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Comparative Study of Tectonomagmatic Evolution of the Earth and Moon: Key for Understanding the Formation and Internal Evolution of Solid Terrestrial Planets

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Abstract—Geological and petrological study of the evolution of the Earth and Moon, as well as data on Venus and Mars, showed that all solid terrestrial planets presumably were initially heterogeneous and developed according to a common scenario, which involved gradual heating of their interiors up to the formation of a liquid core and associated gradual cooling of their outer shells. Such a character of heating was supposedly provided by a wave of centripetal deformations, which arise in a rotating body. At the first phase of evolution, tectonomagmatic processes were related to the ascent of superplumes formed in a depleted mantle. The appearance of liquid cores initiated the ascent of geochemically enriched superplumes of the second generation from the core–mantle boundary. They reached moderate depths, and the spread of their heads led to a fundamental reconstruction of planetary surfaces.

INTRODUCTION

At present, the main concepts of the formation and internal evolution of solid terrestrial planets are based on diverse physical and geochemical calculations and theoretical models. It is implicitly accepted that there is no real relevant material in nature, and the problem is the subject of diverse speculation. In particular, most researchers believe that the Earth originated through the accretion of hypothetical chemically homogeneous planetesimals from tens of meters to several kilometers in size and dust particles [1–4 etc.]. It is suggested that after accretion the temperature of the Earth's interior was high enough to melt iron alloys. The heavy metallic melt flowed down toward the Earth's center forming the outer core, which has been preserved in a liquid state up to now. The intense meteorite bombardment of the surface and tidal effects caused additional heating of the Earth's surface and formed a global magmatic ocean several hundred kilometers deep. During its solidification, the protoplanetary matter transformed into the mantle–crust system composed of terrestrial rocks.

The origin of the Moon is more controversial. The existing models were comprehensively reviewed by Ringwood [2] and Galimov [5], and we will not describe them in detail. A number of hypotheses have been proposed: the Moon originated in the Solar system far from the Earth and was captured when it occurred near the orbit of the latter, double-planet formation with Moon coagulation from the ring of planetesimals around the Earth, fission of the Moon from the Earth owing to instability caused by core separation, and others. However, most scientists suggest that the Moon originated from the Earth's mantle by an impact of a Mars-sized body [6].

All of these hypotheses are speculative and completely ignore the available geological and petrological data on the tectonomagmatic evolution of these bodies. However, these data provide the main information on the internal evolution of planetary bodies. Comparative study of the Earth and Moon revealed a significant similarity in the evolution of lunar magmatism and terrestrial Paleoproterozoic magmatism [7]. No analogues of the products of Archean (granite–greenstone terrains) and subduction-related Phanerozoic magmatic activity were found on the Moon. [8]. This indicates that the Moon evolved more rapidly via a reduced scenario, but within the same regularities. It is important that the evolution of both planetary bodies is characterized by a sudden change, when a principally new material was involved in magma formation; simultaneously all the tectonic processes on these bodies changed also. The aim of our paper is to evaluate the consequences of this fundamental fact for the development of a modern theory of the formation and evolution of terrestrial planets.

MAIN FEATURES OF THE TECTONOMAGMATIC EVOLUTION OF THE EARTH AND MOON

The geologic evolution of the Earth and Moon began after the solidification of global magmatic oceans, producing the primordial sialic crust of the Earth and the anorthositic crust of the Moon. Their formation was presumably related to the upward solidification of the magmatic oceans, which, according to Jeffries [9], was caused by differences between the values

