

CHRONOLOGY AND GENESIS OF HIGH-Ti MARE VOLCANISM: MELTING OF COGENETIC DEPLETED AND ENRICHED RESERVOIRS

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An understanding of the chronology and petrogenesis of volcanic rocks is paramount to unravelling the complexities of the composition and structure of the mantle of the Moon. High-Ti mare basalts represent the best-sampled suite of lunar volcanic rocks and likely represent melts of the uppermost mantle of the Moon. Compiled Nd and Sr isotopic data for high-Ti basalts, combined with weighted average ages determined by various techniques yield a complex melting history for the high-Ti mantle source. Melting occurred during three distinct episodes (3.84 Ga, 3.75-3.69 Ga, and 3.56 Ga) separated by hiatuses of 100 Ma or more. The first episode included the melting of a relatively trapped liquid (KREEPy)-rich source beneath the A-11 landing site. Later melting of this source produced magmas which were relatively trapped liquid-free at the A-11 site. Synchronous melting at the A-17 landing site produced magmas with variable proportions of this evolved trapped liquid component. The final phase of volcanism occurred at the A-11 site and involved the assimilation of an evolved "neuKREEP" component. Continued melting of a similar source, which was nearly exhausted of its ilmenite component, beneath the A-12 landing site may have lead to production of magmas parental to the A-12 ilmenite basalts.

Nd and Sr ISOTOPIC DATA FOR HIGH-Ti BASALTS

Data from all high-Ti basalts (Apollo 11 and Apollo 17 landing sites) display a broad scatter in initial Nd and Sr isotopic composition as shown in Figure 1 [1,2,3,4,5]. Basalts from Apollo 11 generally plot with less radiogenic Nd compared with those from Apollo 17. Although Apollo 11 Group B1 basalts have ε_{Nd} values that are similar to Apollo 17 A, B1, and C basalts, these groups are distinct in Sr isotopic composition. These variations in initial Nd and Sr isotopic compositions have led previous workers to postulate that the basalts were derived from separate sources and have been used as evidence of heterogeneity in the lunar upper mantle [4]. Though this interpretation seems quite adequate, it is difficult to reconcile with the view that the lunar upper mantle was a simple system which crystallized early and has not been subject to later mixing and recycling processes. Furthermore, this interpretation, which includes a myriad of different sources, does not explain the homogeneity in mineralogy and major-element chemistry for these rocks.

FORMATION OF COGENETIC ENRICHED AND DEPLETED RESERVOIRS – Implicit in current understanding of the location of terrestrial enriched and depleted reservoirs is the notion that they are spatially separated. The depleted reservoir on Earth is situated in the upper mantle, and the complementary enriched reservoir is located in the crust. However, Earth reservoirs are continually being modified by recycling driven by mantle convection. The Moon is demonstrably different from Earth in that its evolution was arrested relatively early – effectively within 1.5 Ga of its formation [1]. It is possible that crystallized trapped liquids (from the late stages of a magma ocean) have been preserved as LILE-enriched portions of the lunar mantle. This would lead to depleted (cumulate) and enriched (magma ocean residual liquid) reservoirs in the lunar upper mantle. There is no evidence for significant recycling from the highlands crust back into the mantle. Therefore, reservoirs created at the Moon's inception may have remained intact for over 4.0 Ga.

It is generally believed that for less than the first 0.2 Ga of its history, the Moon differentiated into a small Fe-rich core, an olivine-rich lower mantle, and a differentiated magma ocean [6]. This outer magma ocean, or magmasphere, progressively crystallized to form the upper mantle of the Moon and, once plagioclase became a liquidus phase, its anorthositic crust. The crystallization of the magmasphere likely led to layering of the upper mantle and included phases, such as ilmenite, late in its differentiation. The accumulate portion of the lunar upper mantle would be LREE-depleted and contain relatively low abundances of the incompatible elements.

