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THE EVOLUTION OF MAGMATISM IN THE EARTH'S HISTORY

(Figs. 3)

Abstract: The evolution of magmatism in the history of the Earth is irreversible and manifests itself in change of primitive komatiite-basic magmatism for strongly differentiated one, in increase of diversity of igneous rocks formations, in more prominent roles of calc-alkalic and alkaline rocks, in reduction of spatial and temporal boundaries of magmatic activity manifestation.

There are similar features in the evolution of the magmatism of the Earth as a whole and the evolution of magmatism, which accompanied the opening of young oceans. Magmatism of early stages of the Earth evolution compositionally is close to magmatism of midoceanic ridges, initial sialic magmatism of the cratonic stage resembles island arc magmatism and magmatism of two last stages has chear cut "continental" nature (close of the ocean). The resemblance of these tendencies apparently is caused, in the first place, by fact of gradual decrease of the mantle material role in the magma genesis during evolution processes of the whole Earth and young oceans.

The way of the evolution of the magmatism is determined by decrease of the energy potential of the Earth, progressive diminishing of incompatible, light and radioactive components content in the upper mantle, increase of thickness and heterogeneity of the crust of the Earth.

Резюме: Ведущей тенденцией эволюции магматизма в истории Земли является смена примитивного коматиит-базитового магматизма глубоко дифференцированным в вещественном отношении магматизмом, увеличение разнообразия формаций изверженных пород, усиление роли известково-щелочных и щелочных магматических серий, уменьшение пространственных площадей и временной деятельности магматической активности.

Имеется определенное сходство в эволюции магматизма Земли в целом и эволюции магматизма при возникновении молодых океанов. Магматизм ранних стадий эволюции Земли в вещественном отношении ближе всего к магматизму срединно-океанских хребтов, первично-сиалический магматизм кратонной стадии напоминает магматизм островных дуг, а магматизм континентальной и континентально-океанической стадий носит отчетливо выраженный „континентальный" характер (закрытие океана). Сходство этих тенденций, видимо, обусловлено постепенным понижением роли мантийного материала при магмообразовании как в процессе всей эволюции Земли, так и в эволюции молодых океанов.

Направление эволюции магматизма определяется снижением энергетического потенциала Земли, прогрессивным обеднением верхней мантии некогерентными, летучими и радиоактивными компонентами, возрастанием мощности и гетерогенности коры Земли.

Introduction

Magmatism is the leading process responsible for the evolution of the composition of the Earth's lithosphere. The calculations demonstrate that during the

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geological time even at the contemporary rate of eruptions volcanoes could have brought to the surface the amount of material comparable with the volume of the Earth's crust (Markhinin, 1968). Magmatism played undoubtedly predominant role during the formation of primary crust of our planet, when, as it is suggested by the data on petrology of lunar rocks, the melting and differentiation of the whole outer shell of the Earth took place (Clark — Turekian — Grossman, 1976; Gast, 1976). Far more substantial, as compared with the Moon, energy potential of the Earth resulted in the faster, more profound, and prolonged differentiation of Earth's material. Therefore the terrestrial analogues of lunar rocks known among the Precambrian formations, for instance "grey gneisses" and others, correspond to the later stage of the material evolution of the planets belonging to the terrestrial group.

Evolution of the magmatism in the Earth's history was discussed by investigators (A. Engel — Itson — G. Engel — Stickney — Cray, 1974; Ronov — Yaroshevsky, 1976). However, the majority of the proposed schemes this evolution are restricted by Phanerozoic in time, by continents in space and by earth as the only planet whose geology is throughly known. Available at present time data on the igneous terrestrial rocks of early Precambrian, of oceanic bottom and of the Moon permit to approach the problem of the evolution of magmatic on a global scale and from the point of view of comparative planetology. In this paper a qualitative aspects of the magmatic evolution in relation to the largest stages of the Earth's development are analyzed.

