DIVERSITY IN LOW-TI MARE MAGMATISM AND MANTLE SOURCES: A PERSPECTIVE FROM LUNAR METEORITES NWA 4734, NWA 032, AND LAP 02205.
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Introduction: Lunar meteorites are thought to provide a random sampling of the lunar surface, and therefore have the potential to provide specimens of basaltic units not sampled by the Apollo and Luna missions. Although not identical, lunar meteorites NWA 032 and LAP 02205 (and parings) share many compositional and mineralogical characteristics [e.g. 1-4]. They are both unbrecciated, low-Ti mare basalts with bulk compositions, mineral major element compositions, and ages that have been interpreted as perhaps representing samples of different regions of the same geologic unit on the Moon [2-5]. Furthermore, although it has yet to be extensively studied, NWA 4734 is an unbrecciated, low-Ti basaltic meteorite which shares some compositional and textural features with LAP 02205 [6-8].

The goal of this work is to provide a detailed petrologic, mineralogical, geochemical, and isotopic study of NWA 4734, NWA 032 and LAP 02205 to both elucidate the nature of their petrogenetic relationship (or lack thereof), and to place their compositions and source regions in the context of low-Ti mare basaltic magmatism. Low-Ti basalts (2-4 wt. % TiO_2) are compositionally the most abundant mare basalt type on the lunar surface [9]. These meteorites have the potential to expand our knowledge of the compositional diversity among low-Ti basalts and to establish differences in their source regions produced by LMO crystallization.

Analytical Methods: Phenocrystic phases in NWA 4734, NWA 032 and LAP 02205/02224 (LAP, hereafter) were analyzed for major, minor and trace elements using a JEOL JXA 8200 electron microprobe and a Cameca 4f ims ion microprobe at the University of New Mexico. The major, minor and trace element bulk rock composition of NWA 4734 was determined using ICP-OES and -MS at the Center for Environmental Science and Technology, University of Notre Dame [10]. Mineral separates and measurements of Sm-Nd and Rb-Sr are being made at Lawrence Livermore National Laboratory, following the approach of [3].

Are NWA 032 and LAP 02205 related? Substantial data has been interpreted to indicate that NWA 032 and LAP may be from the same geologic unit. This interpretation is supported by their similar crystallization ages (2947 ± 16 Ma [3] and 3020 ± 30 – 2990 ± 18 Ma [11, 12] respectively). It is also supported by their nearly identical trace element geochemistry (Fig. 1), and similar trace element (i.e. Ni, Co) compositions of olivine phenocrysts. The two basalts also have essentially the same La/Ta ratios (18.1 vs. 18.5, respectively), which supports the pairing. Despite the suggestion by [1, 3] that the olivine in NWA 032 is in equilibrium with the bulk rock, our olivine analyses indicate this is not the case. We calculate that NWA 032 contains ~6.7% accumulated olivine. As noted by [2, 3], a minor difference in their bulk compositions was MgO. Subtraction of this accumulated olivine results in their major element compositions being indistinguishable.

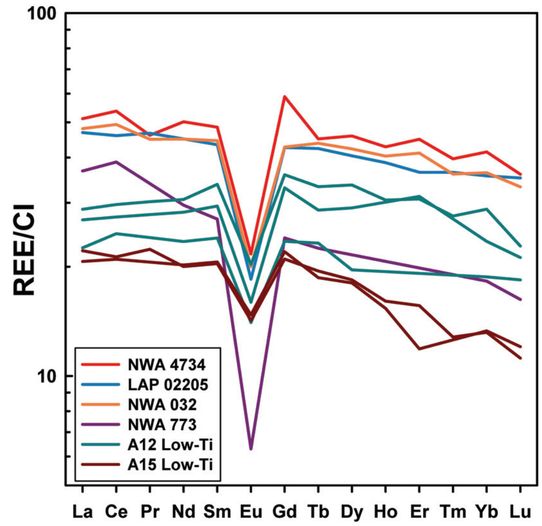

Fig. 1: Chondrite normalized REE patterns for NWA 4734, LAP, NWA 032, the olivine gabbro lithology of NWA 773, and typical A12 and A15 low-Ti basalts.

Texturally, these basalts are not similar. NWA 032 contains phenocrysts of chromite, olivine, and pyroxene set in a fine-grained groundmass, whereas LAP has a more coarse-grained, subophitic texture of plagioclase, pyroxene, ilmenite, minor olivine and other minor phases [e.g. 1-4]. Furthermore, [13, 14] showed that pyroxenes in NWA 032 exhibit a complex oscillatory zoning pattern in Cr, Ti and Al that is not seen in pyroxenes in LAP, suggesting that NWA 032 underwent a more complex cooling history. However, [5] presented a quantitative model of basalt flow stratigraphy that can explain some of the textural differences if NWA 032 represents the more quickly cooled equivalent of LAP in the same flow.

The conclusion that these meteorites are from the same mare flow is most strongly refuted by their initial Sm-Nd isotopic compositions, which differ outside of analytical uncertainty [3]. [12] determined an ε_{Nd} of +2.9 ± 0.9 for LAP, whereas [11] reported an ε_{Nd} of +1.2 ± 0.2. These Nd isotopic compositions are in marked contrast to the ε_{Nd} of +9.71 ± 0.74 determined from the 2931 ± 92 Ma Sm-Nd isochron of NWA 032 [3]. These distinct ε_{Nd} reflect differences in the REE pattern of the source LMO cumulates, with NWA 032 derived from a more LREE depleted source than LAP.

