

INVESTIGATING THE SOURCES OF THE APOLLO 14 HIGH-AL MARE BASALTS.

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Introduction: Basalts were returned by Apollo 14 [1] predominantly as clasts in breccias (e.g., [2,3]), although there are at least two pristine, large basalt samples in the collection (e.g., [4,5]). Trace element data for Apollo 14 high-Al basalts (cf. [6]) suggest a complex origin that cannot be explained by simple fractional crystallization or by short-range unmixing. Initially 5 basalt groups were distinguished [2,3] on the basis of REE abundances. Using the terminology of [2], Group 1 basalts contain the highest REE abundances and Group 5 the lowest. A continuum of compositions [7,8] was defined between Groups 1 and 5, where the sample with the lowest incompatible trace element (ITE) abundances (14321,1422) represented the parental melt. This parent then experienced KREEP assimilation (and fractional crystallization – AFC) to form the compositional continuum.

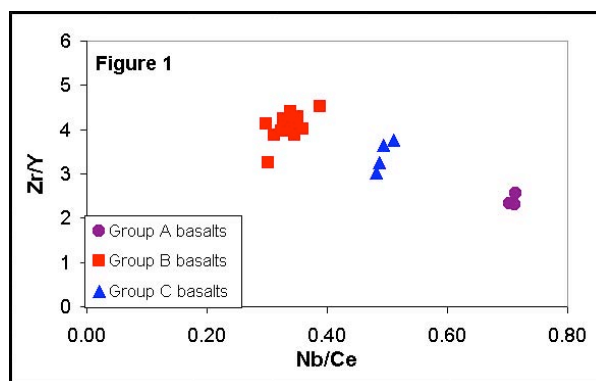
However, Rb-Sr isochrons ages range from 3.95-4.33 Ga [5,9,10]. This brought [11] to the conclusion that the Apollo 14 high-Al basalts define 3 distinct AFC episodes at 4.3 Ga, 4.1 Ga, and 3.95 Ga, all derived from a common source. This was expanded by [12] who concluded that of the three high-Al basalts groups all experienced fractional crystallization, but only the two younger groups assimilated KREEP.

Methods: We analyzed eleven Apollo 14 high-Al basalts and KREEP basalt 15386,48 [13]. These samples were powdered using a clean agate pestle and mortar in a Class 1000 clean lab. Powders were then dissolved and 38 elemental abundances were quantified by solution ICP-MS. Eighteen Apollo high-Al basalt clasts from breccia 14321, which had been fused for major element analysis by electron microprobe and were previously analyzed by [3] and [7] using INA, were analyzed by laser ablation (LA) ICP-MS. With this method we analyzed for 28 trace elements using the NIST 612 glass standard [14] for external calibration and CaO as an internal standard.

Modeling: ICP-MS allows for a broader range in elements than can be quantified by INA. In particular Zr, Nb and Y were quantified, which can be used to derive source compositions. Ratios such as Zr/Y and particularly Nb/Ce do not significantly fractionate during low-pressure fractional crystallization, but rather are constrained by the composition of the source. Thus, basalts with similar ratios of these elements were derived from a common source. On this basis, three groups of high-Al basalts are defined

(Fig. 1). The groupings continue to fall into the compositional/chronological groups as discussed by [11] and [12], but Nb/Ce ratios define three different sources for the Apollo 14 high-Al basalts, not three separate melting events of one source [12].

The model for the Apollo 14 high-Al basalt petrogenesis presented here derives source compositions from the Lunar Magma Ocean (LMO) theory. Using the methods of Snyder et al. [15], we have modeled the major and trace element chemistry of each source composition from a crystallizing LMO. Shortly after or during the final stages of LMO crystallization, dense ilmenite cumulates produced gravitational instability and overturn of the cumulate pile (e.g., [16,17]). Sinking late-stage cumulates would have included varying proportions of KREEP, thus enriching (metasomatizing) earlier LMO cumulates. This type of overturn is thought to have occurred on a Moon-wide scale [16], however not homogeneously, but rather as isolated diapirs on a scale of several hundred meters or less (e.g. [17]).



The source mineralogies calculated for Groups A (the oldest group, corresponding to Groups 4 and 5 of [2]) through C (the youngest group, corresponding to Groups 1 and 2 of [2]) high-Al basalts are hybrid sources in that they contain a mixture of cumulates formed after ~78 PCS, as well as trapped residual liquid (i.e., KREEP). Late-stage cumulates are required to impart the negative Eu (and Sr) anomalies, indicative of plagioclase removal, in the source regions of the Apollo 14 high-Al basalts. The source proposed by Hughes et al. [18] for 14321,1422 cannot produce the characteristic Nb/Ce and Zr/Y ratios of any of the three basalt groups even with variable degrees of partial melting. However, the fact that the source regions are dominated by cumulates from the later stages of LMO