Magmatism evolution

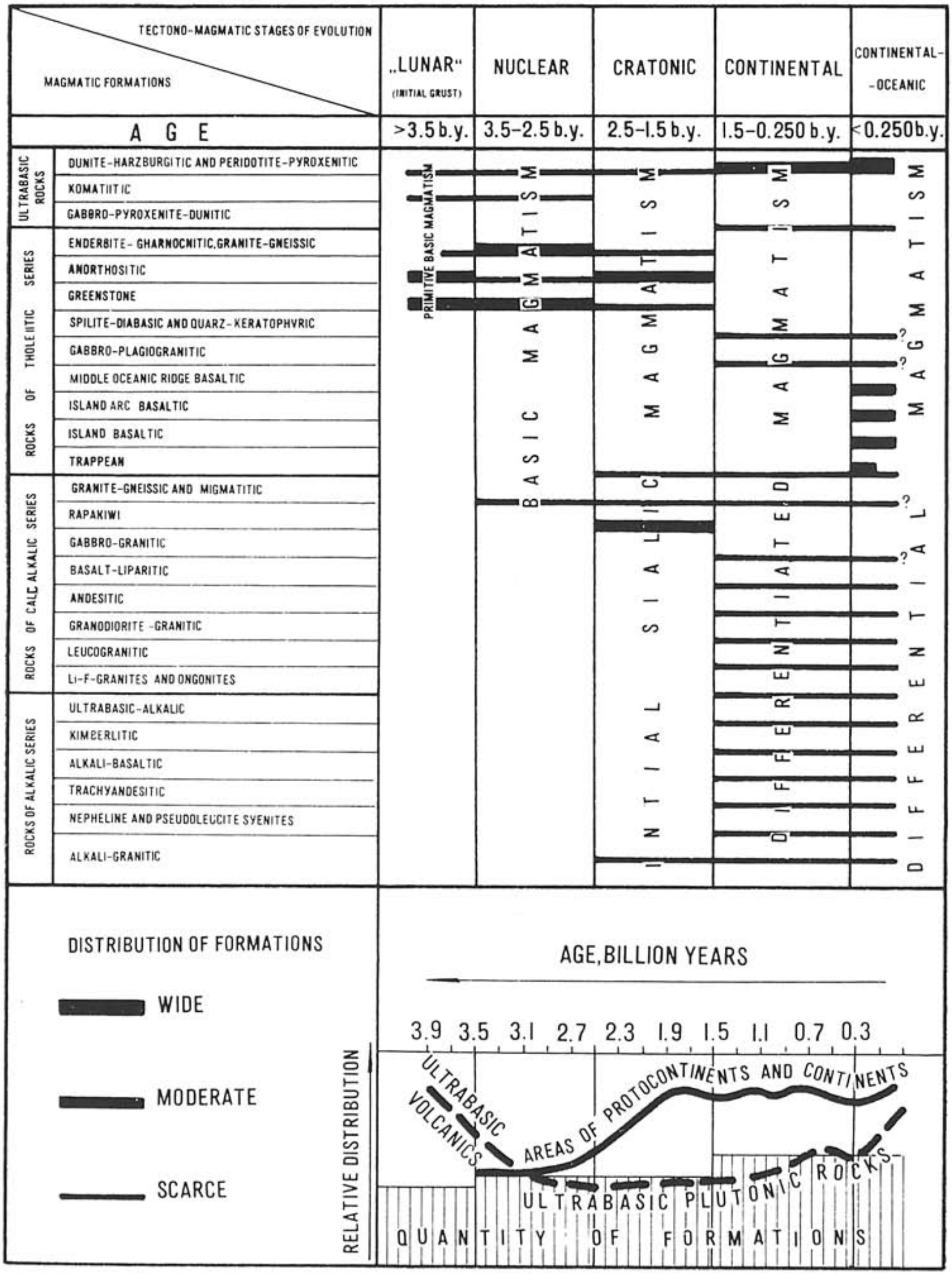
The compositional evolution of magmatism is considered here on the basis of formational analysis distinguishing the major petrochemical series: tholeiitic, calk-alkaline, and alkaline and also a separate group of ultrabasic rocks (Fig. 1). The diagnostic features for the attribution of magmatic rocks to a certain petrochemical series have been published earlier (Andreeva — Bogatikov et. al., 1978; Miyashiro, 1975). The correspondance of magmatic formations to petrochemical series was established statistically.

