

A Sr-Nd-Hf ISOTOPE, TRACE-ELEMENT, AND PETROLOGICAL STUDY OF APOLLO MARE BASALTS AND LOW-TI MARE BASALT METEORITES. James M.D. Day¹, Geoff M. Nowell², D. Graham Pearson³, Lawrence A. Taylor⁴, ¹Scripps Institution of Oceanography, La Jolla, CA 92093-0244, USA (jmdday@ucsd.edu), ²Durham University, Durham, DH1 3LE, UK, ³University of Alberta, Edmonton, T6G 2E3, Canada, ⁴Planetary Geosciences Institute, University of Tennessee, Knoxville, TN 37996, USA

Introduction: Mare basalt compositions are classically interpreted to reflect partial melting of mineralogically distinct source regions, formed during a magma-ocean phase shortly after the formation of the Moon [1-3]. Here we present petrology, trace-element geochemistry and Sr-Nd-Hf isotope data for aliquants of Apollo 12, 15 and 17 mare basalts and La Paz mare basalt meteorites studied previously for highly siderophile element abundances and Os and O isotopes [4-6]. The new isotope data are corrected for the effects of neutron capture [7]. These data allow a comprehensive geochemical assessment of mare basalt petrogenesis and reveal important similarities – and differences – with terrestrial basalt lithophile element variations.

Methods and Data: Petrological study was performed on Apollo 17 [8] and 15596 samples to complement reported data for Apollo 15 and LaPaz samples [9,10]. For example, 15596 is a quartz-normative basalt (9.2 wt.% MgO) and has pyroxene compositions ranging from pigeonite (Wo_5En_{70}), to augite ($Wo_{41}En_{33}$), to extreme Fe-enrichment to pyroxferroite (Figure 1). Otherwise, petrology of these samples is similar to that reported previously (see [8-10]).

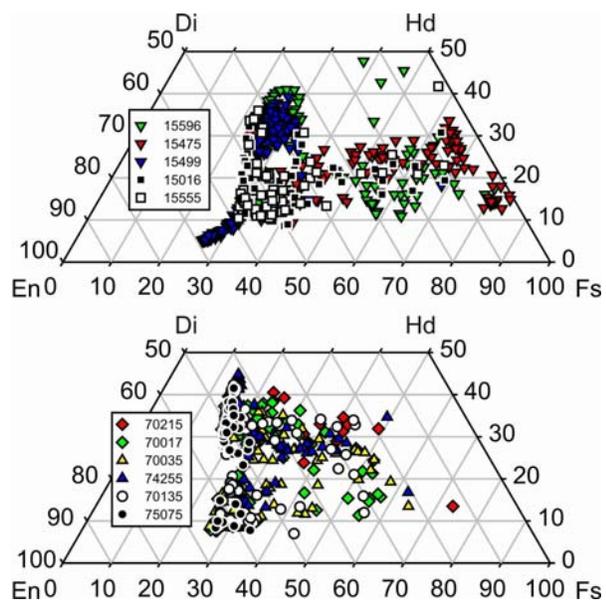


Figure 1: Pyroxene quadrilaterals for Apollo 15 and 17 mare basalts examined in this study.

For Apollo 15, 17, and La Paz mare basalts, major- and trace-elements contents, and Sr-Nd-Hf isotopes

were obtained on aliquots from 2-3 g of homogenized whole-rock powder. Analytical methods were identical to those reported previously (e.g., [9-11]). For Apollo 12 mare basalts, measurements were made using Paar Bomb digestion prior to analysis.

New major- and trace-element data for mare basalts are in close agreement with previous studies. On a double-normalized rare earth element (REE) plot, the light REE (LREE) depletions of Apollo 17 mare basalts are evident (Figure 2). Apollo 12 mare basalts span a range in LREE abundances, with feldspathic basalt 12038 having no Eu-depletion, whereas Apollo 15 mare basalts have steeper REE patterns and more variable Eu-anomalies, relative to other mare basalts.