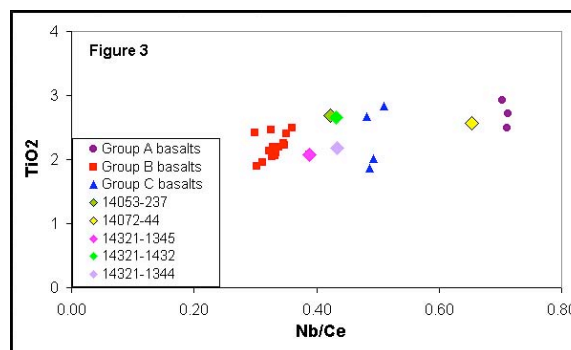
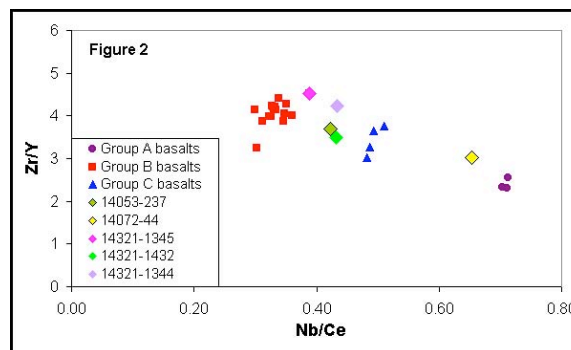
crystallization may explain the uncharacteristically low Ni contents of olivines in the Apollo 14 high-Al basalts reported by Hagerty et al. [19]. The source composition was derived by determining what combination of LMO cumulates would undergo partial melting to produce a composition that could be a potential parental melt to each high-Al basalt group.

Groups A and B basalts originated from sources dominated by Cpx (~82% & 68%, respectively) and olivine (~13% & 24%, respectively), with subordinate amounts of plagioclase, pigeonite, ilmenite, chromite, and KREEP (trapped liquid). Group C high-Al basalts are derived from a source dominated by pigeonite (74%) and olivine (~20%), with subordinate amounts of plagioclase, chromite, ilmenite, and KREEP (trapped liquid).

Discussion: To account for the distinct Nb/Ce ratios (and other characteristic elemental abundances), each source must be dominated by pyroxene. This would imply the source is at a considerable depth, in excess of 10 kbars. What may at first appear to be a large difference in mineralogy between Groups B and C (Cpx & pigeonite) is probably only a matter of nomenclature and simplification from modeling. In the LMO crystallization model of [15] Cpx and pigeonite are simultaneously crystallizing in the final 14%, and it is these cumulate phases that we drew from to achieve the necessary composition to produce the source for the high-Al basalts. In reality the two phases probably represent a changing pyroxene composition dependent on changing conditions during LMO crystallization.

At least three sources and episodes of volcanism for the high-Al basalts are indicated. Basalt ages, element ratio and ITE-CTE plots repeatedly demonstrate the samples break into the same 3 groups. There are a few exceptional samples, however, that do not. These samples (14321,1344, 14321,1345, 14321,1432, 14053, 14072) continually stand as outliers.

14053 is a large, pristine high-Al mare basalt [20] and was originally classified by Dickinson et al. [4] as belonging to Group 3. Based on incompatible trace elements this would correspond to a Group C basalt in our classification. 14053 is the youngest (3.95 Ga) confirmed high-Al mare basalt returned by Apollo 14. This suggested the entire Group C represented the most recent high-Al volcanism in the Apollo 14 collection. However, in light of the new plots (Nb/Ce) it is apparent that 14053 does not share the same evolution as other Group C basalts (Figs. 2,3). 14053 requires a different source with a slightly lower Nb/Ce ratio. 14053 fits in nicely with the set of outliers 14321,1432, and 14321,1344 (and possibly



14321,1345) to form a potential fourth group (Figs. 2,3).

14072 is another pristine high-Al mare basalt [21]. ITE compositions would classify it with 14053 as a Group C basalt. Sr isotopic data dates the sample at 4.00 Ga [9]. The age and I(Sr) for 14072 are within error of 14053, but the Nb/Ce value for 14072 is too high for the two pristine samples to be petrogenetically related (Fig. 2,3). Based on this evidence we believe 14072 represents another possible high-Al group, but the lack of other related samples makes this only a speculation at this time.

References: [1] Wilhelms, (1987) U.S.G.S. Prof. Paper 1348; [2] Dickinson T. et al. (1985) PLPSC 15th, in JGR 90, C365-C374; [3] Shervais J.W. et al. (1985) PLPSC 15th, in JGR 90, C355-C395; [4] Hubbard N. et al. (1974) PLSC 3rd, 1161-1179; [5] Taylor L.A. et al. (1983) EPSL 66, 33-47; [6] Ridley I. (1975) PLSC 6th, 131-145; [7] Neal C.R. et al. (1988) PLPSC 18th, 139-153; [8] Neal C.R. et al. (1989) PLPSC 19th, 147-161; [9] Papanastassiou D. & Wasserburg G. (1971) EPSL 12, 36-48; [10] Dasch J. et al. (1987) GCA 51, 3241-3254; [11] Neal C.R. & Taylor L.A. (1990) PLPSC 20th, 101-108; [12] Kramer and Neal (2003), LPSC 34, #2035; [13] Neal C.R. & Kramer G.Y. (2003) LPSC34, #2023; [14] Pearce et al. (1997) Geostand. News., 21, 115-144; [15] Snyder et al. (1992) GCA, 56, 3809-3823; [16] Ringwood and Kesson (1976) PLSC 7th, 1697-1722; [17] Spera (1992) GCA, 56, 2253-2265; [18] Hughes et al. (1990) PLPSC 11th, 540-541; [19] Hagerty et al. (2005) MaPS, in press. [20] Taylor et al. (2004) Am. Min. 89, 1617-1624; [21] El Goresy et al. (1972) PLPSC 3rd, 333-349