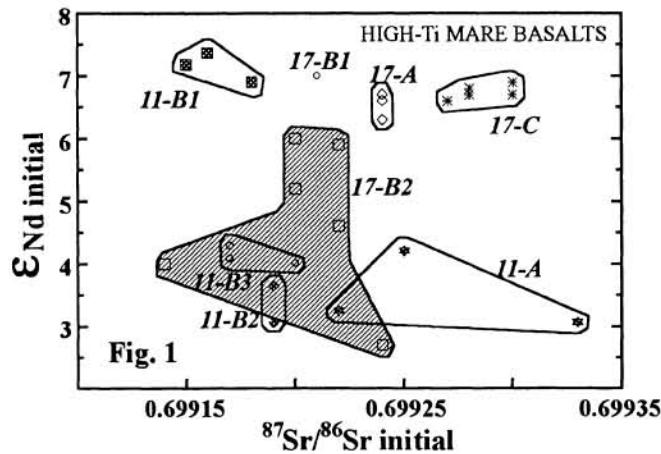


Fig. 1

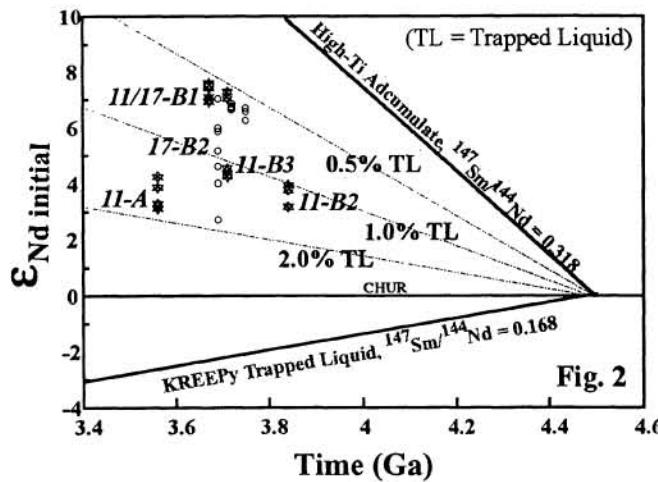


Fig. 2

The residual liquid magmasphere became more evolved with time, leading to enrichment in the LILE. This LILE-enriched liquid could have been trapped in variable, yet small, proportions and effectively "metasomatized" the relatively LILE-depleted crystallizing mafic cumulate. In this way, adjacent regions or layers of the mantle could maintain mineralogic and major-element homogeneity while exhibiting heterogeneities in their trace elements. The LILE-enriched, trapped liquid end-member of the source is represented by residual liquid after 95% crystallization of the LMO (as per Snyder et al.[7]). The isotopic and trace-element composition of this KREEPy liquid component may be represented by KREEP basalt sample 15382 (Rb=16 ppm, Sr=195 ppm, $^{87}\text{Sr}/^{86}\text{Sr}$ (3.84 Ga)= 0.70115; Sm=31 ppm, Nd=112 ppm, $\varepsilon_{\text{Nd}}(3.84)$ = -3; [8, 9]). The cumulate portion of the source is modelled as a cpx-pigeonite-ilmenite-olivine perfect accumulate (Rb=0.01 ppm, Sr=4.16 ppm, Sm=0.631 ppm, Nd = 1.2 ppm, again as per [7]) that has an extremely elevated ε_{Nd} (+8 at 3.84 Ga) and the lowest Sr initial ratio (0.69910) at 3.84 Ga. The Nd isotopic evolution of both end-member components with time is shown in Fig. 2. However, it is not likely that these two components remained distinct over a period of 500 Ma, when the interior of the Moon

CHRONOLOGY & GENESIS OF HIGH-Ti VOLCANISM: Snyder, Taylor, and Halliday

was still hot [10]. Recrystallization of the cumulate-trapped liquid pile could have occurred yielding a source which was heterogeneous in trace elements on the scale of meters. Due to the low Sm/Nd ratio of the trapped liquid relative to the cumulate, those portions of the mantle which contained a larger proportion of this component would evolve with more enriched isotopic signatures.

After an extended period of evolution (e.g., > 0.5 Ga), earliest melting of the trapped liquid-cumulate pair would likely affect regions which were relatively enriched in the LILE (containing heat-producing elements U, Th, and K). Therefore, those regions which trapped the largest proportion of residual LMO liquid would melt first. Melts of these regions would exhibit relatively enriched isotopic signatures (Fig. 2). Later melting would tap regions with less trapped liquid and would yield more isotopically depleted melts. Obviously, the degrees of enrichment and depletion of the melts are highly dependent upon the proportion of trapped liquid and the extent of melting of the cumulate + trapped-liquid pile. However, the trapped liquid component is LILE-enriched (generally by at least an order of magnitude over the mafic cumulate) and would have originally consisted of low-temperature melting phases that would readily remelt. Therefore, even a small proportion (e.g., 1 %) in the cumulate pile will greatly affect the isotopic signature of initial derived melts. However, because of its small proportion, the trapped liquid would have a lesser effect (inversely proportional to the degree of melting) on the major-element composition of the melt.

Similar calculations to discern the proportion of KREEP in these basalts were performed by Hughes et al. [11] and Paces et al. [4]. Both groups concluded that small percentages (generally <1%) of a Rb, Sr, and REE enriched component, with high Rb/Sr and low Sm/Nd ratios, are required to explain the compositions of parental magmas for the high-Ti basalts. However, both groups envisioned this component as distal to the cumulate source and added to the source prior to its fusion, but not cogenetic with its inception – approximately 4.4 Ga ago.

