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Abstract—The main peculiarity of the tectonic and magmatic development of the Moon is its resemblance to the Paleoproterozoic stage of the Earth development. The Moon shows no analogues of both the ancient (Archean) terrestrial magmatism, which produced tonalite series granitoids and minor komatiite and basalt, and Phanerozoic magmatism related to active plate boundaries. The earliest (4.45–4.25 Ga) highland magmatism of the Moon is represented by magnesian series rocks cutting the primary anorthositic crust. These rocks are chemically similar to the terrestrial early Paleoproterozoic igneous rocks (2.5–2.2 Ga) that compose the siliceous highly magnesian series (SHMS), but the lunar melts are more reduced. Similar to the Earth, their intrusive analogues form layered complexes of mafic and ultramafic rocks (ANT series). Starting from an age of 4.34 Ga, the magnesian series associated with rocks enriched in K, REE, and P (KREEP series) including potassium granites. The second stage (3.9–3.2 Ga) of the tectonic and magmatic development of the Moon was characterized by extensive generation of mare basalts, which filled the depressions of newly formed lunar maria. Similar to the oceanic and continental flood basalt provinces of the Earth, two varieties of mare basalts are distinguished on the basis of chemical composition, low-titanium and high-titanium. The former are similar to MORB, and the latter are close to geochemically enriched Fe–Ti picrites and basalts, which first appeared on the Earth in considerable amounts only at 2.2–2.0 Ga, simultaneously with the onset of plate tectonics. Similar to the Earth, the mare magmatism is believed to be related to the ascent of mantle plumes of the second generation from the boundary between the liquid metallic core, which existed then, and the silicate mantle. The spreading of plume heads was probably responsible for the formation of large mare depressions with reduced crust thickness. It is proposed that the formation of the Earth and Moon occurred simultaneously and proceeded in two stages: (1) the formation of their iron cores from a protoplanetary nebula around the Sun and (2) the subsequent accumulation of silicate chondritic material. However, the proximity of the Earth, which more efficiently "scavenged" volatile components (especially, H_2O) from the surrounding space owing to its greater mass, resulted in the depletion of the Moon and especially its core in these components. The differences in the evolution of tectonic and magmatic processes in the Earth and Moon are probably related to different energy capacities of these planetary bodies.

INTRODUCTION

The Moon is the nearest to the Earth and the only planetary body that was visited by a human being and whose rocks were sampled (Fig. 1). This provided a unique possibility to compare tectonic and magmatic processes on the two planetary bodies using modern methods of materials sciences in addition to visual and remote sensing information. As early as in the 1970s, when major publications on the comparative analysis of the development of these planetary bodies appeared, a close similarity was recognized between the lunar magmatism and terrestrial Early Precambrian associations, in particular, with respect to the extensive occurrence of anorthositic complexes (Bogatikov, 1979). The famous saying of the fist geologist–astronaut Jack (Harrison) Schmitt: "The Moon is a dusty window into the Earth's past," dates from that time. However, interest in the comparative study of these planetary bodies has been rather rapidly and unjustifiably lost, because the opinion prevailed that the lunar surface was formed by external forces related to falls of large meteorites rather than internal processes.

On the other hand, in recent years, a considerable advance was made in the understanding of the Early Precambrian history of the Earth (Bogatikov *et al.*, 2000), and the results of continuous investigations of lunar samples and new information from the remote sensing of the Moon (Clementine and Lunar Prospector projects) allowed substantial improvements in the characterization of the chemistry of lunar rocks and their distribution in space and time. It was found that the tectonic and magmatic development of the Moon bears a close resemblance to the processes occurring on the Earth in the Paleoproterozoic (Sharkov and Bogatikov, 1999), which was a most important transitional stage in the Earth history when the ancient plume tectonics of the Archean was changed by the plate tectonics of the Phanerozoic. Thus, it was shown for the first time that the Moon was not unique and, in many respects, its development was governed by the same regularities that operated in the Earth.

This paper deals with the major characteristics of tectonic and magmatic processes of the Earth and Moon and the striking similarity of the lunar magmatism to terrestrial Early Proterozoic events. Based on the available geologic and petrologic evidence, we address the problem of formation and development of these planetary bodies.

MAIN CHARACTERISTICS OF THE TECTONIC AND MAGMATIC DEVELOPMENT OF THE EARTH IN THE EARLY PRECAMBRIAN

Nowadays, we know almost nothing on the geologic processes that occurred before 4.0 Ga, the oldest age of known terrestrial rocks. Starting from that time, the Earth has passed three stages of its development: (1) nuclearic stage, which involved essentially all of the Archean and continued up to 2.7–2.6 Ga; (2) cratonic stage of the early Paleoproterozoic, from 2.6–2.5 to 2.0 Ga; and (3) continental–oceanic stage, which commenced in the late Paleoproterozoic (about 2.0 Ga) and still persists. Our consideration is based mainly on the example of the Baltic Shield, although similar processes occurred in other Precambrian shields (Bogatikov *et al.*, 2000).

1. **Archean (nuclearic) stage.** This stage is characterized by the formation of large extension areas within the ancient sialic crust known as greenstone–granite terranes (GGT). Medium-pressure granulite belts with enderbite–charnockite crustal magmatism were formed between them. A typical GGT consists of abundant sodium granitoids of the tonalite–trondhjemite–granodiorite (TTG) series and an irregular network of greenstone belts (GB) built up of komatiite–basalt volcanic series with minor intermediate and silicic extrusive rocks and sediments. In the rocks of the Baltic Shield, the value $\varepsilon_{Nd}(T)$ varies from –1 to –3 for the TTG series and from +2 to +4 for the Late Archean komatiites, which suggests that the mantle source was depleted long before magma generation. There is isotopic and geochemical evidence that the komatiites and basalts often assimilated the material of an ancient continental crust during melt ascent toward the surface (Puchtel *et al.*, 1998). This suggests that the komatiite–basalt series of GB could hardly be fragments of an oceanic floor. The Nd isotopic characteristics of the silicic volcanics are similar to those of the TTG rocks. Together with some geochemical data, this testifies to the formation of the former through the melting of the latter (Puchtel *et al.*, 1998). The andesites show transitional isotopic and geochemical characteristics. The earliest potassium-rich rocks appeared at the end of the Archean. In the Baltic Shield, they are represented by intrusions of potassic granite (including peralkaline granite) and monzodiorite, which were found in the region of the Keivy Plateau, Kola Peninsula (Mitrofanov and Bayanova, 2000). Occasionally, titanium-rich ferropicrites were noted in the volcanic sequences of greenstone belts. For instance, such rocks of an age of ca. 2.61 Ga were found in the Camsel Lake belt of the Slave Province, Canadian Shield (Francis *et al.*, 1999). However, in the Archean, they were very rare and low-titanium and low-iron komatiite–basalt series were predominant.

2. **Early Paleoproterozoic (cratonic) stage.** Owing to general cooling of the Earth's outer layers, the crust became rigid and capable of brittle deformations, which was manifested in the extensive development of dike swarms and layered intrusions and the grabenlike structure of volcanic–sedimentary belts. Nevertheless, the character of tectonic and magmatic activity did not significantly change: large domains of upwelling and extensions (cratons) with mantle magmatism were accompanied by compensation zones of compression and submergence (medium-pressure granulite belts) with enderbite–charnockite magmatism. The appearance of a consolidated crust resulted also in change in the type of melts: the Archean komatiite–basalt series were changed by the siliceous high-magnesia (boninite-like) series (SHMS).

Melts of the latter series are typical of the early Paleoproterozoic. They are characterized by high contents of SiO_2, MgO, and Cr; moderate Ni, Co, Cu, and V; and low Ti, alkalis, and Nb. Among modern igneous rocks, only the island-arc boninite series shows similar characteristics. This suggests that, similar to Phanerozoic boninites, the SHMS melts were of a mixed origin and involved materials from the strongly depleted mantle and crust. There are significant distinctions in isotopic characteristics: the $\varepsilon_{Nd}(T)$ of SHMS varies from –1 to –2, which, along with geochemical data, suggests a significant contribution of Archean crustal material (Puchtel *et al.*, 1996). This probably resulted from the fact that the ascent of deep-derived high-temperature mantle melts was arrested by the rigid crust and they were accumulated beneath this barrier in intermediate magma chambers. The rise of the melts probably continued via the zone melting mechanism, which promoted extensive assimilation of crustal rocks and, consequently, formation of melts typical of the early Paleoproterozoic (Sharkov *et al.*, 1997).

In the Archean cratons of Precambrian shields, SHMS always formed large igneous provinces similar to the Phanerozoic areas of continental rifting and flood basalt volcanism. The formation of these provinces is related to the ascent of mantle plumes composed of depleted ultramafic material (Sharkov *et al.*, 1997). Their igneous rocks are represented by volcanics varying in composition from low-titanium picrite, magnesian basalt, and high-alumina basalt to andesite, dacite, and rhyolite at the general prevalence of basalts. In addition, very common are swarms of gabbronorite dikes and large layered intrusions. The latter are composed of intercalated dunite, harzburgite, pyroxenite, troctolite, norite, and gabbronorite (including pigeonite-bearing varieties), anorthosite, magnetite gabbronorite, and diorite. The whole Proterozoic is characterized by the development of large gabbro–anorthosite massifs.

The formation of low-titanium potassium-rich rocks persisted. In the Baltic Shield, they are represented by intrusions of potassic granite (including peralkaline granite) and monzodiorite, as well as dike and extrusive varieties of these rocks. An isotopic study of alkali granites from the Keivy region (Kola Peninsula), which formed at 2.45–2.55 Ga, yielded $\varepsilon_{Nd}(T)$ values from –2.4 to +1.8 indicating a mixed crustal–mantle source of their material (Balashov *et al.*, 1997). In the Baltic Shield, extrusive rocks with elevated potassium contents are represented by a volcanic series ranging from low-titanium alkali basalt and picrite to trachyandesite, alkali dacite, and rhyolite. For instance, such a series forms the second volcanic unit (Kuetsjarvi Group, Pittrijarvi Formation) having an age of ca. 2.2–2.3 Ga (Rb–Sr method) and an initial $^{87}Sr/^{86}Sr$ of ca. 0.7035 in the Pechenga structure of the Kola Peninsula (Smolkin *et al.*, 1995). Such melts were probably generated by the infiltration of deep-derived K-bearing fluids into the mantle and lower crust. The pathways of these fluids are traced by the zones of phlogopitization (Kempton *et al.*, 1995).

3. **Late Paleoproterozoic stage (beginning of the continent–ocean stage).** At 2.2–2.0 Ga, a considerable change occurred in tectonic and magmatic processes. Geochemically enriched Fe–Ti picrites and basalts (often alkali-rich) similar to Phanerozoic intraplate rocks became the most widespread intraplate igneous rocks at this stage. For instance, the late Paleoproterozoic (1.97–1.98 Ga) ferropicrites of the Pilgujarvi Formation of the Pechenga structure, Kola Peninsula (part of the Pechenga–Varzuga volcanic–sedimentary belt) contain up to 4–5 wt % of TiO_2 at $\varepsilon_{Nd}(T) = +1.5$ and an initial $^{87}Sr/^{86}Sr = 0.7029 \pm 0.0004$ (Smolkin *et al.*, 1995). These titanium-rich rocks associate with more abundant pillow lavas of low-titanium and low-alkali tholeiitic basalts similar to mid-ocean ridge basalts (MORB). The situation resembles that of modern back-arc seas.

