2.37$ and 2.31–2.07, respectively) [42].

It follows that data on the giant alkali granite province, associated SALK series, gabbro and gabbroanorthosite intrusions suggest that, within the Kola Peninsula in the Archean, a large mantle basaltic chamber existed and experienced deep fractionation in the lower crust or the upper parts of the mantle lithosphere (at the crystallization depths of the early plagioclase cumulates), thus reflecting the large-scale and intense heating of the upper mantle. This phenomenon can be related to a Late Archean mantle superplume, which caused the heating and melting of the depleted upper mantle zone.

Geophysical and geological data [43] indicate the existence of an upper crustal domal structure beneath the Keivy terrain, with boundaries dipping beneath the Murmansk block in the northeast and the Imandra Varzuga block in the south and southwest. A thick transitional layer was found at the lower crust–mantle boundary at depths of 38–40 km. The thickness of this layer reaches 10–12 km, accounting for more than one-fourth of the total crustal thickness of the Keivy region. This unusual structure of the Earth's crust suggests the operation of a mantle plume beneath the central part of the present Keivy terrain in the Late Archean [43].

Data on the SALK series for all regions are reliable enough to justify the appearance of the first alkaline "megacyclic" peak. The maximum of this peak is shifted to the interval of 2660–2680 Ma, being significantly younger than the average values of 2700–2720 Ma obtained from the upper mantle data [6, 21]. The second "megacyclic" peak at 1860–1840 Ma (Fig. 2) shows an approximately 20–40 Ma shift relative to the "megacyclic" mantle peak at 1880 Ma [21]. The third peak (Neoproterozoic SALK series) corresponds to the alkaline activation in the Grenville orogens within 1260–1060 Ma. The maximum of the alkaline activity (1160–1120 Ma, Fig. 2) in this region also shows a shift toward younger ages. Phanerozoic alkaline plumes can be exemplified by the extensive Paleozoic alkaline reactivation at the Baltic Shield at 410–360 Ma [14], with the peak (365–375 Ma) shifted by 35–45 Ma relative to the older general mantle peak (~415 Ma after [21]). Thus, all events of superplume SALK magmatism in the crust are distinctly shifted toward younger ages within the mantle cycles that reflect general mantle endogenous activation. Hence, SALK magmatism manifests only part of complete upper-mantle cycles [21], with other components of the mantle activation still awaiting its examination. It should be noted that a shift of the relatively early alkaline ultramafic and mafic members to the foidite–foidolite compositions, which have not been considered yet on a regional scale, presumably reflects the transition of alkaline plumes to the deeper seated "root" zones. Thus, the detailed anal-

ysis of plume production reveals a chronological evolution of the composition of alkaline magmas with the transition from "head" to "root" plume zones. The same chronological trend can be seen from a comparison of the early mafic (flood basalt) magmatism with the younger SALK series. Such a detailed analysis seems to be promising for deciphering the plume heterogeneity.

Geochronological data on the SALK series can be used for surficial plate tectonics, which, as was mentioned above, controls the accretion and breakup of supercontinents. In particular, geotectonic, geological, chronological, and paleomagnetic data define the existence of the Rodinia supercontinent within 0.9–1.35 Ga [44], which strictly coincides with one of the largest cycles of the Middle Proterozoic activation of SALK magmatism (cycle with a megacyclic maximum at 1160 Ma, Fig. 1).

GENESIS OF SUPERGIANT DEPOSITS

The genesis of giant alkaline massifs extremely enriched in incompatible and volatile elements (Nb, Ta, Ti, Zr, REE, Sr, P, F, Cl, and others) is still largely uncertain, though the enrichment mechanisms of the mantle zones that are the potential sources of these elements for alkaline magmas, owing to mantle metasomatism under a high oxygen fugacity are well known from experimental and natural studies [1, 2, 9, e.a.]. However, only a few hundred of the dated massifs show "ore contents" of incompatible elements. Evidently, petrological data on alkaline rocks are insufficient to decipher this phenomenon. In particular, the enrichment in these elements up to "ore contents" is difficult to explain only by the low distribution coefficients of incompatible elements in the rock-forming minerals and the low degree of melting during the single-stage generation of alkaline magmas. Additional criteria are required. One of them can be regional feature of the repeated occurrence of SALK series in different regions.

