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Comparative study of lunar basalts with terrestrial basalts and Lonar impact crater melts: an evaluation through modern trace element geochemistry

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Abstract

The source mantle of the mare basalts could have been depleted in Al, Rb, some LREE, Eu and perhaps U in its early stage of evolution by a relatively fluid-present (H_2O, CO_2, F, Cl) melting when a feldspathic melt was removed from the primitive lunar mantle. This depleted lunar mantle was enriched in Cr, from which high-Ti and low-Ti mare basalts were later extracted. The parent magmas of both these basalts may have experienced an important phase of olivine fractionation that depleted these magmas in Mg and Ni prior to their eruption to the lunar surface.

1. Introduction

The 3.9-3.2 Ga old mare basalts, which could be similar to terrestrial Flood Basalts (FB) [1], cover ~17% of the lunar surface. These basalts may also be secondary crusts formed by partial melting of the lunar mantle [2], like terrestrial MORBs, or could be impact-melts [3]. To re-evaluate their petrogenesis, we compare the compositions of lunar basalts collected during several Apollo missions [4], with selected terrestrial examples of Archaean and modern MORBs [5, 6], Cretaceous continental FBs [7], and basaltic impact melts from the Lonar crater, India [8].

2. Results

2.1 Major Element Chemistry

In the TAS classification, the high-Ti (3.85- 3.55 Ga), low-Ti and very low-Ti Lunar basalts (3.45-3.15 Ga) plot in the ultrabasic, picro-basalt and basalt, and basalt field respectively. However, their characteristic low Mg# (~0.62 to 0.33) distinguishes them from the Archaean (~0.74) and Indian Ocean Ridge MORBs (~0.50). In FeO_t/ MgO versus SiO_2 plot (Fig. 1a), the high- and low-Ti mare basalts show distinctly different fractionation trends in the way iron and silica co-increase. In this they differ from the very low-Ti mare basalts that rarely show any significant mutual increases of FeO and SiO_2, not unlike the MORBs. Among the other major oxides, the mare high- and low-Ti basalts have lower Al_2O_3 contents (~9.19 and 8.81 wt% in average respectively) compared to MORBs (~15.62 wt%) and continental FBs (~13.75 wt%). Instead, the very low-Ti mare basalts could have an intermediate status. Moderately linear increasing Al_2O_3 trends with decreasing Mg# are also observed for the mare basalts.

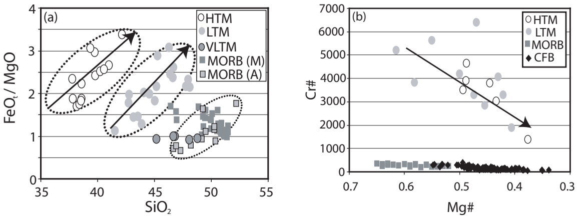

Fig. 1. Important variations of (a) major oxides, and (b) Cr in the mare and terrestrial basalts. HTM: High-Ti, LTM: low-Ti, VLTM: very low-Ti mare basalts, MORB (M): modern and MORB (A): Archaean MORB, CFB: Continental FB.

2.2. Trace Element Geochemistry

The high- and low-Ti mare basalts are extremely enriched in Cr (~1500 to 6000 ppm) and show an overall decreasing linear trend as the Mg# decreases (Fig. 1b). Ni contents in these basalts (<100 ppm) are lower than those of the MORBs. The very low-Ti mare basalts show low Cr (<400 ppm) and Ni (<150 ppm), which are comparable to those of MORBs, and show decreasing linear trends with decreasing Mg#.
Incompatible multi-element spidergram shows that the average high- and low-Ti Lunar basalts have chemistry between the average E-MORB and OIB, although extreme depletion in Rb in mare basalts is comparable to that of the N-MORB (Fig. 2a). Additionally, the mare basalts show positive Nb (1.3-2.69) and negative Sr (0.43-0.53) anomalies. The LREE chemistry of the average mare basalts is also intermediate between E-MORB and OIB, however, the lunar basalts are relatively enriched in HREEs with distinct negative Eu (0.44 and 0.59) and positive

Ho (1.84 and 2.09) anomalies (Fig. 2b), although the latter is absent in more recent data [9]. The mare basalts do not show any REE (La/Sm_N ~0.64, Gd/Yb_N ~1.28, La/Yb_N ~0.80) fractionations, which are important for the terrestrial continental FBs.