In the Baltic shield, first geologic records indicative of plate tectonics date from that time: ophiolite associations, fragments of the lithosphere of the Svecofennian ocean of an age of 1.95 Ga; the Main Lapland Fault, a collision suture zone more than 700 km long composed of a narrow belt of high-pressure granulites; the above-mentioned Pechenga–Varzuga back-arc basin in the back part of this zone; etc. (Sharkov and Smolkin, 1997). Such tectonic and magmatic processes occurred in all Precambrian shields marking the onset of the continent–ocean stage of their development (Bogatikov *et al.*, 2000). Since that time, in the region and the Earth as a whole, two tectonic and magmatic regimes have been established and occurred up to the present time: intraplate activity and processes related to the boundaries of lithospheric plates (plate tectonics proper). In the Middle and Late Proterozoic, the extents of the two regimes were similar, whereas the major igneous activity of the Phanerozoic was confined to active plate margins.

CHARACTERISTICS OF THE TECTONIC AND MAGMATIC DEVELOPMENT OF THE MOON

Similar to the Earth, two major morphological and structural units are distinguished on the lunar surface, highlands and maria (Fig. 1). Highland regions compose most of the surface of the near side of the Moon and essentially all of the far side. Their structure is not uniform: away from the maria, highland areas show a smoothed relief and large ring structures separated by depressions. The largest among the latter are thalassoids. They approach maria in size but are filled with highland material (Kozlov and Sulidi-Kondrat'ev, 1969; Spudis, 1996; Papike *et al.*, 1998). Characteristic elements of the highland structure are grabens, rather wide valleys with bottoms lowered along normal faults.

Isometric lunar maria (basins) filled with basalts are later structures. They are the largest surface depressions lowered a few kilometers relative to the adjacent highlands. In general, these regions show a flat relief and a much simpler structure. Marginal rises (mountains that were discovered by Galileo) are often observed along the boundary with highlands. They embrace mare depressions as arcs. The elevation varies there by up to 2.5–4.0 km (Lucey *et al.*, 1994). The thickness of accumulated lavas filling the maria varies rather considerably, usually within a few kilometers (Spudis, 1996). Epicontinental zones are distinguished within the marginal parts of the maria. The thickness of mare material in these zones is not great and, in many places, large remnant "islands" jut out from it showing structures similar to those of the adjacent highland areas. In the inner parts of maria, there are mid-mare swell-like rises formed by complex systems of ridges. In addition to them, the zones of marginal swell-like rises are observed. Small intracontinental and marginal depressions filled with mare material occur within the highlands.

The crust thickness varies from 25–35 km beneath the basins to 90–110 km in the highland regions of the Moon's far side at an average value of 60–70 km. Accumulations of excess masses were found below the thinned mare crust. They are referred to as mascons (mass concentrations). The lunar highlands are in a state of isostatic compensation, whereas the basins show a considerable scatter in the degree of compensation, which is not correlated with their size and age (Zuber *et al.*, 1994).

The boundary between the upper and lower mantle occurs at a depth of about 500 km. The radius of the

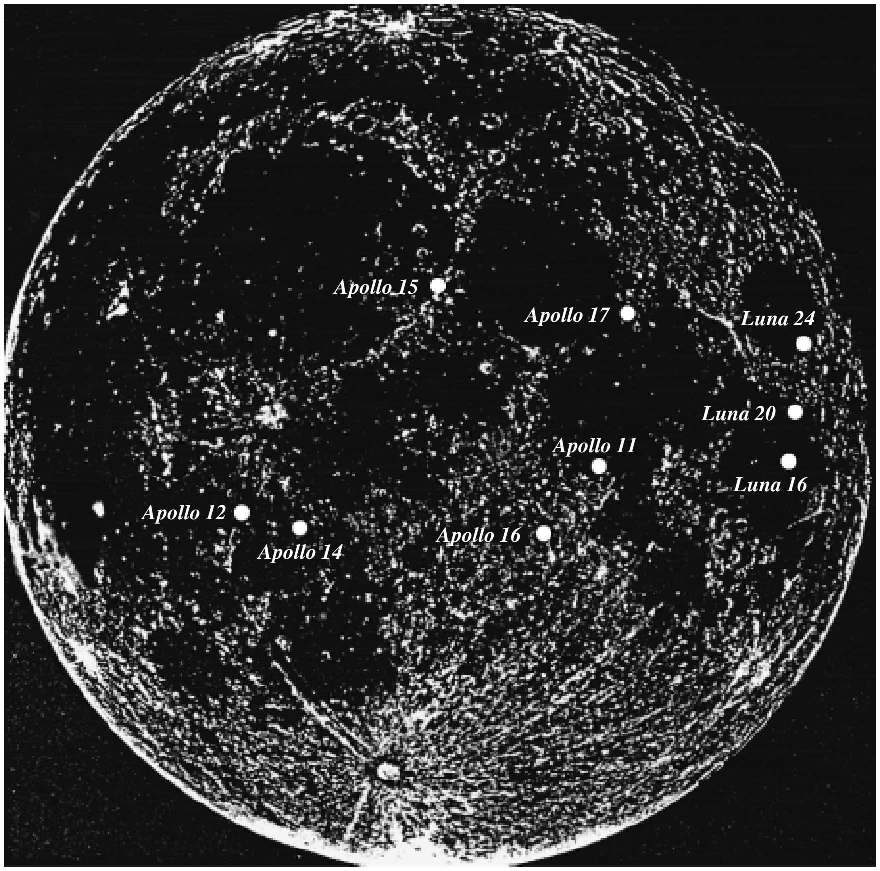

Fig. 1. A map showing Soviet and American mission sites where lunar rocks were sampled (Neal and Taylor, 1992). Highlands are light and mares are dark.

lunar core is estimated as 290–350 km for a Fe-core or 460–530 km for a FeS core (Konopliv *et al.*, 1998; Kuskov and Kronrod, 1999). Thus, the main difference between the interior structures of the Moon and the Earth lies in the relative size of the core, which accounts for about 32% of the Earth by mass and only 2–3% in the Moon.

Highland Magmatism

The highlands are composed of a primary anorthositic crust and two types of younger igneous series. The age of the primary lunar crust, which is made up by iron-rich anorthosite (FAN), is 4.56 ± 0.07 Ga (Alibert *et al.*, 1994). Usually, it is believed to be related to the processes of gravitation differentiation (plagioclase flotation) in a planetary magma ocean, which formed shortly after Moon generation (Ringwood, 1979; Spudis, 1996; Snyder *et al.*, 2000; etc.).

The most common igneous rocks of the lunar highlands, which intrude the primary anorthositic crust, belong to a magnesian series with an age of 4.45–4.25 Ga including volcanics (low-titanium picrobasalts, olivine basalts, basalts, and leucocratic basalts) and their intrusive analogues of the ANT (anorthosite–norite–troctolite) series (Snyder *et al.*, 1995a). The latter are represented by dunite, harzburgite, troctolite, norite, gabbronorite, and anorthosite (more magnesian than the primary crustal anorthosite), which are evolved melts of this series. The rocks are dominated by magnesian olivine, orthopyroxene, pigeonite, and calcic plagioclase with minor chrome spinel, orthoclase, quartz, apatite (or whitlockite), and Ti-bearing phases (ilmenite or armalcolite). These rocks probably composed parts of layered intrusions, which were formed in the lunar crust and tectonically displaced to the surface in the marginal rises (mountains) around maria. This is supported by telephotos of the outcrop of a layered complex, which were obtained by American astronauts at the *Apollo 15* landing site (Fig. 2). In general, the petrographic and mineralogical characteristics of these rocks are similar to those of the terrestrial rocks of early Paleoproterozoic layered intrusions (Sharkov and Smolkin, 1998) differing primarily in a very high anorthite mole fraction of plagioclase, An_{84-98}. In terrestrial rocks, such a plagioclase occurs mainly in the layered complexes of ophiolitic associations. The typical chemical compositions of ANT series rocks are shown in Table 1.

With respect to major and trace element abundances and the character of REE distribution, the rocks of the lunar magnesian series are also similar to the terrestrial early Paleoproterozoic rocks of the SHMS (Fig. 3), and their $\varepsilon_{Nd}(T)$ values (about –1) are consistent with data for terrestrial samples. The only difference is generally much lower alkali contents and higher concentrations of heavy REE. Snyder *et al.* (1995a) supposed that the formation of magnesian series melts was related to the assimilation of rocks of the ancient anorthositic crust by high-temperature mantle liquids ascending through it. Thus, both the chemical composition and formation mechanism of igneous rocks from lunar highlands were similar to the characteristics of siliceous high-magnesium series rocks of the Early Proterozoic cratons of the Earth.

The second type of lunar highland magmatism is much less extensive and is represented by medium-titanium rocks of the KREEP series enriched in K, REE, P, and other incompatible elements (Zr, Nb, U, Th, La, Ba, Rb, etc.). The intrusive analogues of these rocks known as an "alkaline series" are represented by anorthosite, gabbro, norite, and gabbronorite associated with minor monzonite, quartz monzonite, and potassic granite (Snyder *et al.*, 1995b). In contrast to the magnesian series, the composition of plagioclase from the basic rocks ranges from An_{86} to An_{76} and the Mg/(Mg + Fe) ratio of pyroxene, from 0.70 to 0.40. In addition to augite, orthopyroxene, and pigeonite, the rocks contain ilmenite, whitlockite, chrome spinel, zircon, potassium feldspar, Fe–Ni alloy, troilite, and, occasionally, tridymite. The quartz monzodiorite is composed of variable amounts of plagioclase (15–59 vol %), potassium feldspar (2–53 vol %), and iron-rich pigeonite (14–42 vol %); granophyre intergrowths of potassium feldspar and quartz are common. The representative chemical compositions of the "alkaline" series rocks are shown in Table 2.

Isotopic and geochronological data suggests that the formation of alkaline series melts lasted at least 300 m.y., from 4.34 to 4.0 Ga (Snyder *et al.*, 1995b). The Nd isotopic ratio of these rocks is similar to that of the magnesian series, ε_{Nd} is about –1. The ages of potassic granitoids collected during the *Apollo 12* and *Apollo 14* missions also vary from 4.30–4.04 Ga and their $^{87}Sr/^{86}Sr$ is 0.7046 ± 0.0051 (Shin *et al.*, 1994). In general, all these rocks are similar to the terrestrial early Paleoproterozoic low-titanium volcanics with elevated potassium alkalinity (for instance, subalkaline rocks of the Kuetsjarvi Formation of Pechenga, see above) and potassic granitoids. Similar to the Earth, such rocks also played a minor role in the total extent of magmatism of that time.

The occurrence of amphibole and akaganeite [β-FeO(OH)] in the intrusive rocks of lunar highlands suggests the presence of water in the fluid components of the highland basalts (Frikh-Khar *et al.*, 1990) The occurrence of primary reduced phases (troilite, Fe–Ni alloys, etc.) and scarcity of amphibole suggest that the amount of water in the melt was low but exerted a stabilizing effect on the petrogenesis of rocks, which were generally similar to terrestrial analogues. Since the intrusive counterparts of these basalts show the same mineral composition, the low content of volatiles in the melt was not related to the degassing of magmas erupted on the lunar surface but reflected conditions in magma generation regions.

Fig. 2. Rhythmic layering in a block of intrusive rocks from the middle–lower crust exposed on the surface within the marginal swell between Mare Imbrium and Mare Serenitatis (Silver Spoor Range), *Apollo 15* landing site.

The photo shows that the lower and upper parts of the outcrop are separated by a low-angle thrust, along which the block of rhythmically layered rocks thrust over more massive rocks. The escarpment is 600 m high. The telephoto is after Spudis (1996).