Single discontinuous SW–NE-trending band of synchronous abundant mantle alkaline activation traced through Laurentia–Baltica on the basis of data on the Late Archean SALK series in Canada, South Greenland, and Baltic Shield (2680–2660 Ma) is difficult to interpret as an indication of plume and superplume magmatism.

The second peak of alkaline magmatism in these regions occurred at 1880–1820 Ma. In the Canadian Shield, SALK series of this age are mainly confined to the Northwestern territories, being scattered from Baffin Island in the north to Manitoba and Saskatchewan in the south. Within the Baltic Shield, they are widespread in Finland, Sweden, Karelia, and the Kola Peninsula (Soustov and Gremyakha Vyrmes massifs). Numerous basaltic dikes with an age of 1980–1750 Ma occur instead of SALK series of this age in West Greenland.

The third peak (Neoproterozoic SALK series) corresponds to the alkaline activation in the Grenville oro-

gens within Rodinia supercontinent at 1060–1080 Ma. In the Canadian Shield, subalkaline series are restricted to the Grenville Front (Ontario, Quebec, and eastern Labrador), being spatially shifted relative to the Late Archean magmatic peak. In southern and southwestern Greenland, alkaline and syenite complexes (Ilimaussaq, Igaliko, Nunarssuit, Tugtutoq and others), including potassium alkaline massifs (Narssaq and others) and lamprophyre dikes occur within the Late Archean magmatic zone. Within the Baltic Shield, SALK series were described in Norway, Finland, and Sweden and are not found yet in the Kola Peninsula. However, the third abundant appearance of alkaline series occurred there significantly later, in the Paleozoic, being correlated with the megacyclic peak at 360 Ma (Fig. 2).

Thus, the repeated rejuvenation of SALK activity is observed in different age sequences in the three considered regions, with spatial restriction to a single zone in Southern Greenland and the Baltic Shield, and a wide scattering within the Canadian Shield.

Spatial juxtaposition of the alkaline magmatism of different ages in the two former regions reflects not only the relations of plume alkaline activity with crust and mantle structure and tectonics, but, primarily, ensures the inheritance of geochemical changes in the mantle sources (that subsequently accumulated during Archean and Early Proterozoic mantle metasomatism) by the youngest zones of alkaline activation. These considerations suggest that such upper mantle zones can exist for a long time, being favorable traps for new portions of overheated (primarily, fluid-rich) deep-seated material coming from the middle and lower mantle. As a result, volatile and incompatible elements are additionally introduced during repeated plume activity, leading to the formation of alkaline massifs enriched in incompatible elements during the final stages of alkaline activation in each region.

This assumption can be exemplified by Greenland and the Kola Peninsula, where, as was mentioned above, SALK activation occurred two or three times. In particular, among Neoproterozoic alkaline and subalkaline complexes in southwestern Greenland, the Ilimaussaq layered agpaitic alkaline massif (1180 ± 9 Ma [45]) differs in having strongly elevated contents of volatiles (F, Cl, S) and trace elements (Li, Be, Rb, REE, Zr, Nb, and others) [46], being comparable only with the Khibiny and Lovozero Paleozoic (371–361 Ma [47, 14, and others]) layered alkaline massifs [16, 46, 48, 49, and others] in the central part of Kola Peninsula. These massifs are confined to areas of wide abundance of different SALK series, which have much lower contents of rare and trace elements than those of typical SALK series in Canada and elsewehre.

