Earth and Planetary Science Letters 422 (2015) 126–137

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Petrogenesis of primitive and evolved basalts in a cooling Moon: Experimental constraints from the youngest known lunar magmas

Stephen M. Elardo [*,1], Charles K. Shearer, Kathleen E. Vander Kaaden, Francis M. McCubbin, Aaron S. Bell

Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, USA

A R T I C L E I N F O

Article history:
Received 27 October 2014
Received in revised form 6 April 2015
Accepted 8 April 2015
Available online 28 April 2015
Editor: C. Sotin

Keywords:
Moon
experimental petrology
meteorite
mare basalt
lunar mantle
fractional crystallization

A B S T R A C T

We have conducted high-temperature experiments over a range of pressures to constrain the petrogenesis of the youngest sampled lunar magmas, which have contrasting primitive and evolved compositions. Our results indicate that at ∼3 Ga, melting still occurred within the same mantle depth range that produced crystalline mare basalts for the previous ∼1 Ga, although our data cannot support or confirm that the shallowest extents of melting moved deeper into the mantle by ∼3 Ga, as is predicted by most thermal evolution models. Furthermore, melting still occurred in regions with low abundances of heat-producing elements. Basaltic lunar meteorite NEA 003A has some of the lowest abundances of incompatible trace elements among all mare basalts and no negative Eu anomaly. Our experiments show that NEA 003A is multiply saturated with olivine and low-Ca pyroxene on its liquidus at ∼1.1 GPa (∼215 km) and ∼1330 °C. If the primitive NEA 003A liquid composition is a minimally-modified melt, the relatively low Mg# of its source region (73–75), its lack of a Eu anomaly, and its chondritic initial Nd isotopic composition indicate its source region likely escaped mixing during mantle overturn with later-stage magma ocean cumulates that formed after plagioclase saturation. This condition would require the sources of the ultramafic glasses to have experienced cumulate mixing, or for assimilation of later-stage magma ocean cumulates by the ultramafic glass parental magmas before eruption in order to account for their higher Mg#'s and deeper negative Eu anomalies. Alternatively, NEA 003A may have undergone some fractional crystallization, in which case its more primitive source region would be deeper than 215 km and may approach the depth range of the ultramafic glass source regions. Iron- and incompatible trace element-rich basaltic lunar meteorites LAP 02205, NWA 032/479, and NWA 4734 have nearly identical bulk compositions and have a multiple saturation point on their high pressure liquidus at <0.6 GPa (<105 km) and 1150–1200 °C. The P–T conditions of this multiple saturation point are inconsistent with the expectation from thermal modeling of a thick, cold lunar elastic lithosphere at 3 Ga, and likely indicate these melts underwent fractional crystallization before eruption, thus increasing their abundances of incompatible trace elements. However, these LREE-enriched basalts possess a very deep negative Eu-anomaly but do not show other chemical fingerprints of KREEP, indicating that a component of Fe-rich, low-Ti late-stage magma ocean cumulates are required in their hybridized source region.

1. Introduction

The composition and thermal state of the lunar mantle, both at present day and through time, can only be inferred indirectly due to the lack of mantle samples and a global, high-resolution seismic dataset (e.g., Shearer et al., 2006; Wieczorek et al., 2006). Mare basalts and volcanic glasses offer the strongest constraints available on the thermochemical evolution of the lunar interior. The goal of this study is to combine the geochemistry of the youngest known lunar igneous samples, evolved basaltic meteorites LaPaz Icefield (LAP) 02205 and its pairings, Northwest Africa (NWA) 032 and 479, NWA 4734 (collectively referred to as the LAP group hereafter), and the more primitive Northeast Africa (NEA) 003 lithology A (Haloda et al., 2009), with experimental petrology to better constrain the P–T–X conditions of mantle melting and the nature of lunar magma ocean (LMO) cumulate source regions producing magmas at ∼3 Ga in the context of models of lunar thermal evolution.

