ANORTHOSITE FORMATION BY PLAGIOCLASE FLOTATION IN FERROBASALT AND IMPLICATIONS FOR THE LUNAR CRUST.

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Introduction: The processes related to floating and sinking of plagioclase in the large and shallow-level emplaced tholeiitic Sept Iles layered intrusion (Canada) serves as a proxy to refine the crystallization model of the lunar magma ocean (LMO) and explain the vertically stratified structure of the lunar crust, with (gabbro-)noritic rocks at the base and felsic rocks at the top [1].

Processes in Sept Iles: The intrusion (564 Ma) has a dinner-plate shape with a diameter of ca. 80 km, a maximum thickness of ca. 5.5 km and an estimated volume of ca. 20,000 km³ [2]. It is dominated by a basal Layered Series made up of troctolite and gabbro [3], and by anorthosite occurring at the roof of the magma chamber (100-500 m-thick). Anorthosite rocks are comprised of plagioclase, with minor clinopyroxene, olivine and Fe-Ti oxide minerals. Plagioclase displays a very restricted range of compositions for major elements (An_{68}-An_{60}), trace elements (Sr: 1023-1071 ppm; Ba: 132-172 ppm) and Sr isotopic ratios ($^{87}Sr/^{86}Sr_i$: 0.70356-0.70379). This compositional range is identical to that observed in troctolites, the most primitive cumulates of the Layered Series, whereas plagioclase in layered gabbros is more evolved (An_{60}-An_{38}). The origin of Sept Iles anorthosites has been investigated by modeling the evolution of plagioclase and magma densities along the liquid line of descent [4]. The density of the FeO-rich tholeiitic basalt parent magma first increased from 2.70 to 2.75 g/cm^3 during early fractionation of troctolitic cumulates and then decreased continuously down to 2.16 g/cm^3 with fractionation of Fe-Ti oxide-bearing gabbros. Plagioclase (An_{69}-An_{60}) was positively buoyant during fractionation of troctolites and partly accumulated at the top of the magma chamber to form the roof anorthosite. With further differentiation and the fractionation of Fe-Ti oxide gabbros, plagioclase ($<An_{60}$) became negatively buoyant and accumulate only in the Layered Series. Blocks of anorthosite (autholiths) even fell downward to the basal cumulate pile. The presence of abundant positively buoyant plagioclase grains in basal troctolites is explained by the weak efficiency of plagioclase flotation due to in situ nucleation at the floor and formation of coherent plagioclase chains that retain the crystals together. Dense FeO-rich mafic minerals in the roof anorthosite are shown to have crystallized from the interstitial liquid, the proportion of which varying between 12 and 64 wt%. We also show that the composition of interstitial olivine and clinopyroxene cannot thus be used to infer the composition of the parent magma from which the anorthosite, i.e. cumulus plagioclase, crystallized.

Lithologies of the lunar crust: Differentiation of the Moon is interpreted to have resulted initially from the crystallization of the LMO (e.g. [5]). The lunar crust is defined by the appearance of plagioclase in the cumulate succession and seismic data indicate that its thickness is in the range of 45-60 km (e.g. [6-7]).

Number of evidences now suggests that the lunar crust is vertically stratified with mafic rocks at the base and felsic rocks at the top: (1) a seismic discontinuity occurs at ca. 20 km depth beneath the surface of the Apollo 12 and 14 landing sites and the relationship between gravity and density of the Moon suggest a compositional stratification within the crust [6,8]; (2) mostly based on Clementine multispectral reflectance data, it was shown that the ejecta of large basins, the central peaks of some craters and the South Pole-Aitken basin are more mafic (mostly noritic) than the surrounding anorthositic highlands (e.g. [8-10]).

Based on spectral-reflectance data, [1] derived a geophysically-consistent compositionally stratified model for the lunar crust based on the depths of origin of lunar materials from crater central peaks. Data from 11 craters suggest that the lower or middle crust is dominated by anorthositic norite and anorthosite, and is thus highly enriched in plagioclase (average: 78±6 vol%). Based on 6 other craters, that could potentially expose deeper material, these authors concluded that the lower crust is more mafic (norite, gabbronorite, anorthositic norite; 65±8 vol% of plagioclase). Data from 90 craters indicate that the upper crust is mostly made up of anorthosite with minor anorthositic-norite, with an average plagioclase content of 88±4 vol%.