The proposed analysis of the "inheritance" of geochemical specialization of ancient mantle sources by late SALK magmatism should be considered as a means to attract attention to the inferred heterogeneity of the upper mantle for the deciphering of the genesis
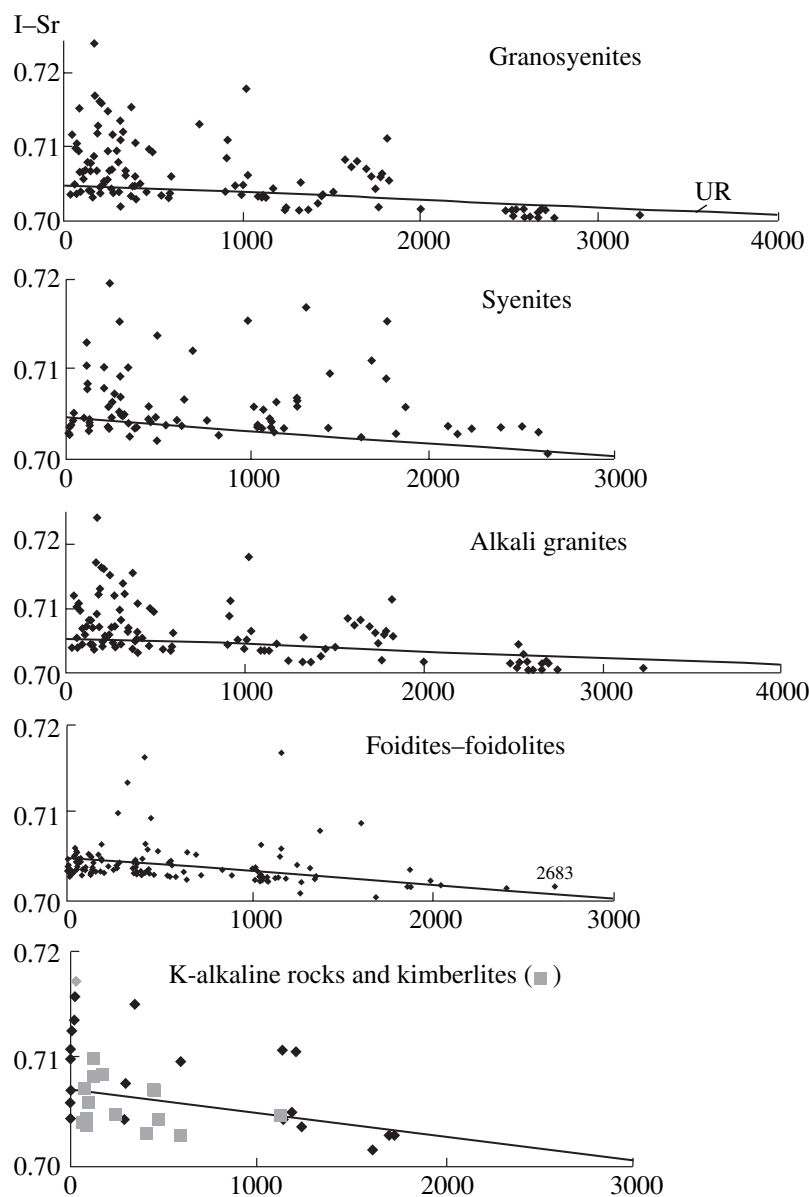
Fig. 5. Variations of the initial Sr isotope ratios in subalkaline and alkaline rocks relative to the mantle level (UR curve).

not only of alkaline, but also of other plume-related magmatism and for more detailed investigations.

SOURCES OF ALKALINE MAGMATISM

Since subalkaline and alkaline magmatism is generated within a wide-depth range in the crust and mantle, the parent mantle chambers widely vary in isotopic systematics and geochemistry even for similar magmas, as well as bare evidence of interaction with the host crustal substrate. The mantle sources can be provisionally inferred from the comparison of the isotope–geochemical parameters of the SALK series and the average mantle ratios of $(^{87}Sr/^{86}Sr)_t$ at Rb/Sr = 0.30 (0.031–0.0294) [50, 51] and $\varepsilon Nd(t)$ at Sm/Nd = 0.3245 [52, 53], taking I–

Sr(0) = 0.70475 (0.7045–0.7050) [53, 54], and $\varepsilon Nd(0)$ for the depleted mantle of 12 (10–14) [55, 56].

