Sharkov E.V., Bogatikov O.A. Magmatic differentiation of deep-seated material of the Earth and the Moon: an experience in the comparative study of tectonic and magmatic processes

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Abstract. Despite number of differences, there is amazing similarity in the evolution of magmatic and tectonic processes on the Earth and the Moon. Evolution of the Moon proceeded by shortened scenario and was relatively transient. The main feature of the lunar magmatism is its closeness to the paleo-Proterozoic terrestrial magmatism. The analogies of both the ancient (Archean) and the Phanerozoic terrestrial magamatism related to the destructive plate boundaries are absent on the Moon.

The major peculiarities of tectonic and magmatic evolution of the Earth

Three main stages of the Earth evolution can be distinguished: nuclearic, cratonic, and continental-oceanic (Bogatikov et al., 2000). The nuclearic stage encompasses practically whole Archean up to 2.6-2.5 Ga. The major geological structures are granite-green-stone belts (GGB) and separating granulite belts (GB). 80-90 per cents of GGB are composed of tonalitic granitoids with the irregular net-work of green-stone belts composed of predominantly volcanics of komatiite-basalt composition and subordinate intermediate and acidic volcanics and meta-sedimentary rocks. The geological structure of the granite-green-stone belts resemble the regions of the Phanerozoic continental rifts, and their formation, apparently, was related to the uplift of mantle plumes composed of moderately depleted ultrabasics. In the end of the Archean, some amounts of low-titanium potassic alkalic melts appear. Their origin is related to the flux of mantle fluids in the magma forming areas.

The cratonic stage includes the Early Paleoprotherozoic (from 2.6 to 2.0 Ga). The major geological structures are rigid cratons and intercratonic granulite belts. Cratons were characterized by silica-rich high-Mg (boninite-like) series (SHMS) as large layered intrusions, abundant series of dykes, and rift-related vocanic-sedimentary belts. They formed huge magmatic provinces, similar to the Phanerozoic flood basalts. Their origin is related to the uplift of mantle plumes composed of depleted ultrabasics. This period is also manifested by abundant potassic granites. As a whole, the cratonic stage is a continuation of the nuclearic stage. However, tectonic and magmatic processes proceeded in the conditions of rigid crust and significantly more depleted mantle. Origin of the SHMS magmas is considered to be related to an assimilation of the crustal material by the mantle melts during their uplift. As in the Archean, spreading of the head portions of mantle plumes occurred significantly below the crustal basement and did not result in its destruction with the formation of the oceanic lithosphere. Geological processes can be characterized by the plume tectonics.

The continental-oceanic stage began about 2.2-2.0 Ga ago and continues today. During this period, the abundant Fe-Ti picrites and basalts, which are characteristic for the Phanerozoic intraplate magmatism. It means that new substance was involved in tectonic and magmatic processes. An appearance of first geological evidences for the plate-tectonics (ophiolite associations, regional suture zones parallel to the subduction zones, backarc basins, etc; Sharkov et al., 2000) is connected with this period.

The major peculiarities of tectonic and magmatic evolution of the Moon

The most ancient (4.45-4.25 Ga) magmatism of the lunar highlands is presented by low-Ti high-Mg series (Mg-rich basalts and their intrusive analogies of the ANT series) truncating the primary anorthositic crust. Chemical, mineral, and isotopic features are close to the terrestrial Early Paleoproterozoic magmatism of the silica-rich Mg-rich series, differing by the higher reduction of melts and the low alkali content. Analogous to the Earth, origin of this magmatism is related to the uplift of the mantle plumes composed of the depleted ultrabasic material and contamination of high-temperature mantle melts by the lunar crustal substance. Spreading of the head portions of such plumes accompanied by melting of their material due to decompression could occur at depths 200-250 km.