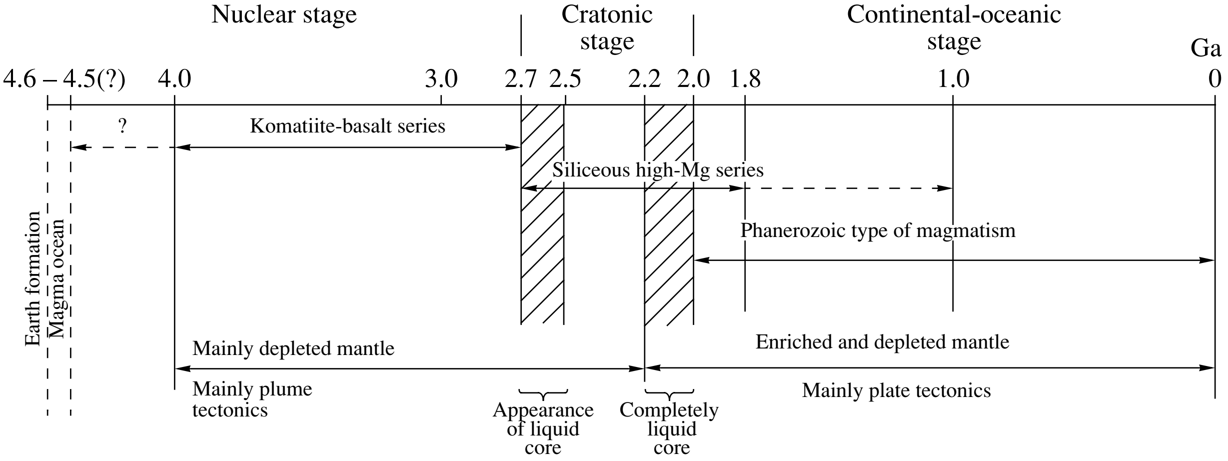

Fig. 1. Scheme of the tectonomagmatic evolution of the Earth.

of adiabatic and melting point gradients of their material. As a result, the surfaces of solidified planets (their primordial crusts) should be composed of low-temperature fractionates. The differences between the compositions of the primordial crusts of the planetary bodies were presumably related to the different sizes of their global magmatic ocean and different compositions of the primary materials (see below).

The geologic evolution of both planetary bodies occurred in two main phases [8]. The first phase was characterized by the predominance of magmas derived from the ultramafic mantle depleted in incompatible components during the formation of magmatic oceans and subsequent magmatic activity. Tectonic processes did not significantly affect their upper shells. The second phase was characterized by the extensive development of geochemically enriched mantle melts and the sharp activation of tectonic processes, which resulted in a significant reconstruction of the outer shells of planetary bodies.

Tectonomagmatic evolution of the Earth. The first phase spanned the Archean and Early Paleoproterozoic. In the Archean (nuclear stage), mantle-derived magmas were represented by low-Ti komatiite–basalt series derived from slightly to moderately depleted ultramafic rocks. In the Early Paleoproterozoic (cratonic stage, 2.5–2.2 Ga ago), the Earth's crust acquired stability and ability to brittle deformations, which resulted in the appearance of rift-related volcanosedimentary belts, giant dike swarms, and large layered intrusions. The magmatism of this phase was mainly represented by siliceous high-Mg (boninite-like) series (SHMS), which were derived from strongly depleted mantle reservoirs (Fig. 1).

The tectonomagmatic processes of the first phase of the Earth's evolution are believed to be related to the ascent of mantle-derived superplumes. Their heads spread within the mantle at depths of about 300–150 km and did not significantly disturb the primordial sialic crust [10], which, according to recent data, appeared at least 4.4 Ga ago [11].

A sharp change in the character of geological processes on Earth occurred at the beginning of the second phase (about 2.2–2.0 Ga ago), when the Earth entered the continental–oceanic evolutionary stage, which continues until now. The phase was characterized by the appearance of geochemically enriched mantle sources. This time was marked by the first appearance of abundant Fe–Ti basalts and picrites typical of within-plate Phanerozoic magmatism. The archaic Early Precambrian plume tectonics was replaced by plate tectonics typical of the Phanerozoic. In addition, at the 2.2 Ga boundary, the intensity of the Earth's magnetic field increased sharply and reached the highest values [12].

We believe that such a change of activity was related to the ascent of mantle superplumes of the second generation, which formed at the boundary between the liquid core and silicate mantle, in the "D" layer. These plumes were characterized by the presence of specific fluids, high in Fe, Ti, alkalis, P, Ba, Zr, LREE, and other elements. Their material was lighter than that of the older plumes and could reach moderate depths, while the spread of their heads occasionally resulted in the break up of the primordial sialic crust and formation of a new oceanic crust [13].