Are NWA 4734 and LAP 02205 paired? [7, 8] suggested that NWA 4734 may be paired with LAP on the basis of identical textures and overlapping bulk compositions. Our bulk rock analyses of NWA 4734 confirm that it is virtually indistinguishable from LAP in terms of major, minor and trace elements (Fig. 1). Their incompatible trace element ratios are also similar, with La/Ta ratios of 15.2 vs. 18.5 and Nb/Ce ratios of 0.42 vs. 0.44, respectively. However, texturally the two basalts are subtly different. Although both basalts have a similar texture, NWA 4734 is somewhat more coarse-grained than LAP. This is observed in plagioclase and pyroxene grain size, but is especially evident in late-stage olivine. NWA 4734 contains fayalitic olivines that are up to 400 μm in the largest dimension and sometimes contain silica inclusions. Late-stage olivines are found in LAP, but are smaller and do not seem as abundant.

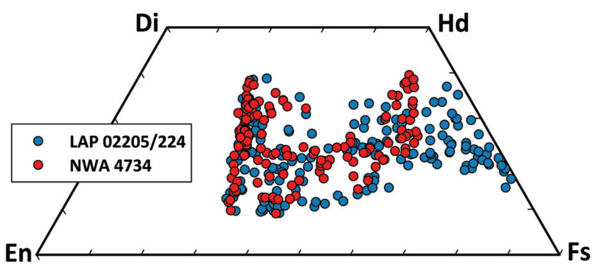

Fig. 2: Compositions of pyroxenes in LAP and NWA 4734.

The discrepancy in grain size does not preclude the meteorites being paired, but rather reflects differences in crystallization kinetics. This difference is apparent in pyroxene compositions. Figure 2 shows pyroxene compositions for both meteorites. Pyroxenes in LAP extend to Fe-rich compositions and reach pyroxferroite; however pyroxenes in NWA 4734 do not. There is excellent overlap in pyroxene compositions between the two outside of NWA 4734 pyroxenes not extending into the "forbidden zone". This is consistent with NWA 4734 being the more slowly cooled equivalent of LAP, and with large fayalitic olivine in NWA 4734.

There is also preliminary isotopic evidence to support a pairing between LAP and NWA 4734. Although more extensive analyses are currently underway, our preliminary Sm-Nd isotopic analyses of NWA 4734 suggest an age and ε_{Nd} that overlap with those reported for LAP by [11, 12] (Fig. 3). This, along with the compositional and mineralogical similarities, would suggest that LAP and NWA 4734 are either source crater paired or represent very similar mare basalts.

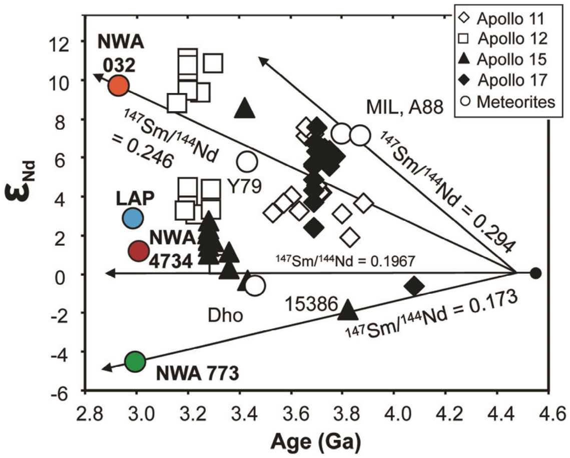

Fig. 3: Plot of initial ε_{Nd} vs. age for various lunar basalts. ε_{Nd} shown for LAP is from [12], while the value from [11] overlaps with the value for NWA 4734. Modified after [3].

Low-Ti Mare Magmatism: Except for the Nd isotopic composition of NWA 032, these basalts are almost indistinguishable. However, they possess some unique compositional features. All three meteorites have elevated REE abundances compared to typical A12 and A15 low-Ti basalts, and deeper Eu anomalies. There is also a decoupling between major and trace element compositions and isotopic composition. Although the three meteorites have nearly identical REE patterns, NWA 032 has an initial Nd isotopic composition indicating derivation from a more LREE depleted source [3] than LAP and NWA 4734. In addition, LAP and NWA 4734 lie along similar $^{147}Sm/^{144}Nd$ evolution paths as low-Ti basalts collected by Apollo, but have different REE patterns. If NWA 032's Nd isotopic composition from [3] is correct, it would suggest a process that decouples REE pattern from Nd isotopic composition. [15] suggested that such differences are due to the percent of intercumulus melt. However, [3] modeled NWA 032's source region and suggested a low degree of partial melting, minimal plagioclase in the source, and minimal involvement from KREEP. The Ti/Sm ratios of all three basalts (2328-2794) would also support minimal KREEP involvement in their petrogenesis. Clearly, these three meteorites indicate substantial diversity in low-Ti mare basalts and the source regions from which they were derived.

References: [1] Fagan et al. (2002) *MAPS* 371 – 394. [2] Zeigler et al. (2005) *MAPS* 1073 - 1101. [3] Borg et al. (2009) *GCA* 3963 – 3980. [4] Day et al. (2006) *GCA* 1581 - 1600 [5] Day and Taylor (2007) *MAPS* 3-17. [6] Connolly et al. (2008) *MAPS* 571 – 632. [7] Korotev et al. (2009) *LPSC* #1137. [8] Fernendes et al. (2009) *LPSC* #1045. [9] Giguere et al. (2000) *MAPS* 193-200. [10] Fagan & Neal (2012) *LPSC* [11] Nyquist et al. (2005) *LPSC* #1374 [12] Rankenburg et al. (2006) *Science* 1369 – 1372. [13] Burger et al. (2009) *LPSC* #2043. [14] Elardo et al. (2011) *LPSC* #2582. [15] Snyder et al. (1992) *GCA* 3809 - 3823