MELTING HISTORY OF THE LUNAR UPPER MANTLE – With this model in mind and utilizing both K-Ar and Sm-Nd ages which have been determined by previous workers, including our group, we can suggest an overall scenario for high-Ti basaltic volcanism on the Moon:

- 1) 3.84 Ga = relatively KREEPy trapped liquid portion of source melted, yielding A-11 B2 (and D?) basalts.
- 2) 3.75 Ga = melting of relatively trapped liquid-free portion of mantle yields A-17 A basalts.
- 3) 3.72 Ga = continual melting of trapped liquid-free cumulate leads to A-17 C basalts.
- 4) 3.71-3.67 Ga = A-11 B3 and B1 basalts produced; volumetrically most significant; high-Ti volcanism ceases (?) at A-11 landing site.
- 5) 3.69 Ga = KREEPyest portion of mantle beneath A-17 site melted yielding A-17 B2 basalts.
- 6) 3.56 Ga = neuKREEP-rich A-11 A basalts extruded (see Jerde et al., this volume).

Finally, there was volcanic activity at 3.2 Ga at the Apollo 12 landing site ages which was relatively high-Ti in tenor. Apollo 12 ilmenite basalts may represent the final known melting of this cumulate source, after it had been nearly exhausted of its ilmenite and trapped liquid components.

The Apollo 12 ilmenite basalts do indicate a source which is even more depleted than the high-Ti basalts (Fig. 3). The extension of the same or a similar high-Ti source beneath the western portion of the lunar near-side hinges on the identification of older high-Ti basalts near the Apollo 12 landing site. Such high-Ti basalt rocks have not been found in the Apollo 12 collection. However, ultraviolet/visible spectral imaging of Oceanus Procellarum (within which the Apollo 12 landing site is located) by the *Galileo* spacecraft has indicated the presence of wide-spread high- to low-Ti basaltic flows in the basin [12]. Also, studies of Whitaker color-difference photographs of the lunar near-side led Charette et al. [13] to classify one of the stratigraphically oldest mare units in the basin as high-Ti in character.

SUMMARY – The interpretation of cogenetic depleted and enriched reservoirs in the Moon is the consequence of events unique to the Moon. First, the late-stage, LREE- and Rb-enriched residual liquid from a crystallizing LMO was trapped in variable and small proportions in the depleted upper mantle cumulates. A lack of recycling in the lunar environment would allow these reservoirs to diverge along separate isotopic

evolutionary paths. This portion of the mantle would remain undisturbed for > 0.5 Ga, prior to being melted to form the oldest high-Ti mare basalts. The isotopic character of the melts would be controlled by the degree of melting, as the least radiogenic reservoir would be melted first – i.e., that portion of the cumulate containing the greatest proportion of trapped liquid would melt first. The range in Sr and Nd isotopic ratios seen in basalts from Mare Tranquillitatis (Apollo 11) is due to melting of a clinopyroxene-pigeonite-ilmenite-olivine cumulate layer with variable proportions of trapped intercumulus liquid. Types B2 and B3 basalts were melted from a portion of the cumulate layer with intermediate amounts of trapped KREEP liquid. Type B1 basalts from both Apollo 11 and 17 are melted from a "near-perfect" adcumulate portion of this layer. Type A basalts may have been extruded from a vent(s) near the Apollo 17 landing site [14] and could, therefore, represent melting of a similar source, albeit with the added complexity of neuKREEP assimilation.

REFERENCES: [1] Nyquist, L.E. and Shih, C.-Y. (1992), *GCA* 56, 2213-2234; [2] Papanastassiou, D.A. et al. (1977), *PLSC 8th*, 1639-1672; [3] Unruh, D.M. et al. (1984) *PLPSC 14th*, B459-B477; [4] Paces, J.B. et al. (1991), *GCA* 55, 2025-2043; [5] Snyder, G.A. et al. (1993) *EPSL*, submitted; [6] Agee, C.B. and Longhi, J., editors (1992), *Workshop on the Physics & Chemistry of Magma Oceans from 1 bar to 4 Mbar*, LPI Tech. Rept. 92-03, 79 pp.; [7] Snyder, G.A. et al. (1992), *GCA* 56, 3809-3823; [8] Nyquist, L.E. (1977), *Phys. Chem. Earth* 10, 103-142; [9] Lugmair, G.W. and Marti, K. (1978), *EPSL* 39, 349-357; [10] Warren, P.H. et al. (1991), *JGR* 96, 5909-5923; [11] Hughes, S.S. et al. (1989), *PLPSC 19th*, 175-188; [12] Sunshine, J.M. et al. (1992), *LPSC XXIV*, 1387-88; [13] Charette, M.P. et al. (1974), *JGR* 79, 1605-1613; [14] Jerde, E.A. et al. (1992), *GCA*, submitted.