Mare Magmatism

The major volume of mare basalts was extruded between 3.9 and 3.2 Ga, in at least four stages. The youngest ages (3.4–3.2 Ga) were obtained for basalts from Mare Crisium and Mare Fecunditatis (Snyder *et al.*, 1994). Compositionally, the mare basalts vary from picrite and olivine basalt to pigeonite and ilmenite basalts. They differ from the highland rocks in higher titanium and iron and lower aluminum and calcium contents (Fig. 4). Based on titanium and potassium abundances, the mare basalts are subdivided into low-titanium (1–5 wt % TiO_2 and 0.06–0.14 wt % K_2O) and high-titanium (8–14 wt % TiO_2 and 0.1–0.3 wt % K_2O) rocks; varieties with intermediate titanium contents (5–8 wt %) are rare (Neal and Taylor, 1992). The latter are represented mainly by unusual rocks, such as high-potassium basalts or tridymite-bearing ferrobasalts, which are probably extreme differentiates of low-titanium basalts (*Apollo 14* collection; Shervais *et al.*, 1985a, 1985b). The low-titanium basalts (including very low-titanium, VLT) are usually more magnesian

Table 1. Major and trace elements in the ANT series rocks (*Apollo 14* mission) after Snyder *et al*. (1995a)

Component	14304	14305	14305	14305[a]	14303	14304[a]	14304[a]	14305
SiO_2, wt %	40	52	55	44.2	43.9	44.2	45	44
TiO_2	0.06	0.28	0.16	0.55	0.26	0.29	0.14	–
Al_2O_3	0.72	20.2	10.7	22.3	29.0	31.9	34.4	35.0
Cr_2O_3	0.09	0.07	0.18	0.08	0.04	0.04	0.03	0.14
FeO	12.1	7.17	6.01	5.17	2.44	1.67	0.75	0.21
MnO	0.12	0.06	0.06	0.06	0.03	0.03	0.01	0.002
MgO	46.4	8.00	22.7	13.8	7.76	3.39	1.02	0.68
CaO	0.52	11.6	5.70	13.1	16.0	17.9	18.9	20.0
Na_2O	0.01	0.70	0.13	0.41	0.45	0.41	0.22	0.31
K_2O	–	0.60	0.03	0.12	0.10	0.12	0.04	<0.15
P_2O_5	0.07	–	–	0.19	0.06	0.05	0.02	–
Total	100.09	100.68	100.67	99.98	100.04	100.00	100.53	100.49
Mg#	87.3	66.5	87.1	82.6	85.0	70.3	70.8	85.2
Sc, ppm	5.4	13.1	16.2	7.8	2.3	3.3	1.2	0.52
Cr	553	1000	2630	570	172	276	237	210
Co	60.0	16.1	25.7	22.3	8.2	7.7	2.3	1.8
Ni	143	50	30	109	56	66	21	12
Ba	11	740	72	429	451	301	272	70
La	1.26	22.5	16.6	33.6	30.0	16.5	10.5	5.01
Ce	3.43	56.5	39.0	85	77.2	40.5	24.8	12.0
Sm	0.52	8.33	3.78	14.2	12.2	5.93	3.49	1.52
Eu	0.06	1.72	0.49	1.83	3.09	2.21	2.49	1.25
Tb	0.118	1.76	0.86	2.68	2.25	1.02	0.573	0.224
Yb	2.44	10.5	5.79	9.69	6.68	3.65	1.69	0.71
Lu	0.512	1.67	0.945	1.41	0.88	0.519	0.215	0.073
Zr	660	410	150	340	280	104	32	<20
Hf	15.9	11.3	3.99	9.98	6.57	3.18	1.18	0.285
Ta	0.049	0.83	0.42	1.11	0.916	0.456	0.156	0.026
Th	0.36	5.13	1.35	5.38	5.49	1.80	1.06	0.123
U	0.24	1.65	0.70	1.66	2.10	0.57	0.20	0.049
Ir, ppb	<1.2	–	–	1.6	0.5	0.8	0.3	–
Au	0.9	<3	<4	<2.5	<1	1.1	<1	<1

Note: 14303–dunite; 14305–norite; 14305[a] and 14303–troctolite; 14304[a] and 14305–anorthosite. Hereafter, the first two digits in the sample number denote the Apollo project mission. Mg# = 100 × Mg/(Mg + Fe). Here and in Tables 2 and 3, dashes mean not analyzed.

and lower in potassium, incompatible elements, and REE.

Mineralogically, the mare basalts are much more different from terrestrial rocks than the highland basalts (Snyder *et al.*, 1994). Similar to other lunar rocks, they are free of magnetite, which is replaced by Fe–Ni metal phases (1.2–8.2 wt % Ni and 1.0–2.6 wt % Co) and ilmenite containing 0.1–1.5 wt % MgO often with ulvospinel inclusions. The rocks may contain up to 20 vol % of ilmenite and often bear troilite. Instead of augite, which frequently occurs in terrestrial basalts, pyroxenes of the pigeonite group are common, from pigeonite proper to pigeonite-augite (subcalcic augite). A characteristic feature of the rocks is the low magnesium fraction of mafic minerals: olivine (sometimes with chromite inclusions), Fo_{38-57}; and pyroxenes of the pigeonite group, En_{20-70}; plagioclase composition corresponds to bytownite–anorthite, An_{87-93}; and some varieties contain orthoclase and tridymite. Shervais *et al.* (1985b) noted the occurrence of interstitial volcanic glass in “high-potassium” mare basalts containing ~65 wt % SiO_2, 17 wt % Al_2O_3, and 10 wt % K_2O. An important characteristic of the mare rocks is the complete absence of hydrous phases, such as kaersutite and

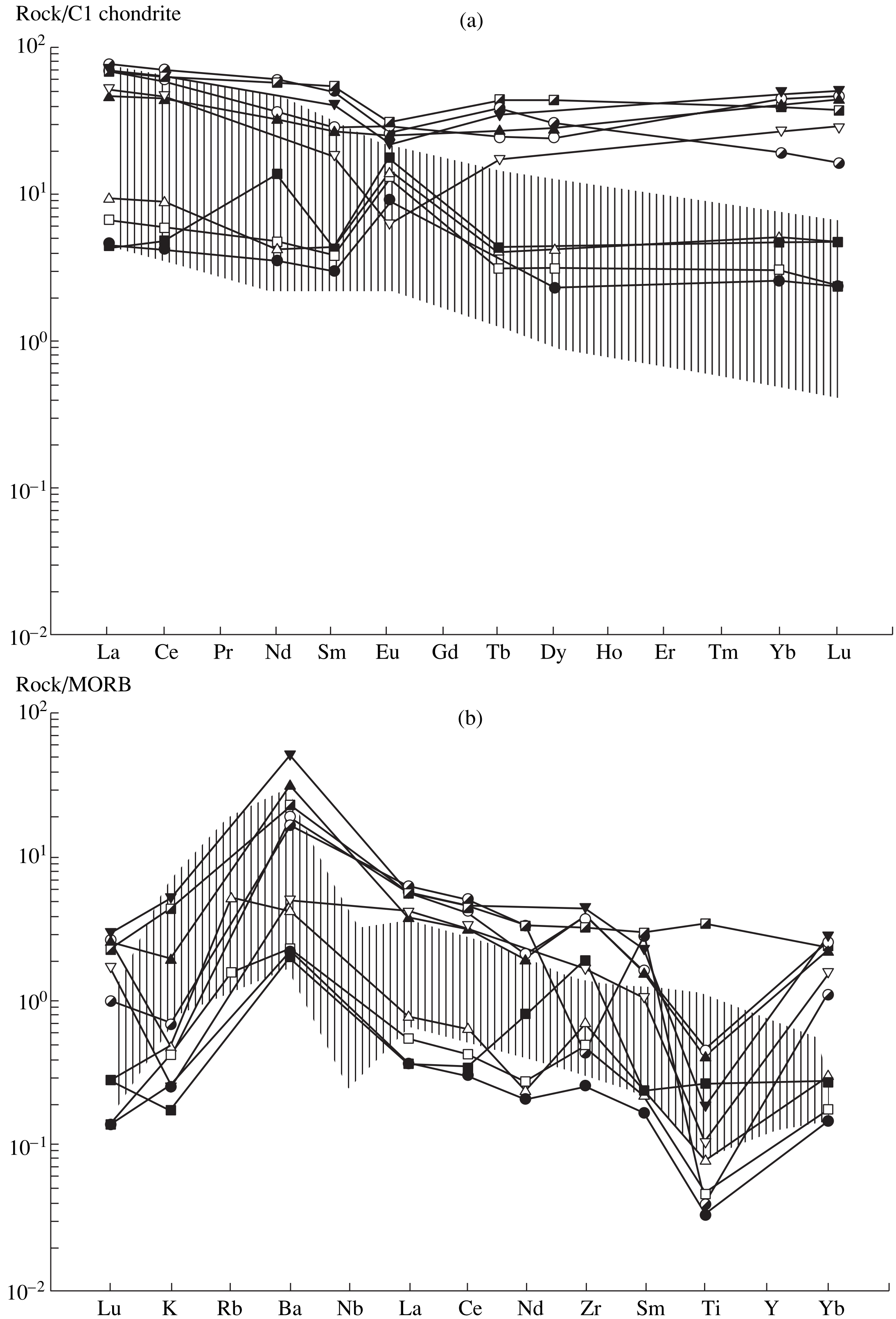

Fig. 3. Geochemical characteristics of the ANT series rocks (Table 1) compared with the rocks of the early Paleoproterozoic Burakovsky layered intrusion, Baltic Shield.

(a) Distribution of REE contents in the rocks normalized to the composition of C1 chondrites and (b) MORB-normalized trace element contents.

Table 2. Major and trace elements in the “alkaline series” rocks after Snyder *et al*. (1995b)

Component	1534.16[2]	A-15 avg	12033	14305	14161	14316	14318	14161	14161	14321	15405	15434
	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2, wt %	51.4	50.7	47.3	43.4	46.3	46.9	49.4	53.9	44.9	74.2	68.1	56.0
TiO_2	2.2	1.9	0.055	0.05	2.5	1.5	0.62	2.4	1.8	0.33	0.90	1.11
Al_2O_3	15.7	15.4	32.9	28.5	12.5	10.6	18.7	12.6	8.5	12.5	10.15	9.8
FeO	10.0	9.8	0.301	2.25	13.0	10.4	8.0	13.4	16.5	2.32	6.99	14.7
MnO	0.15	0.14	0.006	0.026	0.210	0.139	0.106	0.2	0.2	0.023		0.27
MgO	10.0	9.6	0.30	8.3	8.6	15.9	12.3	2.8	6.3	0.07	1.53	5.5
CaO	9.8	9.4	16.9	15.9	10.2	8.40	10.1	8.9	12.9	1.25	4.89	10.5
Na_2O	0.79	0.75	1.56	0.47	1.13	0.783	0.662	1.41	0.75	0.52	0.79	0.66
K_2O	0.60	0.55	0.19	0.069	1.08	0.428	0.228	–	0.35	8.6	3.39	0.72
P_2O_5	0.56	0.56	–	–	2.160	–	–	0.6	1.0	–	–	0.29
Cr_2O_3	0.31	0.33	–	–	0.369	0.239	–	–	4.98	–	–	–
Total	101.51	99.13	99.52	98.97	98.12	95.35	100.12	96.21	97.10	99.81	96.74	99.55
Mg#	64	64	64	87	54	73	73	–	0.143	5	28	40
Sc, ppm	21.2	20.2	0.36	2.6	–	19.0	12.8	30.2	42.2	3.0	–	42.9
V	–	–	<55	–	–	–	–	–	–	–	–	–
Cr	2100	2200	23.1	201	2530	1640	1080	361	982	17	–	1850
Co	19.0	19.8	0.25	12.6	–	38.6	20.3	7.15	15.0	0.94	–	17.6
Ni	–	–	0.36	10	–	295	52	<110	–	4.9	–	–
Rb	–	16	<5	–	–	–	6.1	52	21	210	–	18.9
Sr	180	200	430	211	–	–	–	160	207	55	–	147
Cs	–	–	49	–	–	–	0.92	1.6	0.36	–	–	0.56
Zr	980	900	50	<50	2080	1240	370	4240	7150	–	–	788
Ba	780	720	360	450	4390	850	470	2050	740	2160	–	745
La	74	69	11.6	6.6	314	85	15.6	228	696	44.3	–	46.4
Ce	190	180	23.3	14.8	–	218	39	–	–	117	–	123
Nd	110	105	11.0	8.0	–	134	21.1	–	–	58	–	74
Sm	33.0	30.3	2.41	2.16	131	37.4	5.7	97	326	15.9	–	22.9
Eu	2.70	2.65	6.2	2.6	2	2.9	1.96	3.35	5.68	1.17	–	1.70
Gd	40	37	–	–	–	–	–	–	–	–	–	–
Tb	6.50	6.2	0.31	0.40	23	7.6	1.40	18.7	62.2	4.3	–	5.3
Dy	42	38	1.56	2.33	–	48	9.9	–	–	31.5	–	–
Ho	9.1	8.3	–	–	–	–	–	–	–	–	–	–
Er	–	(25)	–	–	–	–	–	–	–	–	–	–
Tm	3.4	3.1	–	–	–	–	–	–	–	–	–	–
Yb	21.8	20.6	0.62	1.44	96	27	8.9	73.6	146	32.2	–	21.9
Lu	3.20	2.95	0.065	0.19	8.8	1.68	1.49	10.2	18.7	5.1	–	3.03
Hf	23.9	23.2	0.85	0.37	53	25	8.0	100	163	13.9	–	22.8
Ta	2.9	2.7	0.065	0.071	–	2.62	0.74	9.2	4.3	8.3	–	2.0
Th	12.8	11.7	0.162	0.46	–	14.2	3.8	44	37	65	–	10.7
U	–	–	<0.08	0.15	–	4.0	1.25	12	5.4	23.4	–	3.1
Ir, ppb	–	–	<0.03	0.09	–	5.3	0.20	–	–	0.047	–	–
Au	–	–	<0.075	0.190	–	–	0.27	–	–	0.035	–	18.6