In Nb versus Nb/U plot, the low-Ti mare basalts are mostly indistinguishable from the terrestrial basalts, whereas the high-Ti mare basalts show mostly high Nb/U $\geq$ 100 (Fig. 3a). In the process identification plot, the high and low-Ti mare basalts show limited variations of Zr/Y ratios (mostly between ~2.5 and 3.5), few samples of low-Ti mare basalt, however, show significant variation of Zr/Y up to ~6 (Fig. 3b).

The $(Ba/Yb)_{PM}$ ratios of the mare basalts (9.28 and 18.02) are different from that of the Lonar impact-melt (65.61) (Fig. 4a). Also, the average mare basalts differ from the Lonar impact-melt by their positive Nb and negative Sr anomalies. In REE plot, the average Lonar impact-melt shows fractionating REE (La/Yb_N ~4.47) and absence of any Eu anomaly, features not seen among the lunar samples (Fig. 4b).

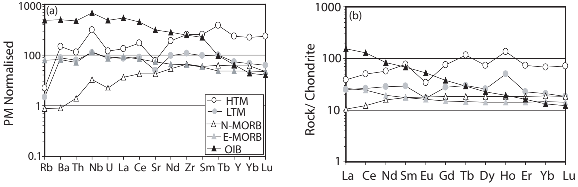

Fig. 2. (a) Incompatible trace element, and (b) REE spidergrams of the average mare basalts and terrestrial oceanic basalts.

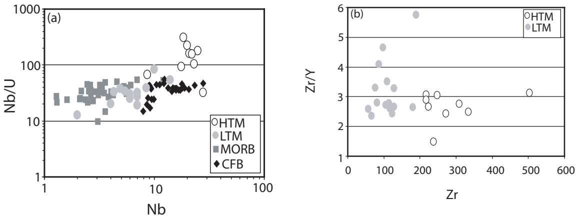

Fig. 3. Plots of mare and terrestrial basalts in (a) Nb/U versus Nb, and (b) Zr/Y versus Zr plots.

5. Summary and Conclusion

Distinct differences in trace element geochemistry between the lunar basalts and Lonar impact-melt (Fig. 4) and their very low Ni contents suggest that the former were perhaps not impact-melts. The present understanding on the Moon [1] has changed dramatically following the discovery of H_2O in the lunar mantle (~0.075 wt %) [9] and by the idea on the non-magma ocean origin of Lunar crust [10]. Comparison with experimental studies [11] suggests the melting of the Lunar mantle could have initiated in a relatively fluid-present (H_2O, CO_2, F, Cl) condition at low-temperature ($<1100^oC$) when a feldspathic magma was produced. The extraction of this melt could have left the lunar mantle depleted in Al, Rb, some LREE, Eu and perhaps U. This refractory mantle could be the source of the parent magmas of the mare basalts that evolved through fractional crystallization as suggested by their bivariant plots (Fig. 1) and limited variation in Zr/Y ratios (Fig. 3b). High Cr contents in mare basalts imply the lunar mantle was Cr rich. During the later phases of melting at higher temperature, the depleted mare mantle could produce basaltic magmas [11], which perhaps evolved through a phase of olivine fractionation that depleted the magmas in Mg and Ni, prior to their eruption on the lunar surface.

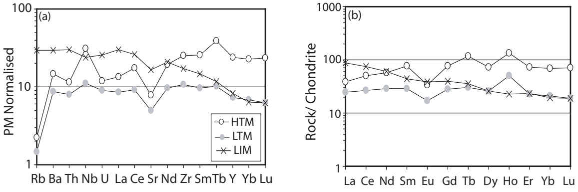

Fig. 4. Comparative (a) incompatible trace element, and (b) REE spidergrams for mare basalts and Lonar impact-melt (LIM).

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