There are distinguished several stages of tectono-magmatic evolution in the history of the Earth (Fig. 1), whose boundaries correspond to statistically proved datings of the global geological events (A. Engel — Itsoh — G. Engel — Stickney — Cray, 1974; Khain, 1973; Pavlovsky — Kolotukhina, 1978; Shurkin — Mitrofanov, 1974).

Fig. 1. Schematic representation of the Earth's magmatic evolution (abundances of magmatic formations on the geological history of the Earth).

Figures in circles indicate the position of magmatic formations in the largest tectonic structural units of the Earth: 1 — greenstone belts, rimming the nuclei of ancient platforms; 2 — eugeosynclinal zones; 3 — midoceanic ridges; 4 — island arcs; 5 — shields (nucleii of ancient platforms) 6 — oceanic islands; 7 — platforms; 8 — orogenic belts; 9 — activization structures; 10 — active continental margins; 11 — continental rifts.

1. "Lunar stage" (or the stage of primary crust), is older than 3.5 b.y. 2. Nuclearic stage: from 1.5 to 0.25 b.y. 3. Cratonic stage: from 2.5 to 1.5 b.y. 4. Continental stage: from 1.5 to 0.25 b.y. 5. Continental-oceanic: younger than 0.25 b.y.



1. "Lunar stage", or the stage of primary crust, is the earliest one and is represented by the rocks older than 3.5 b.y. These rocks (some anorthosites, the most ancient "grey greisses", the rocks of greenstone belts) substantially differ from the lunar rocks similar in age, but one may hypothesize that during the earlier epochs of "lunar stage" the magmatic rocks, which were more similar to the rocks discovered on the Moon, were forming in the outer shell of the Earth (Bogatikov — Dmitriev, 1976). The concept of andesitic-anorthositic primary crust of the Earth deserves attention in this respect (Shurkin — Mitrofanov, 1974).

The difficulty of the unravelling the real "lunar" rocks on the Earth is probably due not only to the more profound material evolution of the Earth, but also because of the globally developed intense metamorphism of the primary crust at the boundary of 3.5 b.y. The type of magmatism of the "lunar stage" may be defined as primary basic.

2. Nuclearic stage according to Pavlovsky et al. (Pavlovsky — Kolotukhina, 1978) was terminated approximately at 2.5 b.y. when according to Engel (A. Engel — Itsoh — G. Engel — Stickney — Cray, 1974) the intense formation of protocontinents commenced (Fig. 1). Sometimes the upper temporal boundary of this stage is placed at 2 b.y. By this time the formation of the major mass of protocontinents had already terminated. The andesitic--basaltic general character of magmatism and the maximal development of komatiitic formations, whose role gradually declined by the end of this stage, are typical for the nuclearic stage in the evolution of the Earth. Plutonic ultrabasic rocks, predominantly tholeiitic volcanic rocks metamorphosed in the facies of green schists and acid rocks of granitic-gneissic ("grey gneisses"), migmatitic and charnokitic groups of formations are also represented among the magmatic formations of nuclearic stage. The first granitic formations appear but the reliable estimates of the abundance of calc-alkaline series among the magmatic formations of nuclearic stage is difficult.

Plagiogranites predominate among acid rocks and they differ from phanerozoic plagiogranites by higher contents of Al, Mg, Na, Sr, Ni, V and Cr and lower concentrations ~~of Mn, K, Ba, Pb,~~ Th and U (Lobach—Zhuchenko — Chekulaev — Baikova, 1974).