---

[*] Corresponding author.
E-mail address: selardo@carnegiescience.edu (S.M. Elardo).

[1] Present address: Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Rd., NW, Washington, DC 20015, USA.

http://dx.doi.org/10.1016/j.epsl.2015.04.014
0012-821X/© 2015 Elsevier B.V. All rights reserved.

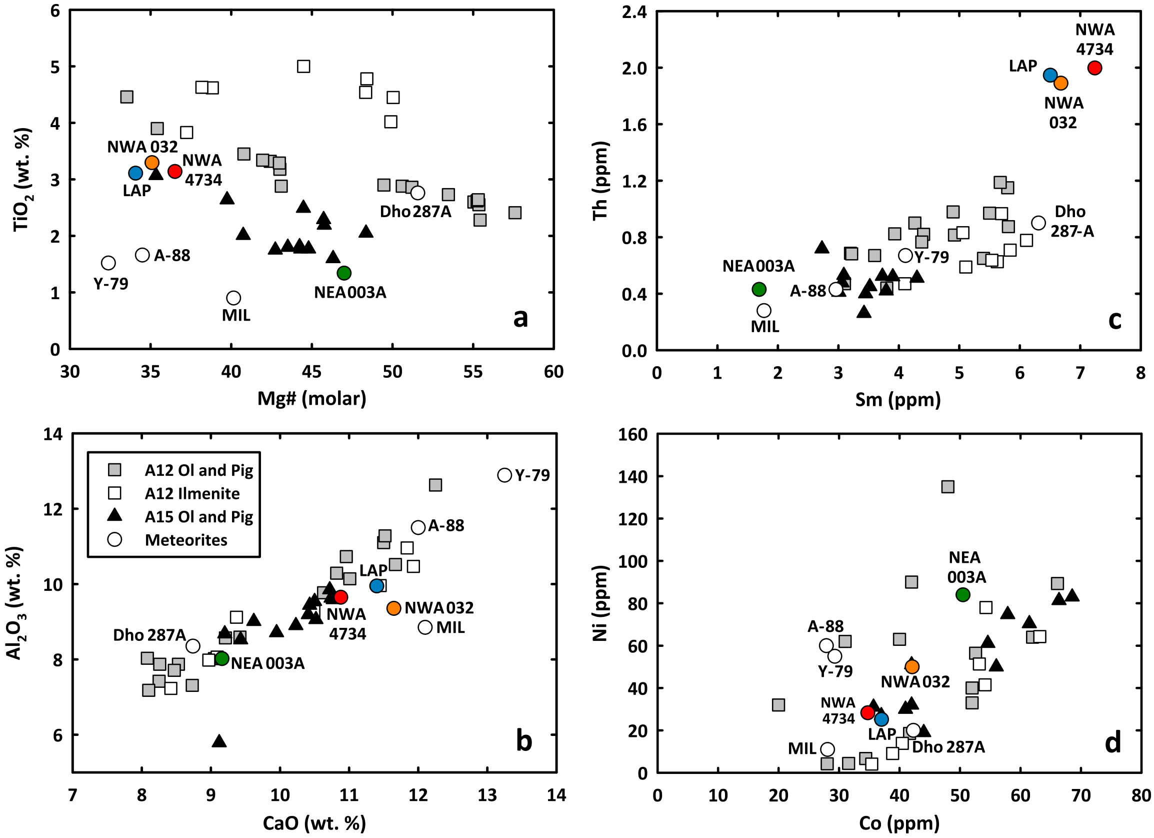

Fig. 1. Plots of (a) TiO_2 in wt.% vs. molar Mg#, (b) Al_2O_3 vs. CaO in wt.%, (c) Th vs. Sm in ppm, and (d) Ni vs. Co in ppm for low-Ti mare basalts from Apollo 12 and 15, and unbrecciated lunar meteorites. Data from Elardo et al. (2014) and references therein.