Note: 1 and 2, KREEP basalts; 3–12, intrusive rocks of the “alkalic” series: 3–4, anorthosites, 5, monzogabbro, 6–7, norites, 8–9, quartz monzodiorites, 10–11, granites, and 12, quartz monzodiorite.

Table 3. Major and trace components in the mare basalts of the Moon after Neal *et al*. (1994) and Jerde *et al*. (1994)

Component	12006	12015	12017	12016	B3	A	B2	D
	1	2	3	4	5	6	7	8
SiO_2, wt %	44.23	44.98	47.27	42.78	42.2	40.7	40.0	41.4
TiO_2	2.59	2.86	3.37	4.02	10.3	11.0	8.93	8.43
Al_2O_3	7.67	8.57	10.0	7.23	9.45	8.20	11.5	11.4
FeO	20.94	20.18	19.72	22.64	17.6	20.2	19.5	19.2
MnO	0.29	0.29	0.29	0.30	0.25	0.23	0.26	0.26
MgO	14.67	11.88	7.63	12.65	8.50	8.01	7.57	7.33
CaO	8.13	9.21	10.97	8.42	11.2	10.5	11.2	11.5
Na_2O	0.20	0.23	0.27	0.22	0.34	0.52	0.43	0.38
K_2O	0.05	0.06	0.09	0.06	0.05	0.30	0.07	0.09
P_2O_5	–	–	–	–	0.07	0.19	0.11	0.21
Total	100.09	100.68	100.67	99.98	100.04	100.00	100.53	100.49
Sc, ppm	40.1	46.1	52.8	49.4	76.5	82.2	76.7	78.0
V	–	–	–	–	106	71.8	70.7	97.0
Cr	6250	4653	3550	3950	2813	22.58	1505	2258
Co	60	51	32	54	17.5	27.7	14.3	16.7
Ni	110	50	–	25	–	–	–	–
Sr	89	94	118	126	–	164	160	–
Rb	–	–	–	–	–	5.68	0.63	–
Ba	56	61	75	59	60	297	130	203
La	–	–	–	–	5.70	26.5	15.9	33.1
Ce	15.7	16.3	–	16.2	23.0	78.5	49.7	93.0
Nd	–	–	–	–	23.0	65.3	43.0	75.3
Sm	3.77	4.31	5.1	5.5	8.10	20.9	14.6	23.3
Eu	0.72	0.81	–	1.06	1.50	2.24	1.89	1.93
Tb	1.02	1.05	–	1.42	1.96	4.61	3.21	4.73
Dy	–	–	–	–	13.0	31.2	21.4	31.7
Yb	3.3	3.7	4.4	5.0	7.65	17.3	11.8	16.8
Lu	0.47	0.53	0.66	0.67	1.14	2.49	1.64	2.39
Y	31	35	–	45	–	–	–	–
Zr	97	110	–	117	–	–	–	–
Nb	6.4	6.6	–	6.1	–	–	–	–
Hf	3.0	3.5	–	6.3	6.4	16.5	10.1	12.6
Ta	–	–	–	–	1.5	2.4	1.9	1.7
Th	–	–	–	–	0.3	3.1	1.2	2.5

Note: 1–4, Collection of *Apollo 12*, low-titanium basalts: 1–2, olivine basalts, 3, pigeonite basalt, and 4, ilmenite basalt; 5–8, collection of *Apollo 11*, high-titanium basalts: 5, "primitive" basalt B3, 6–8, basalts of groups A, B2, and D, respectively.

biotite typical of terrestrial Fe–Ti basalts. The representative chemical analyses of mare basalts are shown in Table 3.

Similar to the highland rocks, the mare basalts also show evidence for fluid components in the melts: significant contents of fluorine, sodium, potassium, sulfur, phosphorus, chlorine, and zinc were found in films on glass beds from orange soil (*Apollo 16* collection) and drops of green volcanic glass of a picritic composition (*Apollo 15* collection), which were formed at flowing and spraying of erupted lava (Cadenhead, 1975; Wasson *et al.*, 1976). The significance of chlorine in the genesis of these melts was supported by mineralogical studies. For instance, glass inclusions with numerous microscopic vacuoles containing halite, sylvite, and oldhamite were found in pyroxene from a sample of

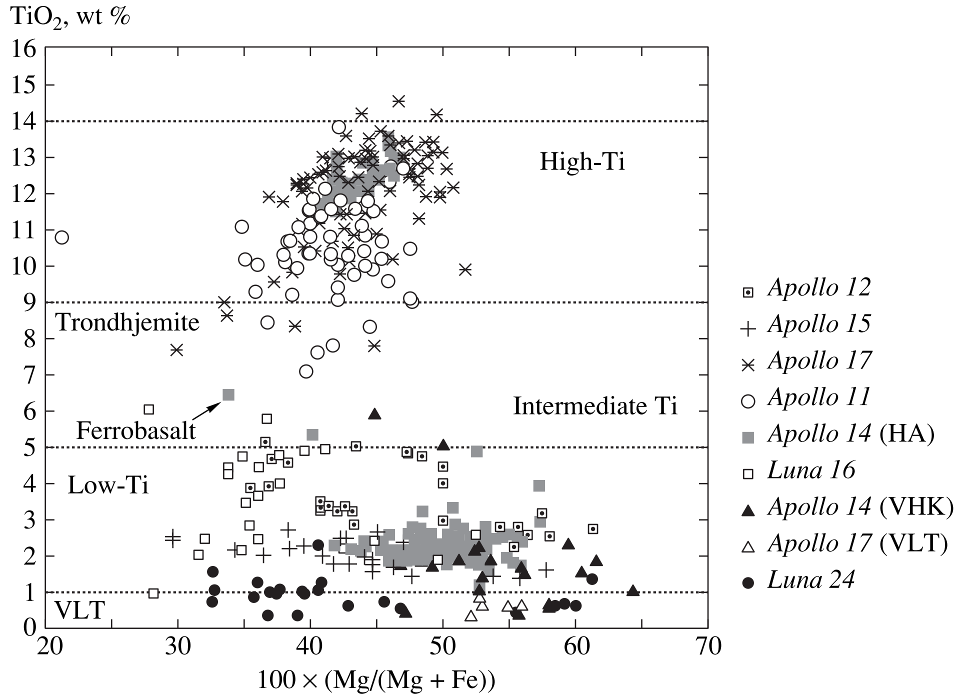

Fig. 4. Titanium concentration versus magnesium number (Mg#) in 500 samples of mare basalts after Neal and Taylor (1992).

regolith obtained by *Luna 20* (Frikh-Khar *et al.*, 1990). However, in contrast to the highland rocks, no evidence was found in the mare basalts for the presence of water, which is the main oxidizer in magmatic processes. This fact is probably responsible for the wide occurrence of mineral phases formed under reduced conditions close to the iron–wüstite buffer.

The intrusive analogues of the high-titanium basalts are probably ilmenite–olivine gabbro, "alkaline anorthosite," leucodolerite, and ilmenite–olivine dolerite containing the sodium richest plagioclase ($An_{73–81}$). In addition to pigeonitic clinopyroxene, which is common in mare basalts, they contain pyroxferroite, a calcium-bearing iron-rich silicate (Bogatikov *et al.*, 1985). Similar to the highland rocks, the identical mineral compositions of lavas and intrusive rocks suggest that the low content of volatile components was an inherent characteristic of melts rather than a result of degassing of erupted lavas.

The bimodality of the mare magmatism with respect to titanium and alkali contents resembles the situation in the oceanic and continental flood basalt provinces of the Earth, where within oceanic spreading zones (mid-ocean ridges, MOR), two types of melts may form: tholeiitic basalts (MORB) in the axial parts of ridges and Fe–Ti alkali basalts of oceanic islands on ridge slopes. We believe that the low-titanium mare basalts could be lunar analogues of terrestrial MORB, while the high-titanium varieties are correlated with terrestrial Fe–Ti picrites and basalts, which are chemically similar but different in mineral composition. It is notable that lunar maria show morphological structures resembling structures on the bottom of the Earth's ocean. Such structures are mid-mare swell-like rises, which could be analogues of mid-ocean ridges, and local zones of swells, possible analogues of oceanic islands.

The value $\varepsilon_{Nd}(T)$ of the high-titanium mare basalts ranges from +3 to +7.5 and the initial ratio $^{87}Sr/^{86}Sr$, from 0.69917 to 0.6994, which is similar to the characteristics of terrestrial oceanic and continental flood basalts. The regression line yields a lower intercept with an age of 4.46 ± 0.17 Ga (Snyder *et al.*, 1994). Geochemically, the main differences between lunar mare igneous rocks and their terrestrial analogues are the following: (1) approximately equal chondrite-normalized (C1) light and heavy REE contents (Fig. 5), which suggests that the magma source regions in the Moon developed under low pressures without participation of garnet; (2) generally low contents of alkalis and light REE; and (3) the appearance of a clear negative Eu anomaly, especially in high-Ti varieties. In contrast to the high-titanium varieties, the low-titanium mare basalts (especially those supplied by *Apollo 15*) are essentially free of any Eu anomaly, and their flat REE distribution patterns suggest chondritic relative abundances of these elements in the source material. The magnitude of the Eu anomaly increases rapidly with increasing contents of titanium, alkalis, and REE in the rocks (Fig. 5).

Evolution of Lunar Basalts in the System Ol–Cpx–Pl–Qtz

The evolution paths of lunar igneous melts from highlands and maria were evaluated in the generalized system *Ol–Cpx–Pl–Qtz* using the method proposed by Sharkov (1983). The chemical compositions of rocks were recalculated to CIPW norms and projected onto the tetrahedron faces. The distribution density of points was determined then by means of a reticle (Figs. 6, 7). Subsequently, the obtained patterns were compared with phase diagrams at various pressures. The confinement of a point cluster to a certain cotectic was considered as evidence for melt evolution under the respective conditions.