Tholeiitic metavolcanics of nuclearic stage also differ from the similar with respect to composition recent rocks in the enrichment of Sr in acid differentiates.

Komatiite-basic magmatism characteristic of nuclearic stage is confined to the greenstone belts and shields of ancient platforms with the numerous granitic-gneissic domes. It is not yet clear, whether greenstone belts are the most ancient preserved geological formations of the Earth (Pavlovsky — Kolotukhina, 1978), or this role is played by granitic-gneissic domes (Shurkin — Mitrofanov, 1980).

The metamorphism of greenstone belts belongs to green schist facies.

The largest deposits of gold, nickel and copper are associated with komatiitic-basic magmatism of nuclearic stage of the Earth evolution (Tugarinov, 1977).

3. Cratonic stage (2.5—1.5 b. y.) is characterized by termination of protoconti-

nents (nuclei of ancient platforms) formation. The thickness of the continental crust was up to 40 km at this stage and area of continents was more than doubled (A. Engel — Itsoh — G. Engel — Stickney — Cray, 1974; Tugarinov, 1977). The main feature of cratonic stage is the mass creation of magmatic formations, which constitute the sialic part of the primary continental crust. Consequently, this stage may be called, also, the stage of primary sialic magmatism.

The creation of magmatic formations specific for the nuclearic stage was still in progress, but the role of komatiites sharply decreased, while abundance of such formations as granitogneissic, migmatitic, charnockitic, anorthositic and graniterapakivi formations clearly increased. Potassic migmatites are more common then sodic ones. Continental rocks became enriched in potassium, uranium, thorium, lead, barium, strontium-87 (A. Engel — Itson — G. Engel — Stickney — Cray, 1974). The specific feature of this stage is emergence of the first formations of traps and alkaline granites, for instance Keiv granites of the Kola peninsula.

The grade of metamorphism of rocks of cratonic stage with primary sialic magmatism is up to amphibolic facies.

About 90 % of all presently existing rocks were formed by the end of the cratonic stage (Zonenshine — Kuzmin — Moralev, 1976). Magmatic formations of the cratonic stage are associated not only with green-stone belts and crystalline shields but with orogenic belts and zones of tectono-magmatic activation as well (Lobach — Zhuchenko — Chekulaev — Baikova, 1974).

The primary-sialic stage of the Earth magmatic evolution is remarkable as the time of mass formation of uranium ore deposits (Tugarinov, 1977).

4. Continental stage (1.5—0.25 b. y.) is notable for the formation of orogenic belts and zones of tectono-magmatic activisation. The most typical feature of continental stage is diversity of contemporaneous magmatic formations and, in petrological aspect, this stage may be called stage of the differentiated magmatism.

At this stage formations of orogenic belts and zones of tectonomagmatic activisation, such as dunite-harzburgite, spilite-diabasic, quartz-keratophiric, gabbro-plagiogranitic and others, are well represented. Magmatic formations of calc-alkalic series (gabbro-granitic, basalt-liparitic, andesitic, granodiorite-granitic, leucogranitic), which are specific for regions with mature continental crust, have a wide spreading. Formations of lithiumfluorine granites and ongonites (Hapala, 1977), are typical formations of the continental stage with differentiated magmatism as well as formations of different alkaline rocks.

Metamorphism in the rocks of this stage is less extensive then in the earlier stages, but it distinguishes itself by the presence of glaucophanic facies rocks among Paleozoic formations (A. Engel — Itson — G. Engel — Stickney — Cray, 1974). During this stage the areal magmatism of previous stages turned into the zonal one.

5. Continental-oceanic stage, according to V. E. Khain (Khain, 1973), includes period from 250 m. y. and up to present time. During this epoch of the geological history the Gondwanaland was disintegrated, and present day continents,

as well as Atlantic and Indian oceans, have been formed. Magmatic activity assumes distinctly differential[1] character, that is continental and oceanic.