Tectonomagmatic evolution of the Moon. The oldest (4.4–4.0 Ga) continental magmatism of the Moon is represented by low-Ti rocks of the magnesian suite. Their plutonic counterparts are layered intrusions of the ANT (anorthosite–norite–troctolite) series, which also includes ultramafic cumulates (dunites, harzburgites, and pyroxenites) [14]. Fragments of these intrusions crop out on the Moon's surface as tectonic nappes in lunar highlands surrounding maria. In terms of major-element composition, mineralogy, geochemistry, and isotopic signature, these rocks resemble cumulates from the Early Paleoproterozoic layered intrusions of the Earth, which were derived from SHMS melts [7].

Fig. 2. Visible surface of the Moon. The light areas are highlands, and the dark areas are maria.

About 3.9–3.8 Ga ago this type of activity was replaced by basaltic mare magmatism, which was associated with the formation of large depressions of lunar maria several kilometers in depth and lunar highlands (Fig. 2). This magmatism continued for up to 3 Ga and presumably completed the tectonomagmatic activity of the Moon. Most researchers believe that maria resulted from catastrophic impact events [6]. However, it should be emphasized that this is only an assumption and is not justified by geological, petrological, mineralogical, and other evidence. However, in spite of the relatively small size, the structure of lunar maria (large depressions with a sharply thinned crust and intense basaltic magmatism) is most similar to that of terrestrial oceans and flood basalt provinces, which are commonly considered as early stages of ocean opening.

Similarly to the Earth, the mare basalts of the Moon are divided into low- and high-Ti types, which are correlated with mid-ocean ridge basalts (MORB) and ocean-island basalts, respectively. However, these rocks differ significantly from their terrestrial counterparts in their low alkalinity, absence of hydrous minerals and titanomagnetite, and presence of native iron, Fe–Ni alloys, ilmenite, and other reduced phases [15]. All these facts indicate a significantly more reducing environment in the magma generation zones of the Moon as compared to those of the Earth.

We suggest that, as on Earth, the pristine magmatism of lunar highlands was related to the ascent of first-generation plumes of depleted mantle material. The mare magmatism was related to the second-generation plumes, which formed at the boundary between the mantle and liquid core, the existence of which is indicated by paleomagnetic data [16]. From these viewpoints, maria could be counterparts of terrestrial oceans and flood basalts rather than results of the impact of giant meteorites. Similar to the Earth, these plumes were lighter than older ones, and their heads spread near the base of the lunar crust, causing significant transformations of the latter with the formation of the lunar maria and surrounding highlands (Fig. 3). The high-density mass concentrations (mascons) are ubiquitous beneath maria and presumably represent solidified heads of these plumes.

DISCUSSION AND CONCLUSIONS

The observed sequence of tectonomagmatic events during the evolution of the Earth and Moon suggests that they initially had a heterogeneous structure and heated inward, while their outer shells cooled. Only this model can explain the fact that the core material was conserved for about 2.5 Ga in the Earth and 1.5 Ga in the Moon and was later involved in tectonomagmatic processes.

The fact that the magnetic field strength of the Earth and Moon attained a maximum at the crucial boundaries (2.2 and 3.9 Ga, respectively) suggests that their