Mare basalts were characterized by the collections of *Luna 20*, *Apollo 14* and *Apollo 17*. Figure 6 shows that the points of analyses form a single elongated cluster. It issues from the olivine volume, reaches the *Ol–Cpx* cotectics along the olivine control line, and terminates at the four-phase peritectic point *Ol–Cpx–Opx–Pl* at a pressure of 1–2 kbar. Under lunar conditions, this corresponds to lithostatic pressure at depths of about 25–50 km. High-titanium basalts plot in the lowest temperature portion of the trend, near the four-phase point *Ol–Cpx–Opx–Pl* and do not show independent clustering. We believe that the main evolution trend of mare melts reflects processes in magma generation regions, i.e., varying degree of melting of a mantle source, whereas the scatter of the points is related to crystal fractionation processes in transitional magma chambers. Note that the compositional field of mare basalts is clearly bounded by the orthopyroxene barrier (Sharkov, 1984), which prevents melt evolution into the region of quartz-bearing compositions.

Highland basalts (magnesian and alkaline series) are represented by collections of *Luna 16*, and *Apollo 12*, *14*, *15*, and *17*. Since our investigation methods are appropriate only for extrusive rocks (chemistry of cumulates does not correspond to the composition of melt from which they were derived), the ANT series is not considered in this paper. In contrast to the mare basalts, the cluster of highland basalts shows an irregular near isometric shape tending to locate near the *Ol–Opx* cotectics (Fig. 7). A compact maximum is confined to the ternary points *Ol–Spl–Opx* and *Spl–Opx–Pl* in the system *Ol–Cpx–Pl–Qtz* at pressures of about 8–10 kbar, which is equivalent to depths of 200–250 km. The melts clustering near the *Ol–Spl–Opx* point were formed at higher pressure as compared to those plotting near the *Spl–Opx–Pl* point. We believe that the transition between these two points was related to the assimilation of lower crust rocks by deep-derived high-temperature primary melts, which is suggested by isotopic and geochemical data (see above). The lack of a distinct trend similar to that of the mare rocks indicates that melt formation occurred in a much more stable environment and, as in the above-described case, the scatter of points probably resulted from melt evolution in a transitional chamber.

Thus, the highland melts were derived at much higher pressures than the mare basalts. In contrast to the latter, the evolution path of the highland melts was not arrested by the orthopyroxene barrier and passed across into the region of quartz-containing compositions (Fig. 6). This is consistent with the occurrence of monzodiorite and granite among the highland lunar rocks. It was shown previously for terrestrial igneous series (Sharkov, 1984; Ryabchikov, 1987) that the crossing of the orthopyroxene barrier is probably related to the presence of water in the melt, which shifts the melt evolution trend toward more silicic compositions. Since there is evidence of water occurrence in the highland igneous rocks, such an explanation can be valid for the lunar melts.

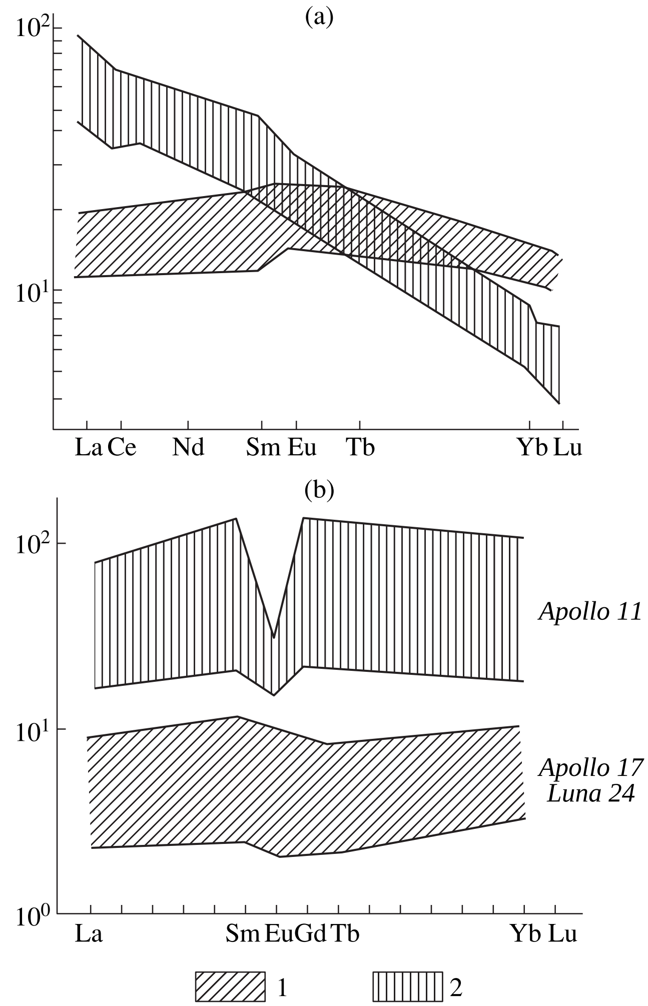

Fig. 5. Chondrite-normalized REE distribution in the lunar mare basalts (Ringwood, 1979; Snyder *et al.*, 1995b) compared with the late Paleoproterozoic basalts of the Pechenga structure, Baltic Shield.

(a) Basalts of the Pilgujarvi Formation of the Pechenga structure: (1) MORB-type and (2) titanium ferropicrites (Smolkin *et al.*, 1995); (b) mare basalts: (1) very low titanium (VLT), collections of *Apollo 17* and *Luna 24* (Snyder *et al.*, 1995b) and (2) high-titanium, collection of *Apollo 11* (Jerde *et al.*, 1994).

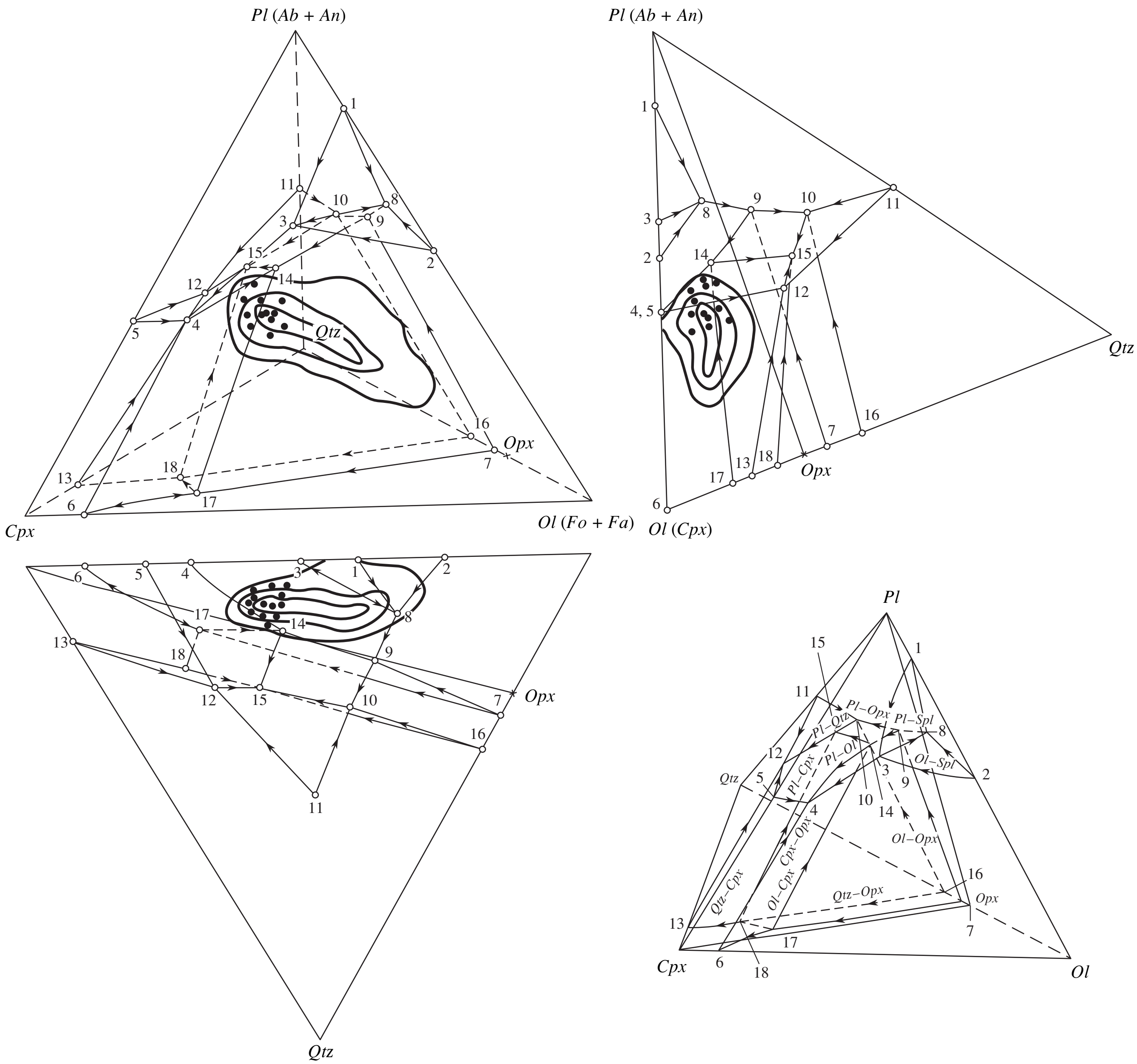

Fig. 6. Position of the compositional points of lunar mare basalts on the faces of the diagram *Ol–Cpx–Pl–Qtz* at a pressure of 1 kbar. The lines comprises 95, 75, and 50% of points, respectively. Here and on Fig. 7, the right left figure is a front view; lower left, a top view; lower right, a general view of the diagram. The points show the compositions of high-titanium basalts.

Thus, the main types of lunar igneous melts show quite dissimilar evolution trends following different cotectic lines under different conditions, low-pressure for the mare rocks and high-pressure for the highland rocks. On the *Ol–Cpx–Pl–Qtz* diagram, the point clusters of the two groups of rocks almost do not touch each other, which supports their different natures. The fact that the highland melts crossed the orthopyroxene barrier is probably indicative of the presence of some water in them.