Lunar rocks and LMO crystallization: The formation of the anorthosite lunar crust was traditionally interpreted as resulting from the combination of two phenomena: (1) crystallization of plagioclase and mafic minerals (olivine, Ca-poor pyroxene, Ca-rich pyroxene and ilmenite) in cotectic proportions from the LMO; (2) separation of plagioclase, floating to the top of the LMO, while mafic minerals sink on previously crystallized mantle cumulates [1,11-12]. This latter widely accepted model was however challenged by the recent compositionally layered model [1] indicating that rocks with only 50 wt% of plagioclase occur in the lower and middle parts of the lunar crust.

There are several evidence against a flotation origin for the whole lunar crust: (1) average estimated densities of the lower crust ranges from 2.94 to 3.04 g/cm^3 [1] and are higher than the highest liquid density of the

LMO [11]; (2) it has been calculated that cotectic assemblages with only 69-80 wt% of plagioclase (ca. 2.88-2.92 g/cm^3) may float on LMO magmas [1,11]. These estimates cannot explain the presence of more than 35 vol% of norite (50 vol% of plagioclase; density: 3.00-3.20 g/cm^3) in the lower crust and the presence of ilmenite-bearing rocks (3.40-3.80 g/cm^3; [13]) in the middle crust.

Model for the stratigraphy of the lunar crust: We propose that the mafic lower crust (norite and gabbro-norite) may have crystallized in situ at the base of the LMO on the previously formed crystal pile, represented by ultramafic mantle rocks. During crystallization of norite and gabbro-norite in the lower crust, plagioclase formed three-dimensional coherent chains that enclose ferromagnesian minerals ± ilmenite. These networks were denser than magmas from the LMO and prevented cumulate rock flotation, even if, as shown for Sept Iles, some isolated plagioclase grains may have escaped the networks and floated to the top of the LMO to form the ferroan anorthosite suite (FAS).

Considering the estimation of LMO differentiation path by [12] and the efficiency of plagioclase flotation observed for the Sept Iles intrusion (up to 30 %), flotation of plagioclase grains allows the formation of a ca. 8 km-thick anorthosite layer at the top of the lunar crust. This thickness is slightly higher than the estimation of [14] but lower than the 15-20 km thickness suggested by most authors. The calculated thickness of pure anorthosite produced by flotation of plagioclase grains may however be underestimated because: (1) the density contrast between plagioclase grains and the equilibrium melts is higher for the crystallization of the lunar crust than for the crystallization of the Sept Iles intrusion. This higher density contrast may have a significant effect on the efficiency of plagioclase flotation that could be significantly higher than 30 % in the lunar crust case. An effective plagioclase flotation of ca. 50 % would be enough to form a 15 km-thick anorthosite layer at the top of the LMO; (2) cotectic proportions of plagioclase (53 % before the saturation of clinopyroxene and 31 % after clinopyroxene in) calculated by [12] are relatively low compared to those observed for basaltic magmas on Earth and are probably underestimated. Higher plagioclase proportion in the cotectic assemblages would result in a thicker anorthosite layer at the top of the lunar crust; (3) calculations were performed considering a total crustal thickness of 60 km. While this thickness is the most commonly accepted, values as high as 120 km have been proposed (e.g. [16], at least for some locations of the crust. Increasing the total crustal thickness would result in the formation of a thicker floated anorthosite layer.

Due to their high densities, ferromagnesian minerals were unable to float at any stage of the LMO evolution. Their presence in FAS is thus interpreted as resulting from the crystallization of the interstitial melt. This hypothesis also explains adequately their iron-rich compositions.

[15] proposed that some locations of the lunar upper crust are made up of practically pure anorthosite (95-98 wt% of plagioclase). To reconcile this observation with the presence of meteorites containing 15-20 wt% of mafic minerals, [17] suggested that meteorites could represent a mixing (breccia) between anorthosites free of mafic minerals and rocks from the more mafic part of the crust. These authors proposed that formation of pure anorthosites results from accumulation of plagioclase in the crystallization zone of post-LMO magmas subsequently followed by diapiric uprising and intrusion of plagioclase concentrations in the more mafic upper crust, which crystallized from the LMO. During plagioclase mush migration, the interstitial liquid is dynamically expelled [18], thus explaining the absence of mafic minerals in pure anorthosites. The mafic mineral-content in Sept Iles anorthosites is between 4 and 21 %, thus covering the whole range observed in the lunar anorthosites. The variable amount of mafic minerals in Sept Iles anorthosites is explained by a non-uniform distribution of the interstitial liquid (12-64 %). A similar model may be proposed for the lunar crust where anorthosites are formed by flotation atop a convecting magma ocean. Convection may result in local expelling of the interstitial, thus leading to the formation of anorthosites crystallized from LMO magmas and showing variable amounts of mafic minerals.

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