THE ORIGIN OF YOUNG MARE BASALTS INFERRED FROM LUNAR METEORITES NWA 4734, NWA 032, AND LAP 02205. S. M. Elardo[1], C. K. Shearer[1], A. L. Fagan[2,3], L. E. Borg[4], A. M. Gaffney[4], P. V. Burger[1], C. R. Neal[2], and F. M. McCubbin[1]. [1]Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131, [2]Dept. of Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN, 46556, [3]Lunar & Planetary Institute, USRA, Houston, TX 77058, USA, [4]Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore, CA 94550. selardo@unm.edu

Introduction: There are currently ten recognized unbrecciated mare basaltic lunar meteorites, five of which (NWA 032/479, LAP 02205, NEA 003A, NWA 773, NWA 4734) have ages that are younger than the mare basalts returned by the Apollo and Luna programs [1-4], and represent the youngest known igneous samples from the Moon. All ten of these meteorites are low-Ti (i.e. 1-6 wt. % TiO_2) mare basalts that have similar major element compositions to those basalts collected by Apollo 12 and 15. However, these meteorites have distinct incompatible trace element (ITE) compositions compared to the Apollo basalts, and span a range from some of the most ITE-enriched mare basalts yet found (NWA 032, LAP 02205, NWA 4734, NWA 773) to relatively low ITE abundances (NEA 003A; flat REEs, low Th) [3-9]. Moreover, the five youngest meteorites span nearly the complete observed range in source region Sm/Nd found in lunar basalts, from highly depleted (NWA 032) to KREEPy compositions (NWA 773) [1].

The variability in ITE and isotopic compositions of the youngest mare basalts suggests that multiple, geochemically and isotopically distinct source regions in the lunar mantle melted as late as ~2.9 Ga to produce these basalts. Furthermore, a subset of these young mare basalts (NWA 4734, NWA 032, LAP 02205) has nearly identical bulk rock compositions and ages, but distinctly different isotopic compositions. Are these three meteorites related, or are they derived from distinct source regions? What is the role of KREEP in the origin of young mare basalts? Is heat from KREEP required for mantle melting late in mare magmatism [e.g. 8]? What is the geochemical diversity in source regions melting at ~2.9 Ga? The goal of this work is to place better constraints on the origin of the youngest mare basalts through a detailed petrologic, geochemical, mineralogical and isotopic study of NWA 4734, NWA 032 and LAP 02205 to answer these questions.

Methods: Phenocryst 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 a Perkin Elmer 3300 XL Optima ICP-Optical Emission Spectrometer [after 10] and a Thermo-Finnigan Element2 high resolution magnetic sector ICP-MS [after 11] at the University of Notre Dame. Mineral separates and measurements of Sm-Nd and Rb-Sr ages and isotopic compositions were made at Lawrence Livermore National Laboratory, using a Thermo Scientific TRITON thermal ionization mass spectrometer, following the approach of [1].

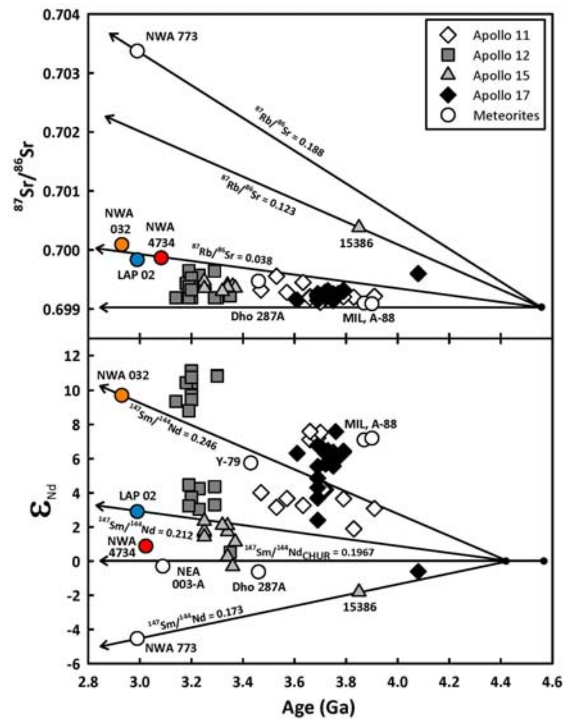

Fig. 1: Plots of initial $^{87}Sr/^{86}Sr$ and ε_{Nd} vs. age for Apollo and meteoritic mare basalts. NWA 4734 data are from this study. References for literature data can be found in [1].

Low-Ti basalt NWA 4734: Petrographic and geochemical descriptions of NWA 032 and LAP have been given in the literature [e.g. 1, 2, 5, 6, 9], so here we focus on NWA 4734. NWA 4734 is an unbrecciated low-Ti mare basalt that is dominated by pyroxene and plagioclase phenocrysts with minor olivine, ilmenite, spinels, and trace phases. NWA 4734 is a subophitic basalt that is very similar to LAP, but is slightly more coarse-grained [4, 12]. NWA 032 differs in that it consists of olivine, pyroxene and chromite phenocrysts set in a fine-grained groundmass. NWA 4734 has a relatively low Mg* (36.5) among lunar low-Ti basalts, it is enriched in LREEs (La = 53.4 x

CI, $[La/Yb]_N = 1.29$) and incompatible trace elements (e.g. Th = 2.0 ppm), and has a deep, negative Eu anomaly ($Eu/0.5*[Sm+Gd]_N = 0.43$).