DISCUSSION

Petrogenetic Comparison of Lunar Igneous Rocks with Their Terrestrial Analogues

According to current concepts, the primary anorthositic crust of the Moon, which comprises about 40% of lunar Al_2O_3, was formed by the processes of plagioclase flotation in a global magma ocean, which appeared shortly after the origination of the Moon (Ringwood, 1979; Spudis, 1996; Snyder *et al.*, 1999). This ocean could be up to 400–500 km deep. Crust for-

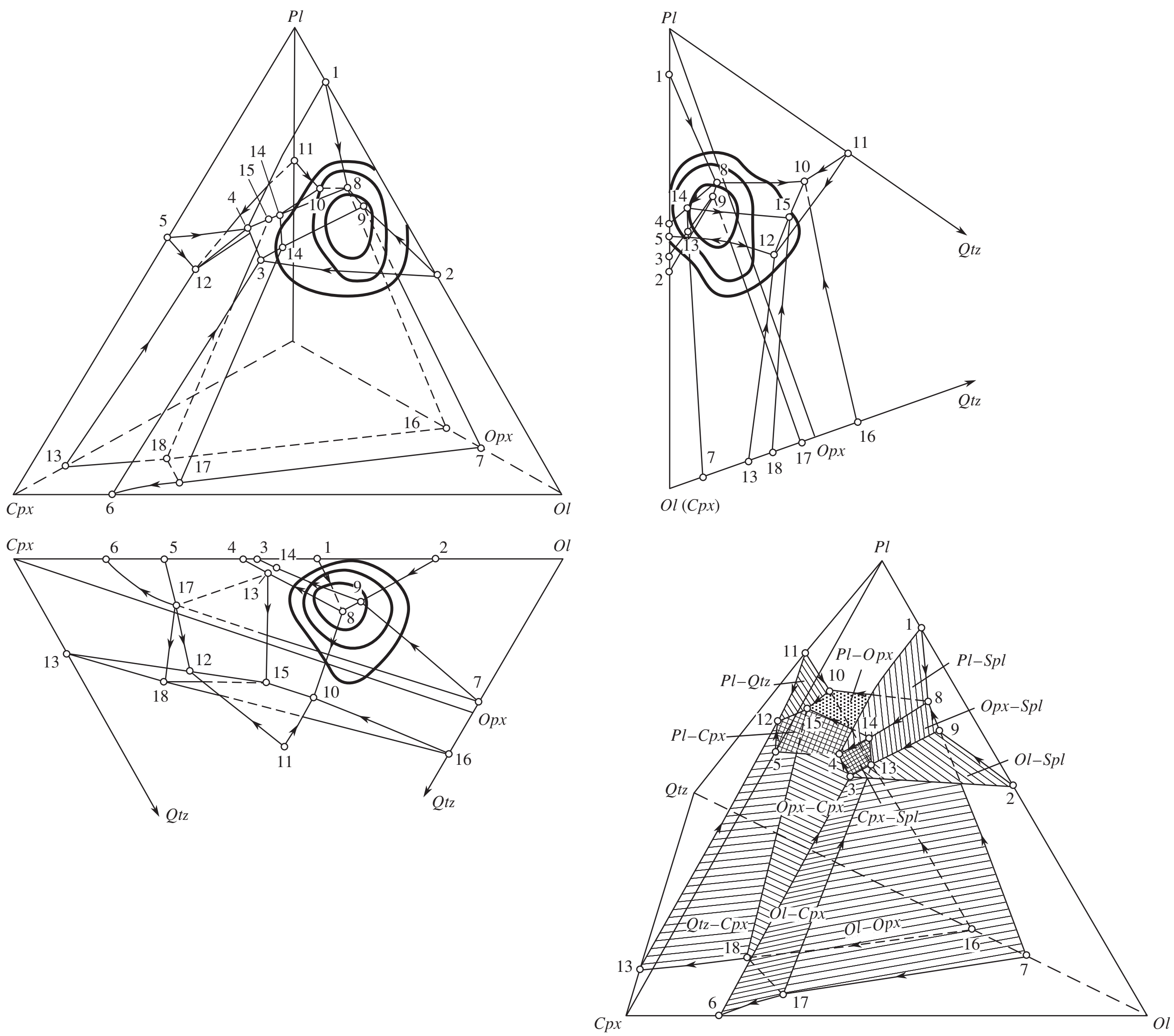

Fig. 7. Position of the compositional points of highland basalts (magnesian and "alkaline" series) on the faces of the diagram at a pressure of 10 kbar.

mation probably began after 75–80% solidification of the ocean when plagioclase appeared on the liquidus. It is thought that a layer of ilmenite-rich cumulates was generated immediately below the crust. It is underlain by a thicker zone of Ti-poor peridotites composed of olivine and orthopyroxene with minor clinopyroxene, which build up the Moon's upper mantle. The residual melt enriched in K, REE, and P (urKREEP) could be retained in the mantle for some time in interstices between grains and (or) in larger segregations. These melts ascended toward the surface and occasionally gave rise to the "alkaline" magmatism, although their major volume crystallized in the lower crust as intrusive bodies.

The second stage of Moon development commenced at about 3.9 Ga and was related to near-contemporaneous falls of large meteorites (known as the lunar cataclysm), which provided impact-induced melting of the lunar lithosphere and formation of depressions of lunar maria (basins) from 300 to 1100 km in diameter. Since the composition of the mare basalts differ significantly from that of the highland rocks, it is believed that the melt generation occurred at considerable depths, 20–60 km (which is consistent with the above-discussed estimates) and involved the material of the lower crust and even of the upper mantle including the proposed ilmenite-rich cumulates (Spudis, 1996; Snyder *et al.*, 2000).

However, these models are to a large extent of a speculative character and are based mainly on the assumption that, in contrast to the Earth, the development of the Moon's surface was controlled by external impact processes. The possibility of the internal endogenous development of the Moon is thus ignored and without sufficient reason the Moon is set against other terrestrial planets, where the significance of endogenous processes is beyond doubts. The importance of impact processes in the formation of the Moon's surface is unquestionable. However, in our opinion, their significance is evidently overestimated. The consideration of factual evidence suggests that the character of igneous melts and evolution of tectonic and magmatic activity on Earth and Moon had remarkably much in common (Sharkov and Bogatikov, 1999). Hence, it is reasonable to revisit this problem taking into account recent data on the endogenous development of the Earth.

Igneous Series of Highlands

It was noted above that the igneous rocks of lunar highlands are similar to the early Paleoproterozoic rocks of the Earth. In both cases, magmatism was related to the ascent of mantle plumes composed of ultramafic material strongly depleted during previous magmatic activity. The head parts of these plumes attained their buoyancy level, where they spread at significant depths and melted owing to decompression. On the Earth, the products of melting of this material and interaction of newly formed liquids with the rocks of ancient sialic crust were represented by siliceous high-magnesia series, which were widespread in that time. They are associated with potassium-rich rocks, such as monzodiorite and potassic granite (often peralkaline) and low-titanium subalkaline volcanics, such as the rocks of the Kuetsjarvi Formation of Pechenga. The source of potassium in these rocks is probably the mantle affected by metasomatic enrichment.

The character of igneous processes at lunar highlands was in general close to the early Paleoproterozoic magmatism of the Earth. The magnesian series is in many respects similar to SHMS and was probably derived by the melting of mantle plumes composed of depleted ultramafic material and subsequent assimilation of crustal material by the ascending high-temperature mantle magmas. Physicochemical data (see above) suggest that the melting occurred at depths of about 200–250 km. The rocks of the "alkaline" series (KREEP) are also similar to the early Paleoproterozoic potassic terrestrial rocks. This allows us to suggest that these potassium-rich rocks were also related to mantle fluids released at the degassing of the plume material during cooling. An important fact is the presence of water among fluid components, which probably played an important part in the petrogenesis of highland melts.

Igneous Series of Maria

Similar to the Earth, two types of basalts occur in the mare structures of the Moon: low-titanium and high-titanium. Tentatively, they can be correlated with MORB and Fe–Ti basalts of oceanic islands and seamounts, respectively. Both types of basalts appeared on the Earth only in the late Paleoproterozoic simultaneously with the earliest geologic records of plate tectonics. They are the most widespread products of igneous activity in the Phanerozoic composing oceanic floor and continental flood basalt provinces. On the Moon, these basalts terminated the period of its active development. This type of magmatism has occurred on the Earth up to the present day, which allows its relatively good understanding. The formation of respective melts is related to the ascent of mantle plumes of the third generation, which form at the boundary between the liquid (outer) core and the mantle, in the D" layer (Olsen *et al.*, 1990; Dobretsov and Kirdyashkin, 1994). The material of such plumes is characterized by the presence of a specific fluid phase enriched in Fe, Ti, alkalis, P, Ba, Zr, REE, and other elements, which is suggested by the development of mantle metasomatism (occurrence of interstitial kaersutite, phlogopite, carbonates, etc. in the mantle rocks) and vein bodies of titanium-rich hornblende peridotite, pyroxenite, hornblendite, and glimmerite (mica rocks), which formed at the crystallization of fluid-saturated melts in the mantle. The fragments of such bodies are known as the "black series" of mantle xenoliths (*Magmaticheskie gornye…*, 1988). Because of the presence of volatiles, the material of these plumes was less dense than the material of Archean and early Paleoproterozoic plumes. This resulted in that the plumes of the third generation could reach the basement of the crust, and spreading of their heads caused ruptures of the ancient continental crust and formation of the oceanic lithosphere. This was accompanied by the appearance of subduction zones, where redundant crustal material was consumed.

However, paleomagnetic data suggest much earlier generation of the liquid core of the Earth at about 2.6 Ga (Hale, 1987). Petrologically, this is supported by the rare occurrences of Late Archean ferropicrites, which were mentioned above. Probably, the initial scale of fluid infiltration was low and, judging from the first appearance of potassic rocks in the Late Archean, potassium was the dominant constituent of the fluid. The progressive heating of the core changed the component composition of fluid and increased its amount. As late as at 2.2–2.0 Ga, these processes attained a critical level when superplumes initiated by fluids could reach the basement of the crust.

The lowest concentration of fluid components are observed in MORB and the highest, in Fe–Ti basalts of the intraplate type. On the example of mid-ocean ridges, it is evident that the second type of basalts is of subordinate importance and often occurs on ridge slopes, where magma generation processes related to oceanic spreading played a minor role (Anderson *et al.*, 1992). Away from the axes of mid-ocean ridges, the composition of melts becomes more alkaline and richer in titanium. A similar situation is observed in continental flood basalt areas, which are also related to the ascent of superplumes: they are dominated by tholeiitic basalts similar to MORB, whereas moderately alkaline Fe–Ti basalts occur in minor amounts at the base of trap plateaus and their peripheries (Fedorenko *et al.*, 1996). The occurrence of continental flood basalts often predates ocean opening and they may be hence considered as the first stage of development of oceanic structures.

The nature of coexistence of the two types of basalts is not yet understood. The zoning of magmatism from the central parts of spreading zones toward margins allows the suggestion that the main reason is different mobilities of silicate and fluid components in plumes. They probably moved together in the axial parts of plumes, but the situation changed when the plumes reached their buoyancy level and their heads spread, which was accompanied by cooling and sinking of their outer parts. This resulted in the release of a fluid phase, which could accumulate in local "traps" and promote generation of a new type of melts, picrites and basalts enriched in alkalis, titanium, and iron. Fluid fractionation should be most extensive far from spreading axes, where the plume material cooled and ancient depleted mantle peridotite above the plume roof was entrained into melting. This gave rise to melts with extremely high contents of alkalis and titanium (up to 6–7 wt % of TiO_2), such as alkali picrite, meymechite, and kimberlite (Kogarko and Ryabchikov, 1995).

By analogy with the Earth, the petrogenesis of mare basalts could be connected with the plume-type activity. Similar to the Earth, the plumes generated at the core–mantle boundary and the spreading of their head parts caused formation of large mare depressions with reduced crust thickness. In contrast to the Earth, the liquid metal core of the Moon has not preserved, and the present-day Moon has no dipole field. However, there is paleomagnetic evidence on the existence of such a field between 3.9 and 3.2 Ga, which suggests the presence of a liquid core (Rancorn, 1983). The development of lunar maria occurred in the same period. Such a coincidence is hardly fortuitous, because plumes of the new generation could be formed only under such circumstances. The main distinctions of fluid components of lunar plumes from those of similar terrestrial plumes are higher contents of Ti and Fe, lower contents of alkalis, and almost complete absence of water. Melting occurred in a much more reduced environment close to the iron–wüstite buffer.

It is remarkable that the earliest magnetic anomalies on the Moon appeared at ca. 4.2 Ga, and the highest magnetic field intensity of 1 Gs was attained only at 3.9 Ga, when it was twice as high as the present-day value near the Earth's poles (Rancorn, 1983). This suggests that the formation of the liquid lunar core commenced at least 4.2 b.y. ago and continued until the core attained the critical size at 3.9 Ga. To a considerable degree, this transitional period coincided with the formation of potassium-rich rocks of the "alkaline" series, which resembled the situation on the Earth in the Late Archean and early Paleoproterozoic. In both cases, the processes occurred similarly to the Phanerozoic ones: deep-derived fluids probably accumulated in "traps" resulting in a local enrichment of melting areas in potassium.