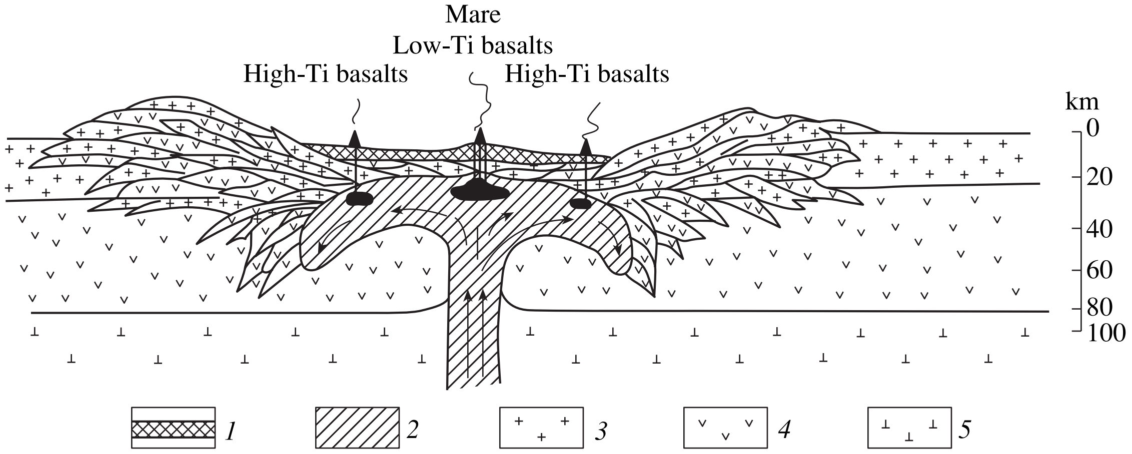

Fig. 3. Formation of the lunar maria. (*1*) Mare basalts; (*2*) mantle plumes of the second generation; (*3*) upper crust; (*4*) lower crust; and (*5*) lithospheric mantle.

cores had completely melted by that time. Taking the radii of the Earth and Moon as 6371 and 1738 km, respectively, the rate of the heating wave can be estimated as about 2.4 m/yr for the Earth and 3.5 m/yr for the Moon. The similarity of these values indicates the similarity of the driving mechanisms. The liquid core of the Earth presumably began to form in the Late Archean (2.7–2.6 Ga ago), when small amounts of low-Ti alkaline rocks of the potassium series first appeared [17] and magnetic field strength increased [18]. The nucleation of the liquid core on the Moon is presumably marked by the appearance of highland KREEP basalts, which were enriched (in lunar scale) in K, REE, and P, about 4.3 Ga ago. The same period shows the first evidence of the existence of the lunar magnetic field [16].

The advance of the heating waves into the planetary bodies was accompanied by the cooling of their outer shells. In particular, judging from the oxygen isotopy of old detrital zircons from Australia, liquid water existed on the Earth's surface 4.4 Ga ago [10]. The global cooling of the Earth presumably began about 2 Ga ago, soon after the complete melting of the core and the exhaustion of its initial energetic resources. The difference between the values of adiabatic and melting-point gradients caused the upward solidification of the liquid core, which resulted in the formation of the solid inner core. Its present-day radius is about 1300 km. This indicates that the solidification rate of the Earth's core is about 0.65 m/yr. This value is about an order of magnitude lower than the above discussed heating rate, which indicates the different nature of these processes.

On the Moon, the liquid core is now absent, and its magnetic field disappeared about 3.0 Ga ago; i.e., the active stage of the existence of the lunar core lasted about 0.9 Ga. The radius of the lunar core is about 350 km [19]. Correspondingly, the solidification rate of the Moon's core could be about 0.4 m/yr, i.e., about one-third less than that of the Earth's core. This is possibly related to the significant differences in the core–mantle proportions of these planetary bodies. The core accounts for 0.32 and only 0.02–0.03 [2] of the total mass of the Earth and Moon, respectively. The thick mantle serves as a specific heat isolator, which lowered the rate of core solidification. By analogy with the Earth, this rate was an order of magnitude lower than the heating rate of the Moon.

At the first phase of planetary evolution, superplumes formed within the mantle, whose depletion in incompatible components gradually increased with time, resulting in the appearance of extremely depleted mantle materials in the Earth in the Early Paleoproterozoic. The second phase was related to the appearance of liquid cores and mantle superplumes, the ascent of which led to a fundamental change in the style of the tectonomagmatic processes in these bodies. Fragments of pristine lithospheres preserved only on the Precambrian shields of the Earth and beneath the highlands of the Moon. The inferred sequence of processes is shown for the Earth in Fig. 4.

The nature of the directed heating of planetary bodies is unclear. It is possibly related to a centripetal deformation wave, which was established experimentally in rotating bodies [20]. It was discovered that such a mechanism of energy transfer is most intense at the first stages of flyweel acceleration and less intense during steady rotation. This is consistent with our data on the evolution of planetary bodies, with gradual centripetal heating at the first phase and nearly complete absence of heating at the second phase.