In terrestrial systems, the most compositionally primitive magmatic liquid compositions within a suite of samples are the least likely to be affected by fractionation processes after melt extraction and therefore represent the best candidates for high P–T experiments designed to constrain the conditions of melting. Many of the ultramafic volcanic glasses are thought to be the most likely candidates for near-primary melts in the lunar environment (Delano, 1986; Longhi, 1992a; Shearer and Papike, 1993; Elkins-Tanton et al., 2003; Shearer et al., 2006). NEA 003A (Sm–Nd age of 3.09 ± 0.06 Ga) has a flat rare earth element (REE) pattern with no negative Eu-anomaly, high Ni and Co abundances, and some of the lowest incompatible trace element (ITE) abundances among all mare basalts (Figs. 1 and 2; Haloda et al., 2009), and therefore represents a good candidate for such experiments. After removal of accumulated olivine (Haloda et al., 2009), its Mg# (molar $Mg/[Mg + Fe] * 100$) of 47 is not among the highest observed in mare basalts, but is still near the higher end of the low-Ti basalt range (Fig. 1). Conversely, the LAP group (Sm–Nd and Rb–Sr ages of 2.93–3.02 Ga), with a more evolved Mg# of ∼36, a LREE-enriched REE pattern with a deep negative Eu-anomaly, low abundances of Ni and Co, and higher ITE abundances (e.g., Righter et al., 2005; Zeigler et al., 2005; Anand et al., 2006; Joy et al., 2006; Rankenburg et al., 2007; Borg et al., 2009; Elardo and Shearer, 2014; Elardo et al., 2014), have been suggested to represent liquids having experienced extensive fractional crystallization (i.e., Day et al., 2006, 2007). Models of LMO crystallization suggest that Fe and ITE-rich regions may be the source of evolved basalts such as the LAP Group rather than crystal fractionation after partial melting (Snyder et al., 1992; Shearer and Papike, 1993, 1999; Hess, 2000; Shearer et al., 2006; Elardo et al., 2011, 2014), although these processes are not mutually exclusive.

NEA 003A and/or the LAP Group can potentially be used to constrain models of lunar thermal evolution. These models predict that the lunar elastic lithosphere grows as the Moon cools and may be as thick as 150 km at 3 Ga (Parmentier and Hess, 1998). These models also predict that the upper extent of mantle melting will move deeper through time (Wieczorek and Phillips, 2000; Hess and Parmentier, 2001; Spohn et al., 2001; Ziethe et al., 2009; Grimm, 2013; Laneuville et al., 2013). This prediction can be tested if relatively young samples can be found that represent minimally-modified mantle partial melts. NEA 003A and the LAP group have the potential to offer such insight. Therefore, we have conducted high-P–T experiments on synthetic NEA 003A and LAP group liquid compositions to (1) assess the P–T–X conditions of melting and (2) test models for the origin of the evolved LAP group basalts. We combine these experimental results with constraints from the geochemical and isotopic compositions of these basalts, geochemistry of Apollo mare basalts and ultramafic volcanic glasses, petrogenetic models of their origin, and thermochemical models of the lunar interior to gain a better understanding of basalt petrogenesis in the waning stages of the main pulse of mare magmatism.

2. Experimental and analytical methods

2.1. Starting materials

The composition of the LAP meteorites (LAP 02205, 02224, 02226, 02436, 03632, 04841) from Day et al. (2006; Table 1) was chosen because it yields the most appropriate olivine-melt Fe–Mg exchange K_D for lunar low-Ti basalts (Delano, 1980) using the most magnesian olivine (Fo_{65}) from our previous studies (Elardo and Shearer, 2014; Elardo et al., 2014). Interpretation of this composition indicates it is a magmatic liquid composition. However, the bulk compositions of LAP 02205, NWA 4734, and NWA 032/479