The data points of the initial Sr isotope ratios (I–Sr) for the SALK series (Fig. 5) are divided by the curve of the average mantle ratio (UR) into three fields: (1) with I–Sr close to UR within the measurement accuracy; (2) with I–Sr lower than UR (depleted sources); and (3) with I–Sr higher than UR (enriched mantle and crustal sources). It is seen that the two former groups distinctly record mantle signatures, which are traced from the Phanerozoic to different Archean intervals (with the exception of K rocks, data on which are constrained by the range of 1700–0 Ma). Similarly, $\varepsilon Nd(t) \geq 0$ values correspond to the mantle average (CHUR) and depleted mantle sources (Fig. 6).
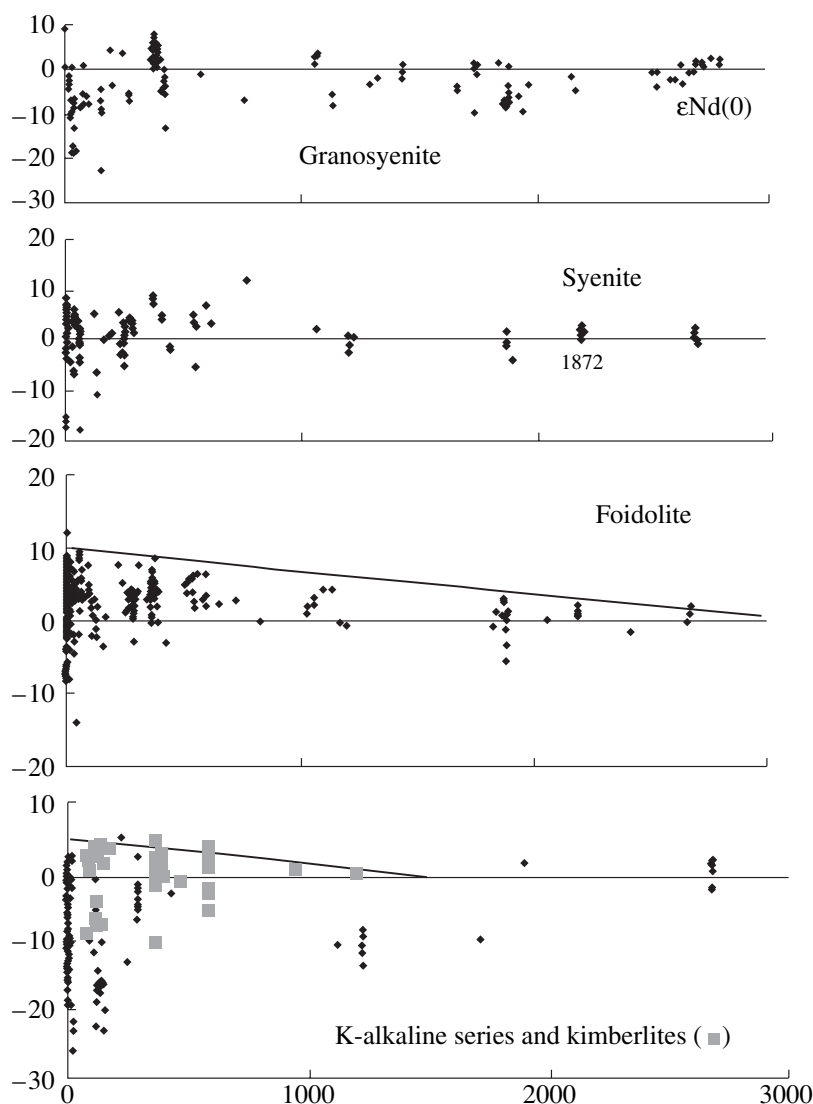
Fig. 6. Variations of εNd(T) for subalkaline and alkaline series relative to the average mantle level (chondrite REE composition). Large boxes are data on kimberlites.