According to Galimov [5], the Earth–Moon pair represented the case of a double system. We suggest a two-stage formation of these bodies from a gas–dust cloud surrounding the Sun, with the initial formation of iron cores and subsequent accumulation of silicate material on them, as was proposed by Vinogradov [21]. The Earth, as a heavier body, could more intensely scavenge volatile components, especially water, from the surrounding medium. This presumably explains

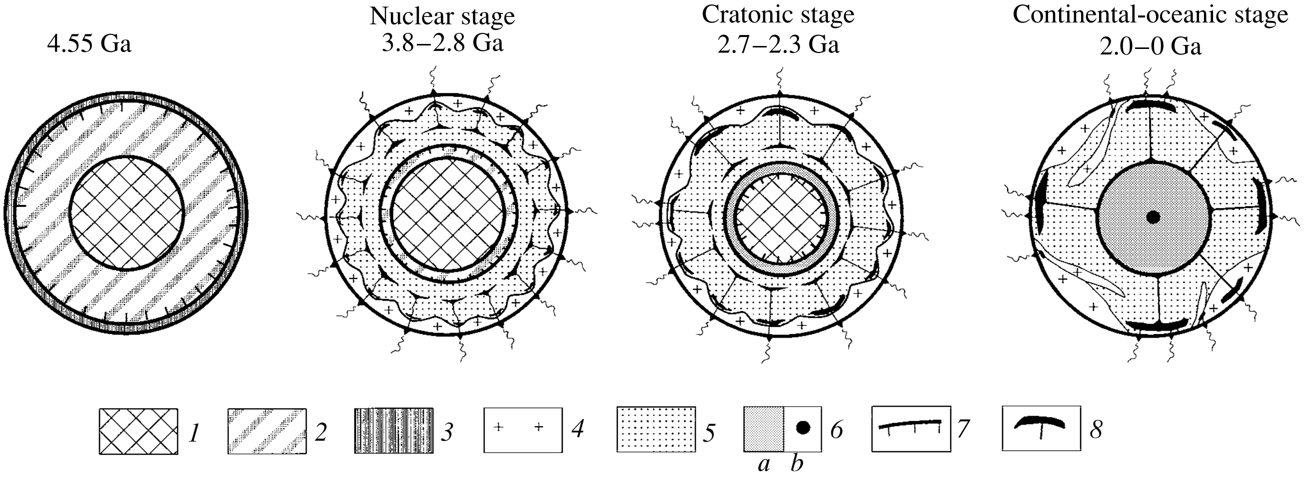

Fig. 4. Major stages of the internal evolution of the Earth. (*1*) Primordial core; (*2*) primordial mantle; (*3*) magma ocean; (*4*) sialic crust; (*5*) depleted mantle; (*6*) core: (*a*) liquid and (*b*) solid; (*7*) heating front; and (*8*) mantle plume.

why the Moon is depleted in volatiles and enriched in refractory components [2, 22]. This also indicates that the planetary bodies formed not through the accretion of hypothetical planetesimals but rather through the accumulation of dust particles, which composed the cloud. The latter mechanism could be more efficient in providing the observed geochemical differences between the bodies.

Thus, the available petrological and geochemical data indicate that the Earth and Moon formed as independent neighboring bodies within a single gas–dust cloud. The differences between their compositions are possibly related to the larger size of the Earth, the gravity of which disturbed the mass balance in the environment where the Moon formed. Consequently, it is highly improbable that the Moon originated at the expense of the Earth's mantle during the catastrophic collision of a Mars-sized body with the Earth.

Venus and Mars also contain two major morphostructures: abundant basaltic fields and older uplifts with a complex relief (planum of Mars and tessera of Venus). This indicates that these planets also formed in two phases. The first phase was responsible for the formation of a primordial lithosphere as a result of the solidification of a global ocean and the activity of plumes of the first generation. The second phase involved extensional processes associated with intense basaltic magmatism, which was related to the ascent of second-generation superplumes from the liquid core–mantle boundary. The presence of similar morphostructures is also supposed for poorly studied Mercury.

Thus, the comparative study of the geologic and petrologic evolution of the Earth and Moon, as well as data on Venus and Mars, suggest that all solid terrestrial planetary bodies were initially heterogeneous. They developed according to a common scenario, which involved the gradual heating of their interiors up to the formation of a liquid core and associated cooling of the outer shells. Such a heating was supposedly related to a wave of centripetal deformations, which arose in rotating bodies. At the first phase of their evolution, tectonomagmatic processes were related to the ascent of superplumes of depleted mantle material. The nucleation of liquid cores initiated the ascent of chemically enriched superplumes of the second generation from the core–mantle boundary. They reached moderate depths, and the spread of their heads resulted in a fundamental reconstruction of the planetary surfaces.

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