Magmatic formations belonging to tholeiitic series (basaltic formation of mid-oceanic ridges, basaltic formation of oceanic islands, basaltic formation of island arcs) definitely predominate in oceanic segments of Earth's lithosphere. There are also represented calc-alkaline island arc formations and alkaline basaltic formations of oceanic islands.

On the continents the following formations are found; formations of ultrabasic rocks, spilite-diabasic, quartz-keratophyric, gabbro-granitic, basalt-liparitic, andesitic, granodiorite-granitic, formations of lithium-fluorine granites and ongonites, ultrabasic-alkalic formations kimberlitic, alkaline basaltic, trachyandesitic, formations of nepheline and pseudoleicite syenites, formations of alkaline granites (Fig. 1).

The actualistic approach to the problem of origin of magmatic formations which is extensively used in a number of geological and tectonical works is largely as applied to continental-oceanic stage of Earth's evolution characterized by differential magmatism (Zonenshine — Kuzmin — Kovalenko — Saltykovsky, 1974: Zonenshine — Kuzmin — Moralev, 1976). E. g., the comparison of magmatic formations of Mezozoic of the Mongolian--Okhotsk belt with western part of the north American continent permitted to establish that the tectonomagmatic zoning and chemical composition of magmatic formations of these regions is similar. This similarity probably results from the development of magmatism in the same geodynamic regime of an active continental margin (Kovalenko — Kuzmin, 1977; Zonenshine — Kuzmin — Moralev, 1976). Analogous comparative geological-petrological analysis shows that magmatic formations belonging to certain structural-formational zones of the Greater Caucasus are similar to magmatic formations of present day island arcs and marginal (Borsuk, 1977).

Such analogies are certainly not always valid, and their substantiation requires very thorough work on the compositional and chronological correlation between concrete magmatic formations. We should also note that there exists an opinion about the predominance of sialic crust within the boundaries of modern continents at least during the whole Phanerozoic. From this point of view the zones of development of basic-ultrabasic formations within continents (eugeosynclinal zones) are considered not as the remnants of the crust of the real large oceans, but as a material of the deeper parts of lithosphere squeezed out along relatively narrow (as compared with the oceans) spreading zones of continental blocks similar to present day rifts. It should be emphasized that magmatism is related not only to horizontal movements of lithospheric plates. Vertical displacements also undoubtedly exist, especially inside the plates (Gilluli, 1978) and, in particular, the vertical descent of the western part of Mediterranean sea is well proved. Voluminous intraplatform trap magmatism also develops parallel to vertical tectonic movements (Dmitriev, 1973).

The most obscure aspect of the evolution of Earth's magmatism is the problem

[1] On should distinguish differential character of magmatism corresponding to its sharp differences in the oceans and on continents from differenciated character manifested in the diversity of magmatic formations.

of the evolution of composition of the formations arising in succession and belonging to the same type.

It has been demonstrated by Ronov, Khain and Balukhovsky (Ronov — Khain — Balukhovsky, 1979) that the extensive development of volcanism took place during upper Cretaceous time, the activity of volcanic eruptions increased during lower Cretaceous on continents and during upper Neogene in oceans. They also noted substantially higher abundance (two orders of magnitude) of tholeiitic basalts both in oceans and on continents as compared with the abundances of intermediate and acid volcanics of orogenic and island arc formations and also of alkaline basalts.

The predominance of volcanics over intrusive rocks is apparently characteristic of the modern etape of continental-oceanic stage, and among intrusive continental rock diorites, granodiorites and granites are the most abundant (A. Engel — Itson — G. Engel — Stickney — Cray, 1974). E. g., for the early Mezozoic of Mongolian-Okhotsk belt the proportion of outcrops of gabbro-diorites, granodiorite-granites, leucocratic granites and the rock of elevated alkalinity is 2.5:30.4:54.1:13.0 (Yakimov — Kovalenko, 1977).