The age of NWA 4734, determined from a Sm-Nd mineral isochron, is 3024 ± 27 Ma. Its initial ε_{Nd} is +0.88 ± 0.20 (Fig. 1). This is concordant with the ages of NWA 032 [1] and LAP [2], and makes NWA 4734 currently the 4th youngest dated lunar igneous rock. The $^{147}Sm/^{144}Nd$ calculated for the NWA 4734 magma source is 0.212 ± 0.001. The Rb-Sr system is disturbed due to desert weathering, but leached whole rock and plagioclase fractions produce a two-point tie line with a concordant age of 3083 ± 42 Ma and an initial $^{87}Sr/^{86}Sr$ = 0.699867 ± 13. The $^{87}Rb/^{86}Sr$ calculated for the NWA 4734 magma source is 0.038 ± 0.002.

Overall, NWA 4734 is remarkably similar to LAP and NWA 032. Texturally, they are consistent with being derived from different locations in a thick lava flow [e.g. 13], with NWA 032 representing the quickly cooled margin, and LAP and NWA 4734 representing more slowly cooled interior regions. This is supported by their nearly identical major, minor and trace element compositions, ages, overlapping olivine Ni/Co, and similar mineral chemistries. These overwhelming similarities suggest the three basalts may originate from the same source crater or even a single lava flow.

Despite these similarities, their isotopic compositions indicate derivation from multiple sources. The source region $^{87}Rb/^{86}Sr$ for NWA 032 (0.044 ± 0.001) [1] is more enriched than that of LAP (0.035 ± 0.001) [2] and NWA 4734 (0.038 ± 0.002) (Fig. 1). The latter two are consistent with a single source. The magma source regions for the three meteorites have distinct $^{147}Sm/^{144}Nd$: 0.201 ± 0.001, 0.212 ± 0.003 [2], and 0.246 ± 0.004 [1] for NWA 4734, LAP and NWA 032, respectively. These isotopic compositions indicate that NWA 4734, NWA 032, and LAP are derived from at least two, and possibly three, magma source regions, despite their other geochemical similarities.

Origin of young mare basalts: It has been suggested [e.g. 8, 14] that KREEP reservoirs in the Moon's interior may have been a heat source for melting late in mare magmatism after the Moon had cooled significantly. Thus, it is important to determine what role KREEP played in the origin of the youngest mare basalts in order to understand the thermal state of the lunar mantle. Based on our data and literature data, we do not find evidence for the physical involvement of KREEP in the origin of NWA 4734, NWA 032 and LAP, although a contribution of heat (without mass) from KREEP for melting cannot be ruled out. First, their $(La/Yb)_N$ and Ti/Sm are within the ranges defined by the KREEP-free Apollo basalts and are not of sufficient in magnitude to suggest ITE enrichment from KREEP. Next, apatite analyses from LAP [15] and NWA 4734 indicate that they are relatively OH-rich and Cl-poor, contrary to the observations of KREEPy lithologies [15]. Lastly, their isotopic compositions are inconsistent with KREEP. NWA 032 has the most enriched source Rb/Sr, yet the most depleted source Sm/Nd. Along with identical ITE compositions among all three basalts, this is inconsistent with mixing of a depleted parental basalt with a KREEP-rich lithology.

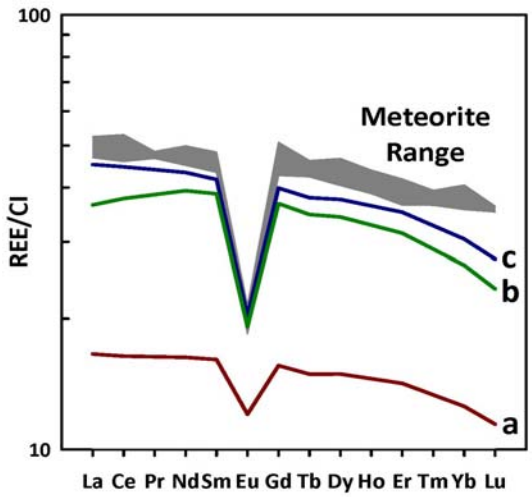

Fig. 2: CI-normalized REE patterns of NWA 4734, NWA 032 and LAP (gray field), and 1% modal equilibrium partial melts of LMO cumulates horizons from [16].

Rather, these three basalts are more consistent with low degree partial melting of relatively late-stage LMO cumulate horizons. Fig. 2 shows calculated 1% partial melts of cumulates formed from 78-86% LMO crystallization (curve a) [from the model of 16 using bulk Moon REE abundances from 17], 86-95% (curve c), and a 50:50 mixture of the two (curve b), with 1% trapped instantaneous residual magma ocean liquid. The REE pattern produced from the 86-95% cumulate horizon is similar in shape and magnitude to the meteoritic basalts. These arguments suggest that KREEP is not required in order to produce mare basalts enriched in ITEs [i.e. 1] and that KREEP was not a component in the source regions of all young mare basalts.

References: [1] Borg et al. (2009) *GCA* 3963-3980. [2] Rankenburg et al. (2007) *GCA* 2120-2135. [3] Haloda et al. (2009) *GCA* 3450-3470. [4] Elardo et al. (2012) *LPSC* #2648. [5] Zeigler et al. (2006) *MAPS* 1073-1101. [6] Fagan et al. (2002) *MAPS* 371-394. [7] Jolliff et al. (2006) *GCA* 4857-4879. [8] Borg et al. (2004) *Nature* **432,** 209-211. [10] Mahoney et al. (2001) Proc. Ocean Drill. Prog. [11] Neal (2001) *JGR,* 27,865-27885. [12] Wang et al. (2012) *GCA* 329-344. [13] Day and Taylor (2007) *MAPS* 3-17. [14] Hess and Parmentier (2001) *JGR-P*, 28,023-28,032. [15] McCubbin et al. (2011) *GCA,* 5073-5093. [16] Snyder et al. (1992) *GCA,* 3809-3823. [17] Warren (2005) *MAPS,* 447-506.