The second varieties of the highland magmatism are K, REE, P enriched rocks of the “alkaline series”, i.e. KREEP basalts and their intrusive analogs, including quartz monzodiorites and potassic granites, formed later, 4.34-4.0 Ga. The rocks of the “alkaline series” have many common features with the low-Ti potassic magmatism of the Early Paleoproterozoic on the Earth, and are more reduced as well. Analogous to the Earth, origin of such melts is related to the processes of mantle potassic metasomatism triggered by accumulation of fluids in local “traps” during degasing of the plume substance of first generation.

The final (3.9-3.2 Ga) stage of the tectonic and magmatic evolution of the Moon is characterized by abundant mare basalts filling the depressions of newly formed lunar maria. Similar to the terrestrial oceanic and flood provinces, two varieties are distinguished among mare basalts: low-Ti and high-Ti. The first type resembles MORB toleites, the second is close to enriched Fe-Ti picrites and basalts, which appeared on the Earth only at 2.2-2.0 Ga. However, they significantly differ in mineral composition from the terrestrial analogs by high reduction of mineral forming environments (close to the iron-wüstite buffer).

The maria formation is considered to be related to nearly contemporary meteorite fall (“lunar cataclysm), which resulted in impact melting of the crust and upper levels of the mantle as well. However, a presence of some similarity between the mare lunar basalts and the terrestrial oceanic and flood basalts, allows another interpretation. Similar to the Earth, we think that the mare magmatism was related to the uplift of mantle plumes of new generation initiated on the core-mantle interface. The uplift of such plumes resulted in an abrupt change in tectonic activity in the upper levels of the Moon. On the Earth, this process resulted in the plate-tectonics, whereas on the Moon it was confined by the formation of large maria depressions with significant thinning of the crust and the intensive basaltic magmatism. Following to the physico-chemical data, melts were supplied from the depth of 25-50 km, where spreading of the plume heads occurred. The lunar maria have no analogs on the Earth and are more close to the flood-basalt continental regions. Mascons, i.e. dense masses under the lunar maria, are believed to be the solidified plume heads. The formation of such plumes, similar to the Earth, can be explained by the flux into the mantle of Fe-Ti fluids from the boundary of the liquid metallic core. In contrast to the Earth, these fluids were practically water-free, that provided the high reduction of melts.

In contrast to the Earth, the active period of the Moon evolution continued just about 1.5 Ga and was characterized exclusively by tectonic and magmatic processes, which are characteristic for Paleoproterozoic. This period was the most important and critical time in the Earth history. During this period, a transition from the Archean plume tectonics to the Late Precambrian and Phanerozoic plate tectonics occurred.

Discussion. The observed sequence of tectonic and magmatic events during the evolution of both the Earth and the Moon, apparently, implies that these planetary bodies were heterogeneous (essentially ferric inner partion and the silicate outer portion). Their heat-up proceeded gradually up down, from the surface to the core, being accompanied by cooling of the outer portions. The second stage of their evolution began then the heat-up front reached for the inner portions of the planetary bodies, and the liquid core appeared. From this moment, the formation of plumes of new generation, originated at the core-mantle boundary, became possible. The fluid-enriched plume substance can reach for the crust basement. That resulted in the change of geodynamic processes. On the Earth, the relics of the ancient lithosphere were preserved only under the Precambrian shields, on the Moon, they build its continental regions.

It is suggested that the formation of the Moon and the Earth was practically contemporary and proceeded by two stages. Firstly, their ferric cores were formed from the gas-dusty cloud around the Sun. After that, accumulation of the silicate chondritic material from them occurred. However, due to closeness of the Earth, which owing to its larger mass effectively “extracted” volatile components, especially H_2O, from the surrounding space, the lunar material is depleted in these components. The mostly effective process would be on the stage of the formation of ferric cores, because of the difference in sizes. As a result, the lunar core is practically deprived of water. This, apparently, means that the Moon hardly was formed from the terrestrial mantle due to the blow of the body commensurable with the Mars.

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