Another important distinction of many mare rocks from their terrestrial analogues is the presence of a significant Eu anomaly, which usually results from plagioclase fractionation in the magmatic process. In particular, this gave rise to the idea that plagioclase was removed by a previous fractionation event (flotation) from the source region of mare basalts during the existence of the magma ocean. However, Fig. 5 demonstrates that the lowest titanium and highest magnesium (most primitive) mare basalts are essentially free of any Eu anomaly or show a slight negative or positive anomaly. The medium titanium varieties show a distinct anomaly, while all high-titanium rocks have a considerable negative Eu anomaly increasing with titanium content. Because of this, the later workers regarded the Eu anomaly in the mare basalts as a consequence of their origin through the remelting of mesostasis of the anorthositic crust, filter pressing of the mesostasis of KREEP cumulates, or crystal fractionation of KREEP basalts (Ringwood, 1979; Snyder *et al.*, 1995a). However, geochemical data do not support such opinions (Neal and Taylor, 1992).

We believe that the Eu anomaly phenomenon in some mare rocks is most likely a consequence of the reduced character of lunar interiors. It is known that the ratio Eu^{2+}/Eu^{3+} in a magmatic system depends on f_{O_2} and, in a reduced environment, Eu occurs essentially entirely as Eu^{2+} (Wilson, 1989). In terrestrial basaltic melts, Eu occurs in both oxidation states and the removal of one of them is compensated by the accumulation of the other. In contrast, in lunar basaltic melts, Eu occurs only in a bivalent form and fractionation must strongly affect the content of this element in the residual melt. Consequently, the Eu anomaly in mare titanium-rich basalts could be due to plagioclase fractionation in intermediate magma chambers (intrusions) in a form of various gabbroids. Since the abundance of Eu in basalt increases rapidly with increasing Ti concentration (Wilson, 1989), this process was most efficient in titanium-rich melts.

By analogy with the terrestrial trap magmatism (Fedorenko *et al.*, 1996), the existence of two types of mare basalts and the confinement of Eu anomaly predominantly to the high-titanium rocks can be considered as indications for the involvement of material from the ancient lunar lithosphere into melting processes. This is supported by the above-mentioned Nd model age of high-titanium mare basalts (~4.46 Ga). The repeated melting of such a material affected by the Fe–Ti bearing fluid phase must produce a Eu-depleted melt. In other words, the same mechanism of magma formation that is observed in oceans and continental

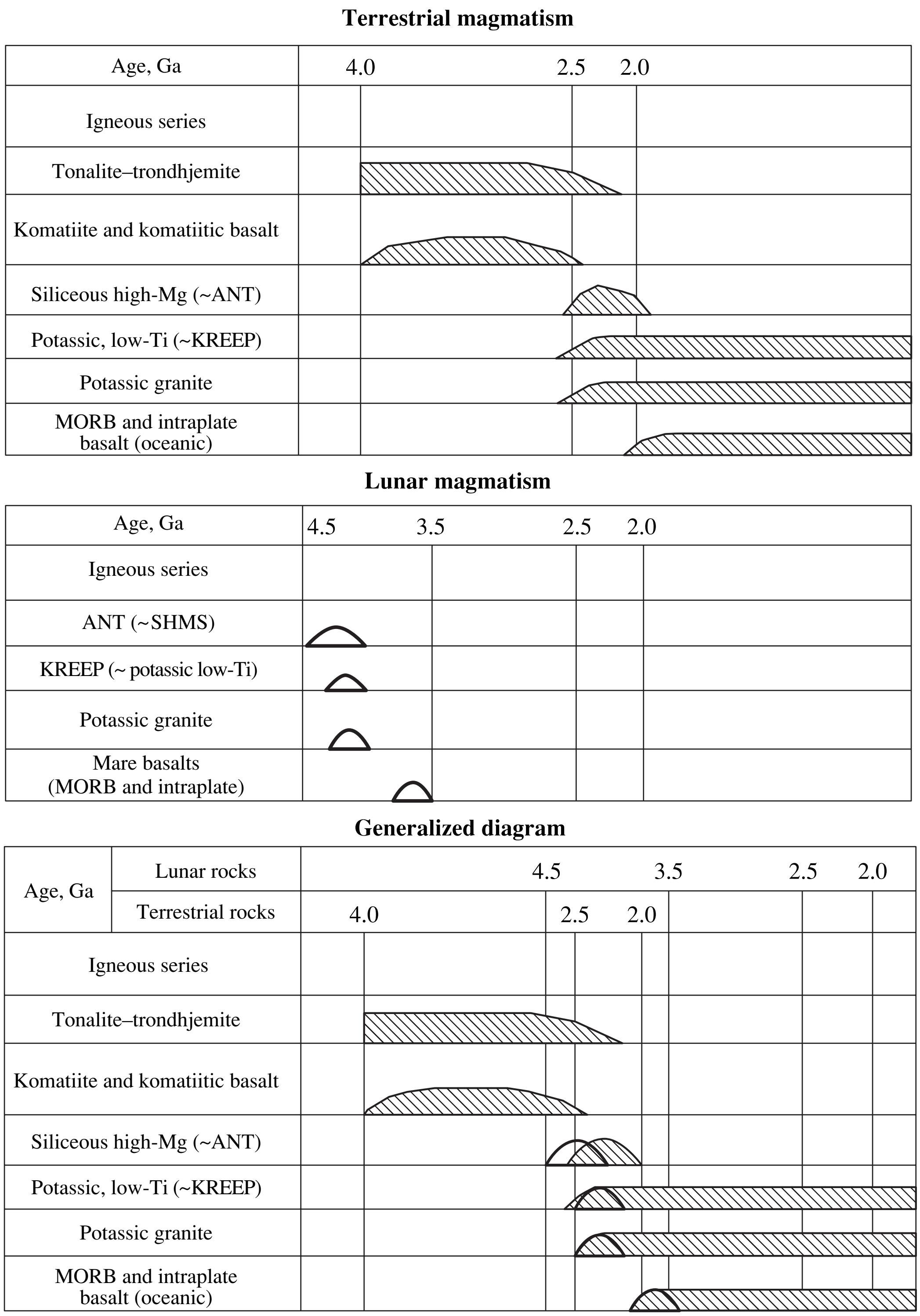

Fig. 8. Diagram illustrating the magmatic evolution of the Earth and the Moon. The hatched intervals show the distribution of the main types of terrestrial igneous series and bold lines show intervals of the development of the main types of igneous series of the Moon.

flood basalt regions of the Earth could occur on the Moon: in the peripheral sinking parts of mantle plumes, the fractionation of fluid phase takes place, and the most mobile components infiltrate into the overlying rocks of the ancient depleted mantle causing their melting and formation of geochemically enriched high-tita-

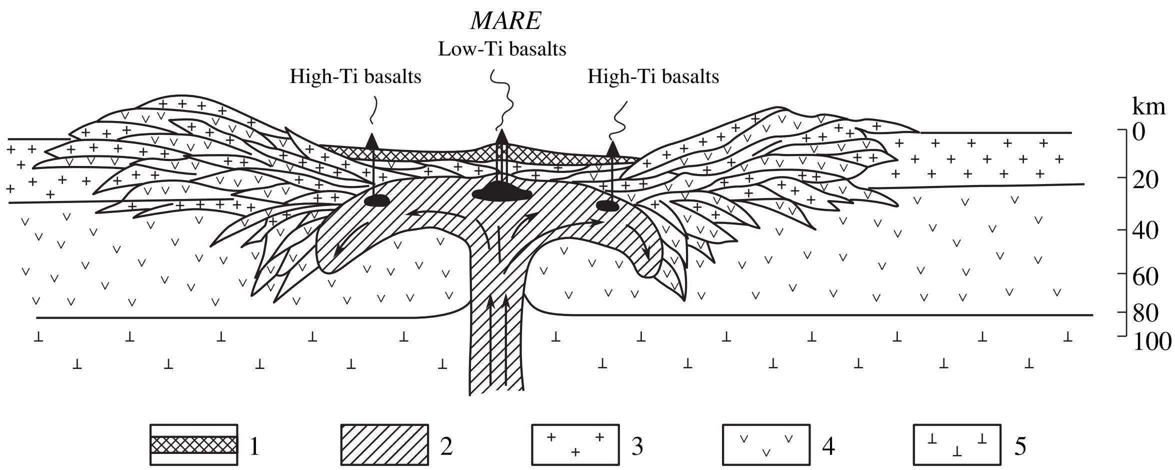

Fig. 9. A schematic diagram illustrating the process of lunar mare formation.
(1) Mare basalt, (2) mantle plume, (3) upper crust, (4) lower crust, and (5) lithospheric mantle.

nium melts. Under conditions of the relatively weak gravitation field of the Moon, difference in the depth of magma formation areas has no significant effect on pressure, and the low-titanium and high-titanium varieties of mare basalts do not form separate fields in diagrams (Fig. 7) overlapping in the region of low-temperature compositions.

Tectonic and Magmatic Processes of the Earth and Moon

The analysis of tectonic and magmatic activity at the early stages of planetary body development demonstrated that its character on lunar highlands bore resemblance to that on Earth in the early Paleoproterozoic (Fig. 8) (Sharkov and Bogatikov, 2001). Similar to the Earth, two types of igneous series formed in the lunar highlands: magnesian series derived from depleted mantle sources with a significant contribution from crustal material and KREEP ("alkaline") showing evidence of mantle metasomatism. Moreover, as on the Earth, two major types of tectonic structures were originated: upwelling areas developing in an extension regime and resembling terrestrial cratons and depressions between them (talassoids). The latter probably represented territories between plumes, where the descending movement of material took place. In this respect, they resembled terrestrial areas, where granulite belts formed in the early Paleoproterozoic (Sharkov *et al.*, 2000). Both on the Earth and Moon, the formation of these largest tectonic domains caused considerable changes in the primary anorthositic crust. The spreading of plume heads of the first generation occurred at great depth, which is consistent with our data on the physicochemical evolution of highland melts (see above).

The appearance of a new type of tectonic and magmatic structures, lunar maria, was accompanied by the formation of large areas of mare basalts. As was mentioned above, the mare structures are associated with accumulations of excess masses (mascons) with a thinned crust above them. Many workers argued that the mascons originated owing to the ascent of mantle material at crust discharge resulting from the ejection of crustal material during large impact events (Spudis, 1996). However, this is not consistent with the aforementioned prolonged development of mare magmatism and its bimodal character. Petrologically, it is more probable that mascons are heads of the solidified mantle plumes that were responsible for mare magmatism. Their possible terrestrial analogues are large lenslike bodies of anomalous lighter mantle material under modern mid-ocean ridges and continental rift regions (Grachev, 1987; Anderson *et al.*, 1992).

Because of the presence of mantle fluids, plumes of the second generation ascended to shallower levels and spreading of their head portions resulted in more extensive crust transformations related to the formation of mare depressions. The excess ancient crustal material was heaped as packets of tectonic slices at the outer parts of spreading plumes resulting in the development of a mountain morphology at the boundary with highlands (Fig. 9). The available data suggests that these slices contain fragments of deep-derived layered intrusions with well-preserved rhythmic layering (Fig. 2). Similar structures are known on the Earth in the modern Alpine belt, where large depressions with the ocean-type crust formed above spreading heads of plumes (Alboran and Tyrrhenian seas, Pannonian depression, etc.) and mountain ranges appeared at their margins (Gibraltar arc, Apennines, and Carpathians, respectively). The latter are built up of tectonic slices composed of upper crustal rocks with fragments of the lower crust and blocks of mantle rocks, such as Ronda, Beni Bouchera, and other massifs (*Magmaticheskie gornye…*, 1988; Bogatikov *et al.*, 2000). In other words, similar to the Earth, the ascent of such plumes was accompanied by significant alteration of previously formed crust and formation of large depressions with reduced crust thickness and their mountain framing, where tectonic blocks of deep-seated rocks were brought to the surface.