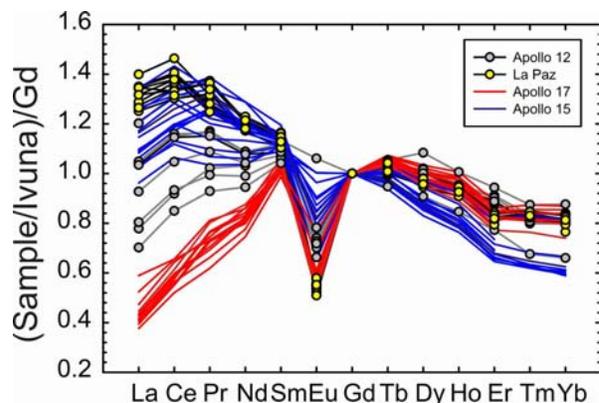


Figure 2: Double-normalized REE plot (relative to CI Ivuna and Gd) for Apollo 12, 15, 17 and La Paz mare basalts.

New $^{87}\text{Sr}/^{86}\text{Sr}_i$ and neutron capture-corrected $\epsilon_{\text{Nd}i}$, and $\epsilon_{\text{Hf}i}$ values for Apollo 15 and Apollo 17 mare basalts are similar to those reported previously [7]. However, LaPaz mare basalts possess more radiogenic Sr and similar Nd and Hf isotope compositions to Apollo 15 mare basalts. Apollo 17 high-Ti (13.3-17.5 wt.% TiO_2) basalts span a range in $\epsilon_{\text{Nd}i}$ and lie close to the Nd-Hf isotope terrestrial mantle array (Figure 3).

Discussion: Fractional crystallization has played a major role in the formation of mare basalts, in agreement with previous studies (e.g., Figure 1). However, such crystallization trends cannot explain the large range in relative and absolute abundances of trace elements in mare basalts. Instead, these variations further emphasise the presence of mineralogically distinct sources in mare basalt petrogenesis.

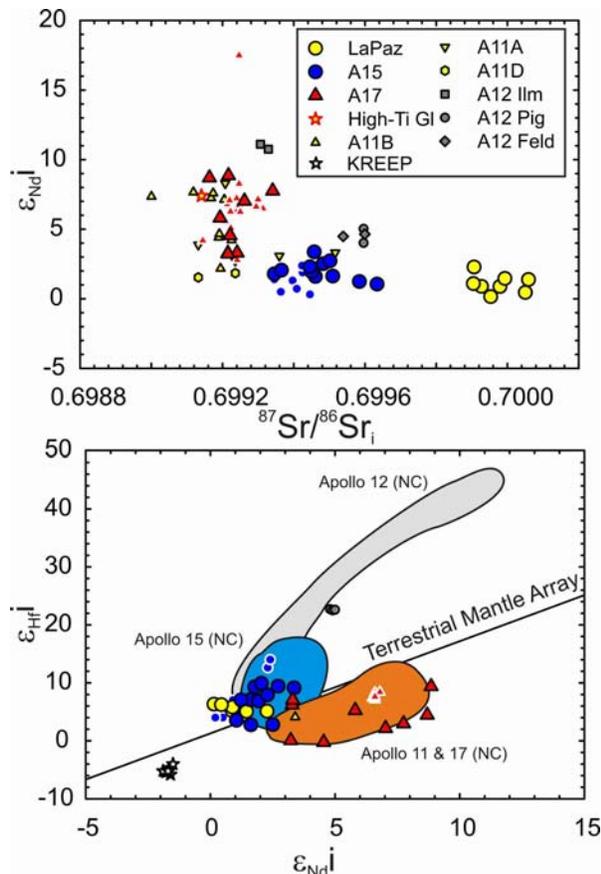


Figure 3: Age- and neutron capture-corrected Sr-Nd-Hf isotope data for Apollo 15, 17 and La Paz basalts versus neutron-capture corrected (small symbols [7]) and uncorrected (NC fields [2]) published data.