Comparative analysis of the data on the character and formation conditions of igneous rocks belonging to various formations at diverse stages of the Earth's evolution permit to reach the following conclusions concerning the regularities of magmatism evolution in the course of geological history.

a) Going from early to late stages of magmatic evolution we observe reduction up to complete disappearance of the following magmatic formations: komatiites, charnokites, anorthosites (autonomous), granitic gneisses and migmatites.

b) Plagiogranites of the earlies stages of magmatic evolution give way to more and more potassic granites of the later stages alongside with the increase in the dispersion of $^{87}Sr/^{86}Sr$ ratios for the younger granites.

c) Formations of alkaline rocks, lithium-fluorine granites and ongonites appear only beginning from cratonic stage of primary sialic magmatism.

d) The relative role of tholeiitic rocks decreases at the late stages of magmatic evolution at the expense of the rise of abundance of formations belonging to calc-alkaline series.

e) The areal character of magmatism of the early stages gives way to linear magmatism.

f) Relatively continuous in time magmatism of the early stages is followed by pulsating, discrete magmatism of the late stages.

On the whole, the leading tendency of the magmatic evolution in the Earth's history is the change from primitive komatiite-basic magmatism to differentiated magmatism with the successive extension of the spectrum of the compositions of magmatic rocks.

Let us consider possible reasons of the unravelled regularities.

The most apparent and important factor controlling the evolution of magmatism in time are the variations of the Earth's thermal regime.

The maximum thermal resources were available on the Earth's soon after its formation when according to many investigators the complete melting and differentiation of the Earth's outer shell took place resulting from accumulation of accretion energy, gravitational compaction and radiactive decay, and which also led to the formation of primary crust. This crust, due to the more contrasted fractionation of material under action of more intense gravitational field of the

Earth, possibly had less basic composition than gabbro-anorthosite-basaltic crust of the Moon.

Intense convective flows in the not material of young Earth led to the fast ascent of mantle diapirs to the surface, and the high extent of their melting resulted in the formation of the large volumes of komatiitic magmas in early Precambrian.

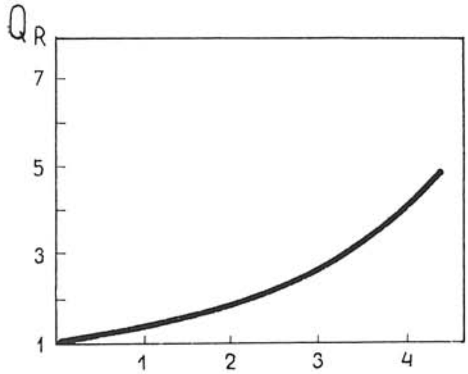


Fig. 2. The ratio of the radioactive heat production in past to present time value, calculated for the Earth composition corresponding to carbonaceous chondrites belonging to Orguell type from the data of the work (Dickinson — Luth, 1971).

Later due to the dissipation of thermal energy into surrounding space and decrease in potential radioactivity energy the Earth starts to cool (Fig. 2). At the boundary of "lunar" and nuclearic stages of the Earth's evolution the production of radioactive heat exceed present time value by a factor of 3 (Fig. 2), later at the boundary of nuclearic and cratonic stages this ratio falls to 2, and during the continental stage the production of radioactive heat was greater than the modern lever by a factor not higher than 1.6.

With the decrease in heat flow the role of ultrabasic volcanism markedly diminishes. In contrast, the contribution of other formations increases, because the generation of respective magmas does not require so high temperature as komatiitic melts. Parallel to the cooling of the Earth and differentiation of its material the role of the magmas produced at great depths at low degrees of partial melting of mantle substance (alkaline magmas) increases.

The changes in the Earth's thermodynamic regime in time should have also noticeably affected generation of magmas within the crust. This can be seen from the comparison of P-T coordinates of steady state geotherms of varying age with the phase diagram of the system granite-water (Fig. 3). It shows that the present time geotherms lie in the region of much lower temperatures than isoplets of the system granite-water at the plausible water concentrations in natural magmas. On the other hand, steeper geotherm for 2.5 b. y. intersects the field of partial melting in the system granite-water at much lower pressures and in the extensive range of water concentrations in the melt.