It has long been known that the "syenite" and "foidolite" groups were generated from depleted upper mantle sources [57 *etc.*]. A new fact is the discovery of similar mantle sources for the most primitive subalkaline group and alkaline granites in the Mesoarchean. A sharp increase in the abundance of SALK rocks with crustal signatures starting at 1800–1900 Ma, as is inferred from the I–Sr values, presumably reflects a shortage in information, since crustal Nd signatures are traced in SALK from the Early Proterozoic (Fig. 6). An increase in crustal contamination toward the Phanerozoic, as was inferred from Sr and Sm–Nd isotope data, provokes no doubt. This is emphasized by separate data on the deepest seated rocks, kimberlites, which, in addition to mantle Proterozoic isotope signatures, sometimes provide evidence of crustal contamination.

The general trend of an increasing in the abundance of rocks with crustal Sr and Nd isotope signatures from the Neoproterozoic to Phanerozoic presumably has different reasons: (1) an increase in the upper mantle heterogeneity owing to the introduction of subduction-related crustal components [58 etc.]; (2) an increase in the lower crustal heterogeneity owing to the melting of metamorphosed fragments of the older rocks during the generation of some subalkaline magmas; (3) the regional contamination of mantle magmas by host crustal materials (fenitization and other processes). All the cases imply not only the heterogeneity of the source, but also intense fluid reworking during mantle and crustal metasomatism, which is confirmed by model estimates of the Sr isotope variations [59] and numerous data on the variations in stable isotope ratios. The increase of such an influence on the generated subalkaline and alkaline complexes is associated with the activation of contrasting tectonic processes, a higher occurrence frequency of plume tectonics, and subduc-
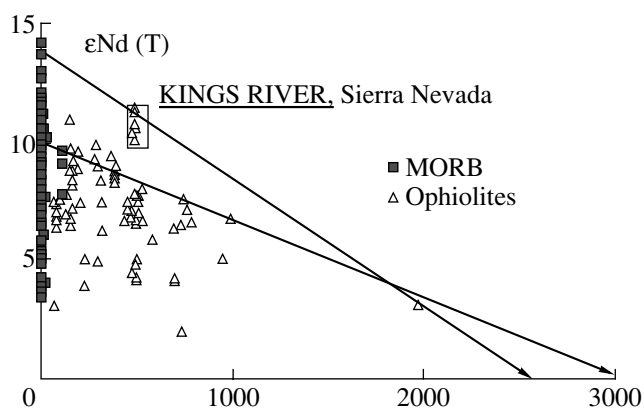
Fig. 7. Time of the primary formation of mantle MORB sources inferred from $\varepsilon Nd(T)$ for MORB and ophiolites is constrained by Late Archean.

tion toward the Phanerozoic and, as a result, a global increase in the activity of mantle metasomatism and the generation frequency of intrusive and volcanogenic facies of subalkaline and alkaline rocks [1].

RESULTS AND DISCUSSION

Using subalkaline and alkaline magmatism as an example, we attempted to show that the cycles of both types of mantle activation are well correlated with global mantle cycles, which were distinguished by comparing all data on mantle rocks with those on crustal endogenous events [21]. This indicates the universal participation of the SALK series in the evolution of mantle cycles and the global influence of plume magmatism on crustal growth. Geochronology of the SALK series indicates a systematic increase in the diversity of rock associations (from subalkaline and alkaline) with the transition from the Early–Middle Archean to the Late Archean and Proterozoic, as well as a widening range of the generation depths of all types of SALK series toward the Phanerozoic. All of these data can be considered as a convincing example of the global influence of the gradual cooling of the Earth's mantle production over the geological time. However, the Sr–Nd systematics demonstrated that the intensity of the interaction of mantle SALK series with the crust also simultaneously increases owing to the introduction of crustal material into the primary magma generation areas during the consolidation of mantle magmas within the crust. According to [1, 59, etc.], this interaction is governed by mantle and crustal metasomatism, which primarily implies an intense influence of volatiles or their exchange. Mantle zones are enriched in volatiles and incompatible elements during repeated plume influence and repeatedly generate alkaline magmas, thus producing alkaline massifs strongly enriched in incompatible elements (up to ore contents).