The LREE-depleted compositions of Apollo 17 mare basalts are also reflected in the long-term Nd isotope compositions of these samples. La Paz mare basalts have age-corrected Nd and Hf isotope compositions similar to Apollo 15 mare basalts, whereas the range of published Apollo 12 Hf isotope data indicates that they originate from sources with elevated $^{176}\text{Lu}/^{177}\text{Hf}$ (0.06) for both pigeonite- and olivine-normative basalts (Figure 4). The long-term elevated Sm/Nd and Lu/Hf ratios required to explain the composition of mare basalts and low Sm/Nd and Lu/Hf ratios required to explain KREEP are consistent with preservation of late-stage incompatible element liquids during differentiation of the Moon at ~ 4.4 Ga.

As well as being the youngest lunar basalts, La Paz meteorites also have the highest initial $^{87}\text{Sr}/^{86}\text{Sr}$, suggesting a source with more elevated Rb/Sr than other mare basalts. The combined data for these basalts are permissibly consistent with age-progressive partial melting of less-depleted sources with time during mare basalt petrogenesis [11]. None-the-less, the low

$^{87}\text{Sr}/^{86}\text{Sr}$ values of mare basalts emphasise the volatile-depleted nature of lunar source regions. A notable feature of the neutron-capture corrected Nd-Hf isotope data (this study and [7]) is that they extend both above and below the Terrestrial Mantle Array defined by ocean island- and mid-ocean ridge-basalts. While magma ocean differentiation led to early large variations in Sm/Nd and Lu/Hf in the lunar mantle, initial Hf and Nd isotope compositions of the lunar silicate reservoir were similar to chondritic compositions.

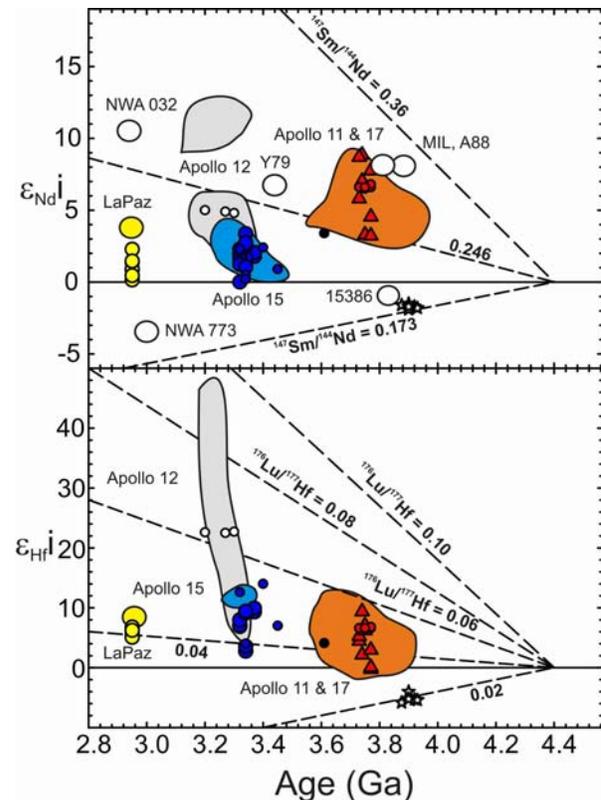


Figure 4: Age-corrected Nd and Hf isotope data for Apollo 15, 17 and La Paz mare basalts versus neutron-capture corrected (small symbols [7]) and uncorrected (fields [2]) published data. Solid line denotes chondritic values [12]. Dashed lines indicate sources with variable Sm/Nd and Lu/Hf formed at 4.4 Ga.

References: [1] Neal & Taylor (1992) *GCA*, **56**, 2177. [2] Snyder et al. (2000) In: *Origin of the Earth and Moon*. 361-395. [3] Nyquist et al. (1995) *GCA*, **59**, 2817. [4] Day et al. (2007) *Science*, **315**, 217. [5] Day & Walker (2011) *M&PS*, **46**, A54. [6] Spicuzza et al. (2007) *EPSL*, **253**, 254. [7] Sprung et al. (2013) *EPSL*, **380**, 77. [8] Hill et al. (2006) *LPSC*, **37**, 2067. [9] Schnare et al. (2008) *GCA*, **72**, 2556. [10] Day et al. (2006) *GCA*, **70**, 1581. [11] Day et al. (2006) *LPSC*, **37**, 2235. [12] Bouvier et al. (2008) *EPSL*, **43**, 278.