These arguments, in addition to the conception on the more extensive participation of water in Archean endogenic processes, are capable of explaining the areal character of migmatitization in Precambrian and predominantly linear character of granitic magmatism during the later epochs.

Alongside with the lowering of heat flow from the Earth's depths an important factor of the evolution of magmatism may be the changes in the chemical composition of mantle material with respect to volatile, petrogenetic and trace element.

First of all, we may note that the primitive mantle was probably richer in water, whose later separation may be responsible for the formation of the oceans.

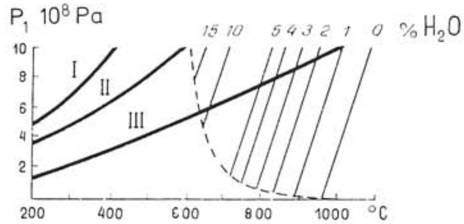


Fig. 3. P—T diagram for the liquidus of the system granite-water (Kogarko—Ryabchikov, 1978) in comparison with the geotherms.

I — present day geotherm of Precambrian shields (Klark—Ringwood, 1964). II — present day geotherm of oceanic regions (Klark—Ringwood, 1964). III. — hypothetic steady state geotherm 2.5 b. y. ago (Ryabchikov—Bogatikov—Babansky, 1978). IV — liquidys osopleths of the system granite-water. V — melting curve for granitic minimum in the presence of the excess of aqueous fluid.

It can be seen from the comparison of steep Archean geotherms with the phase diagram of the system lherzolite-water (Ryabchikov — Bogatikov — Babansky, 1978) that the partial melting of relatively enriched in water (0.4 wt per cent H_2O or more) mantle material in Archean could have taken place at depths less than 30 km. The composition of intersticial liquid should have been similar to basaltic andesite. It is possible, that such processes could have been one of the principal causes of the formation of primary sialic crust.

During the Earth's evolution and with the increase in the thickness of lithosphere its permeability reduced which together with the lower values of heat flow during the later stages of the earth's evolution and deepening the level of magma generation led to the change of areal and continuous magmatism for discrete magmatism manifested along the zones where the accumulation of thermal energy took place and in particular along the boundaries of lithospheric plates.

During the continental-oceanic stage of differential magmatism the localization of igneous rock formations of oceans and their active margins was largely controlled by the lithospheric plates interaction. With the closing of marginal seas and with the convergence of island arcs and continental plates the primitive tholeiitic basalts, calc-alkaline rocks of islands arcs and granites generated by partial melting of crustal material submerged into mantle were found sometimes to be close in space.

In the central parts of lithospheric plates magmatism is related to the ascending flows of not mantle material and is localized at the regions of the melting of lithospheric blocks (so called "not spots") or in the zones of disjunctive displacements.

On the whole, we may note certain similarity between the general tendencies in the evolution of terrestrial magmatism and the development of magmatic phenomena during the formation of young oceans. Magmatism of the early stages of the Earth's evolution is similar with respect to composition to the magmatism of mid-oceanic ridges, primary sialic magmatism of cratonic stage reminds island arc magmatism, and magmatism of the two latest stages possess distinct "continental" character ("closing" of the ocean). The similarity between these tendencies is probably due mainly to the gradual rise of the role of crustal material (at first oceanic and later continental) and respective reduction of the role of mantle material during the generation of magmas both in the process of the evolution of the Earth as a whole, and during the evolution of young oceans.

Summing up, we may state that the reduction of the Earth's energy potential, progressing impoverishing of the upper mantle in incompatible, light and radioactive components, involvement of continental crust in the generation of magmas, increase in the thickness and heterogeneity of continental crust, growing complexity of the geodynamic conditions of magma generation — all these factors cause the irreversible character of the evolution of magmatism manifested in the increasing diversity of igneous formations, growing role of calc-alkaline and alkalic rocks, shrinking of spatial temporal boundaries of the magmatic activity.

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