It is noteworthy that the major tectonic and magmatic activity of the Moon is confined to its near side facing the Earth; whereas on its far side, maria are virtually absent, the highland crust is significantly thicker, and the surface morphology is much more smoothed. This peculiarity was first noted by Neal (1999), who referred it to as a lunar "hotspot" and attributed it to the influence of the Earth's gravity. Probably, the tremendous Earth mass influenced the character of lunar endogenous processes. This factor resulted in the localization of the ascent of mantle plumes and, consequently, the asymmetry of the Moon structure.

Thus, apart from some details, there is a fundamental similarity between the tectonic and magmatic development of the Moon and the Paleoproterozoic stage of Earth development. In both cases, melts of a crust–mantle origin prevailed at the first stage. They were formed from the material of the depleted mantle and previous ancient crust. In both cases, local flows of mantle hydrous potassium-bearing fluids took place and resulted in the formation of the lunar KREEP series and low-titanium subalkaline potassium series of the Earth. Mantle melts were predominant at the second stage: the character of lunar mare magmatism was generally similar to that of terrestrial oceans and continental flood basalt provinces where, in addition to low-titanium tholeiitic basalts (MORB), Fe–Ti basalts of elevated alkalinity occurred. The latter also showed a similar bimodality with respect to titanium content. In general, the geologic position of lunar maria is transitional between those of continental flood basalt and oceanic areas of the Earth differing from the latter in the absence of oceanic lithosphere. In addition to maria, this type of magmatism occurred, to a lesser extent, in highlands in small depressions filled with mare basalts and resembling regions of intraplate activity on terrestrial continents.

Possible Reason of Distinctions in the Magmatic Evolution of the Earth and the Moon

Currently, the most popular opinion is that the Moon's material was ejected from the Earth's mantle through a catastrophic impact of a Mars-sized body (Spudis, 1996). However, in comparison with the Earth, the Moon, as a whole, shows higher SiO_2, FeO, and refractory element contents but lower MgO and Fe/Si ratio. These facts are at odds with such an origin (Kuskov and Kronrod, 1998, 1999). On the other hand, the observed analogy of lunar highland rocks with terrestrial early Paleoproterozoic rocks suggests the close similarity of materials of the silicate mantles of the two planetary bodies. This is consistent with geochemical and geophysical data: despite the above-mentioned distinctions, the average composition of the lunar crust and mantle is very close to the composition of the Earth's upper mantle differing in lower volatile and low-melting components. The average density of the Moon, ~3.34 g/cm^3 (compare with the average density of the Earth, 5.5 g/cm^3) is very close to the density of the Earth's upper mantle (Bills and Ferrari, 1977). The silicate material of the two planetary bodies is probably similar to the composition of C1 chondrites, although that of the Moon is depleted in alkalis and volatile components including water. The character of mare magmatism suggests even greater differences between the concentrations of these elements in the metallic cores of the planets. The material of the lunar core was depleted in volatile components, especially water and alkalis, which are most characteristic of intraplate basalts of the Earth related to the activity of the outer core.

The nature of these differences in the compositions of the planetary bodies is not yet adequately understood. Probably, the Earth and Moon could begin their development concurrently as independent planets, i.e., the Earth–Moon pair was a binary system. If this system evolved in such a way that the outer (main) part of the proto-Moon cloud was captured by the Earth, the Moon was accreted of only inner part of its dust cloud depleted in volatile components (Galimov, 1995). On the other hand, owing to its greater mass, the Earth could more efficiently scavenge the most volatile components from the environment. Probably, the Moon also captured a small amount of lightest volatiles during growth, which resulted in the occurrence of small concentrations of water in the lunar mantle in contrast to the essentially anhydrous composition of the Moon's core. It is difficult to decide now between these mechanisms. Nevertheless, in either case, the available petrologic data allow us to believe that both planetary bodies were initially formed independently from slightly different materials. Consequently, in contrast to the opinion of many researchers, the Moon could hardly be formed on the expense of material ejected from the Earth's mantle by a catastrophic impact of a Mars-sized body.

The presented data demonstrate that the Moon bears no analogues of the early nuclearic stage of the Earth's development, which comprises the earliest third of its geologic history. The Moon is free of tonalite (plagiogranite), which compose about 90% of the Archean crust of the Earth, and the rocks of the komatiite–basalt series. There are no analogues of Phanerozoic magmatism related to convergent plate boundaries and subduction zones. However, the magmatic processes of the Moon are similar to the Paleoproterozoic processes on the Earth (Fig. 9). The general trends of magmatic development are also similar on the two planets: from magnesian series originated in strongly depleted mantle sources to geochemically enriched titanium-rich basalts.

Probably, considerably smaller size of the Moon and, consequently, lower energy capacity of this planetary body played a major role in that the first nuclearic stage of the Earth's evolution with the highest temperature komatiitic mantle magmatism did not manifested itself. The development of the Moon commenced directly from the second, lower energy cratonic stage.

An important feature of the further evolution of the Earth and Moon is the occurrence of a sharp change in the character of tectonic and magmatic processes. Probably, this is indicative of the fact that, from a certain moment of time, some material inactive before that time was entrained into geologic processes in the outer layers of these planetary bodies. We believe that in both cases, the formation of such melts was related to the ascent of mantle superplumes generated at the boundary of the liquid metallic core and silicate mantle owing to infiltration of Fe–Ti-bearing fluids into the lower mantle. The spreading of the head portions of such superplumes probably resulted in the rupture of the continental crust and formation of oceans on the Earth and mare structures on the Moon with specific magmatism resembling the oceanic magmatism of the Earth. In contrast to the terrestrial analogue, the mare magmatism was characterized by low contents of alkalis and volatiles and high degree of melt reduction. The sequence and petrologic sense of events were generally similar in the two planetary bodies.

The analysis of available petrologic material on the tectonic and magmatic development of the Earth and Moon gives rise to two inferences: (1) the iron cores of the Earth and Moon retained low-melting and volatile components, which could not have been conserved at the differentiation of initially homogeneous material; thus, the iron cores and silicate mantles were initially generated from different sources; and (2) heating of these planetary bodies occurred from their surfaces toward central parts, because geochemically enriched iron–titanium basalts, which are petrologic indicators of the activity at the core–mantle boundary, appeared long after the beginning of the geologic development. The reason of such a character of heating is not clear. It is probably related mainly to heat generated at the gravitation compaction of the planetary bodies. The internal heating of planetary bodies was accompanied by cooling of their outer layers owing to heat loss into the surrounding space.

These data are consistent with the model of the heterogeneous accretion of the terrestrial planets, which was developed by Vinogradov (1975) and some other researchers (Wänke, 1981; O'Neill and Palme, 1998). According to these authors, the formation of these planets occurred in the region of the inner margin of the protoplanetary nebula and began from the accumulation of iron cores, which served then as centers of silicate matter accretion.

Thus, the Moon is probably really a "dusty window into the Earth's past," moreover, into a most interesting and important transitional stage of its development. Two fundamentally different stages of tectonic and magmatic development are distinguished for the Earth and the Moon. The first stage was probably related to the processes of material heating in the upper mantle and the second stage was related to the formation of a liquid metallic core and involvement of its fluid components into the formation of a new plume generation. Perhaps, the existence of such a change is a fundamental moment in the development of solid planets, because it is manifested even in the Moon despite its small size and short period of its active development. In principle, the Moon is an excellent model for the understanding of the global evolution of the Earth and provides a clue to the important stages of its development starting from a global magma ocean, formation of the primary crust, generation of early mantle plumes composed of ultramafic material depleted to a varying degree, and formation of superplumes owing to the appearance of a liquid core. The latter stage was accompanied by the destruction of the ancient continental lithosphere and formation of a new lithosphere type: mare on the Moon and oceanic of the Earth (Sharkov, 2000). Judging from the Moon, the development of a planetary body terminates after the solidification of its liquid core. The Earth's core is mainly liquid and will not solidify soon. Other terrestrial planets are intermediate in size between the Earth and the Moon and it is conceivable that a similar sequence of events took place (and probably is taking place) in them.

CONCLUSIONS

1. The main characteristic feature of lunar magmatism is its similarity to the early Paleoproterozoic magmatism of the Earth. The Moon is completely free of analogues of ancient (Archean) terrestrial magmatism, when the leading part was played by tonalitic granitoids at subordinate significance of komatiite–basalt magmatism, and the analogues of Phanerozoic magmatism related to convergent plate boundaries.

2. Similar to the Earth, the tectonic and magmatic development of the Moon has gone through two major stages. The earlier stage (4.45–4.0 Ga) was marked by the magmatism of lunar highlands represented by the rocks of the magnesian series, which was a little later supplemented by the "alkaline" (KREEP) series. Mineralogically and chemically, the rocks of these series were similar to the typical terrestrial igneous series of the early Paleoproterozoic: siliceous highly magnesian and moderately alkaline potassic series. The lack of magnetite in the rocks, the occurrence of reduced phases (Fe–Ni alloys, troilite, etc.), and rarity of hydrous minerals suggest that melt generation occurred in a moderately reduced environment. By analogy with the Earth, the formation of highland melts was related to the ascent of mantle plumes composed of depleted ultramafic material, which experienced melting at the formation of the global magma ocean. The spreading of

the heads of such plumes occurred at depths of 200–250 km.

3. The second, final stage (3.9–3.2 Ga) of the tectonic and magmatic development of the Moon was characterized by extensive occurrence of mare basalts, which filled the basins of newly formed lunar maria. Similar to oceanic and continental flood basalt provinces of the Earth, two rock varieties are distinguished on the basis of chemical composition, low-titanium and high-titanium. The former are similar to MORB, and the latter resemble geochemically enriched Fe–Ti picrites and basalts, which appeared in significant amounts on the Earth only at 2.0–2.2 Ga simultaneous with the earliest geologic evidence of plate tectonics. However, in mineral composition, they differ sharply from the terrestrial analogues in that they are free of hydrous phases and titanomagnetite, which are replaced by native metals, primarily Fe–Ni alloys, ilmenite, and other reduced phases.

4. By analogy with the Earth, the formation of mare magmatism was related to the ascent of a new generation of mantle plumes. They initiated at the boundary of the mantle and liquid core, which was present at that time. Similar to the Earth, the ascent of such plumes caused a sharp change in the character of tectonic activity in the outer layers of the planet. In the Earth, it resulted in the extensive development of plate tectonics. In the Moon, the effect was reduced to the formation of large mare depressions with a thinned crust and intense basaltic magmatism. According to physicochemical data, the melts were derived at depths of 25–50 km. The accumulations of dense masses observed under lunar maria (mascons) are likely to be hardened plume heads. Lunar maria have probably no direct analogues on the Earth and are most similar to trap provinces.

5. The observed sequence of tectonic and magmatic events in the processes of developments of both the Earth and the Moon suggests that these planetary bodies were probably heterogeneous and their heating occurred gradually from surface to center and was accompanied by gradual cooling of the outer parts. The second stage commenced from the appearance of liquid cores and formation of mantle superplumes of a new generation, whose ascent resulted in the break-up of the cratonized lithospheres of these planetary bodies and a change in the character of geodynamic processes. The remnants of the ancient Earth's lithosphere are preserved only under Precambrian shields. On the Moon, they probably compose highland areas.

6. It is suggested that the formation of the Moon and the Earth began essentially simultaneously and occurred in two stages. Initially, their iron cores were formed from the protoplanetary gas–dust cloud around the Sun. Then, the accumulation of silicate chondrite material followed. However, because of the proximity of the Earth, whose greater mass allowed more efficient capturing of the most volatile components, especially H_2O, from the space around the developing bodies, the lunar material is depleted in these components. This process should occur particularly efficiently at the stage of iron core formation because of the great difference in their size, which resulted in almost complete absence of water in the lunar core. Taking into consideration these facts, it is suggested that the Moon could hardly be formed from the Earth's mantle as a results of an impact of a Mars-sized body.

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