It is particularly interesting to compare the "primitive" and depleted sources of the SALK series. The former is the least changing type of mantle source, which is identified in the isotope parameters of different alkaline rocks up to the Early Archean (Figs. 5 and 6). In spite of the limited information, the I–Sr and εNd values corresponding to the depleted upper mantle zones occurred at least from the beginning of the Late Archean, reaching I–Sr = 0.702–0.703 and $\varepsilon Nd(T)$ from + 5 (10–14) to the end of Phanerozoic. However, the deepest seated mantle rocks, kimberlites, show approximately a two times lower deviation from the average mantle Sr and Sm–Nd isotope signatures as compared to those of other SALK series. This indicates that the contribution of the primary mantle parameters of the mantle magmas considered above increases with depth, and strongly depleted mantle zones occur at higher mantle levels. Mass balance calculations for the crust have showed that some elements can be additionally introduced from the middle and lower mantle [50, 60, 61, and others]. The same data indicate that considerations on isotope parameters of "primitive" mantle, which are based only on Late Phanerozoic data and identified with "normal" oceanic basalts (MORB) in isotope characteristics (model of Kostitsyn [62–64] or BSE model of Pushkarev [65]), are hardly acceptable, since they are based only on the Late Phanerozoic types of oceanic magmas. These models have the following constraints and contradictions.

(1) Ignoring of other types of mantle magmas, including those developed in the Proterozoic and Archean; (2) Different degree of the depletion of SALK series and similarity of their $\varepsilon Nd(t)$ with average mantle level $\varepsilon Nd(t) = 0$ with an increasing rock age (Figs. 5 and 6), which is inconsistent with the proposed for the early Earth initial isotopic and geochemical parameters.

(3) MORB and EM (alkali oceanic basalts) are the differentiates of mantle sources, complementary to crust in terms of Nb and Pb concentrations [66]; this indicates the long-termed generation of sources of MORB, EM and crust.

(4) Possible restriction of MORB age by Late Archean (Fig. 7), not allowing the consideration of isotope and chemical data on MORB as corresponding to the Earth's average values.

(5) Correlation fields of depleted isotope and geochemical parameters of Cenozoic MORB reflect real estimates for basaltic melts generated from the surface zone of ultramafic substrates and do not coincide with those of ultramafic rocks and eclogites from the deeper seated portions of upper mantle (carrying as xenoliths of the deepest seated portions of the upper mantle), which are identical or close to the average mantle values (Fig. 8).

Thus, ignoring isotope data on subalkaline and alkaline series and mafic–ultramafic upper mantle substrate, which reflects compositional evolution of the oceanic and continental mantle, leads to arbitrary global conclusions on the Earth's composition and evolution of crustal formation through geological time. Such
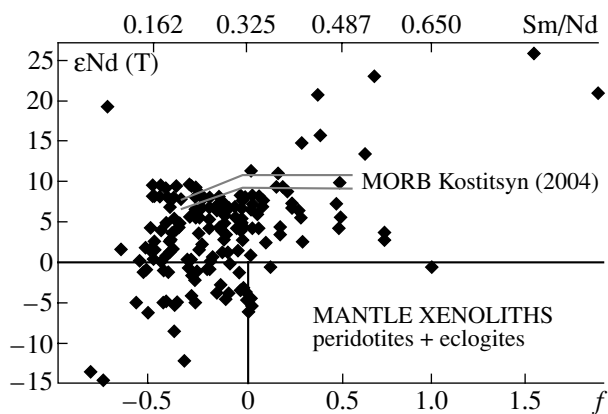
Fig. 8. Differences in εNd(T) between MORB (Kostitsyn, 2004) and xenoliths of mantle peridotites and eclogites from alkaline rocks.

global considerations based only on the variations of isotope parameters without considering redistribution of rare and trace elements between individual geospheres and geodynamics of the Earths' shells and core formation are insufficient, as have been already mentioned in the literature [2, 3, 16–18, 50, 51, 56, 61, 67, etc.].

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