METEORITIC EVIDENCE FOR EXTENSIVE COMPOSITIONAL VARIABILITY ON THE MOON. L. Borg1, A. Gaffney1, C. Shearer2, B. Jolliff3, & C. Neal4. 1Inst. of Geophys. & Planet. Physics, Lawrence Livermore Nat. Lab., CA 95440, 2Inst. of Meteoritics, Univ. of New Mexico, NM 87131, 3Dept. Earth & Planet. Sci., Washington University, St. Louis, Mo 63130 4Dept. Civil Engineering & Geol. Sci., Univ. of Notre Dame IN 46556.

Introduction: Crystallization of the lunar magma ocean occurred ~4.4 Ga [e.g., 1-4] and produced three principal magma source regions [5-6]. These sources are characterized chemically by low titanium (Ti), high Ti, and high potassium, rare earth element, and phosphorous (KREEP) abundances. The KREEP component was produced after nearly complete solidification of the magma ocean and is highly enriched in all incompatible elements not partitioned into the main mineral phases [7-9]. Compositional variability of lunar basalts [Fig. 1] is interpreted to reflect mixing of materials derived from these three sources [5,6,9].

New lunar meteorites, however, have compositions and ages that differ from the basalts in the Apollo and Luna collections, suggesting that there is greater diversity on the Moon than was previously recognized. Below we discuss some of the compositional, chronological, and petrogenetic differences between these two groups of basalts and assess to what extent the magma ocean model of lunar differentiation can accommodate these differences. Ultimately this exercise offers insights into the advancement of lunar geologic science that will result from a lunar exploration program in which new samples are returned to Earth.

Compositions of basaltic meteorites: Several of the basaltic lunar meteorites have mineralogical and/or geochemical characteristics that differ from previously collected samples. Although these basalts share some compositional characteristics with other lunar basalts [Fig. 1], their geochemical and isotopic systematics are distinctive. Representative examples that we have completed, or are in the process of completing, detailed chronologic investigations on and are discussed below and include: Northwest Africa (NWA) 032, NWA 773, NWA 4898. In addition, we include the unusual meteorite Asuka 881757.

Each of these samples has unique mineralogical and/or compositional characteristics. Northwest Africa 032 has elevated Th concentration (1.9 ppm) and Th/Sm ratio (0.28) that is similar to many KREEP-rich samples [10-12]. However, unlike KREEP, this sample has a moderate TiO₂ concentration (~3.0 wt. %; 10-11) indicating that its source region has not experienced the same extent of ilmenite fractionation. Northwest Africa 773 also has an elevated Th/Sm ratio, but unlike NWA 032 has many other KREEP-like geochemical characteristics [12,13]. This sample is mineralogically distinctive because it is the only KREEP-rich sample of basaltic origin dominated by olivine and containing a minor amount of Ba-K feldspar. Northwest Africa 4898 has a major element composition similar to Apollo 14 and Luna 16 high-alumina basalts except that it has significantly lower Mg/Fe ratio suggesting that it is more evolved [14].

Ages of basaltic meteorites: As demonstrated by Gaffney et al. [16], the age distribution of the basaltic meteorites differs from those represented in the Apollo and Luna collections. The most striking feature is the young ages of the meteorites. A substantial proportion of these samples are younger than any of the Apollo or Luna samples. However, despite their very young and nearly concordant ages, the young meteorites do not appear to be related by a simple petrogenetic process. Northwest Africa 773 (2993 ± 32 Ma) is derived from a KREEP-rich source [11,15], whereas NWA 032 (2947 ± 16 Ma) appears to be derived from a low Ti olivine and pyroxene-bearing source region [17]. Furthermore, the Mg-rich nature of NWA 773 indicates that it cannot be derived from a more Fe-rich parent like NWA 032.

Northwest Africa 773 also illustrates how apparent chronologic relationships between different Apollo sample suites may be an artifact of sample collection in a few locations on the lunar near side. Prior to age determinations on NWA 773, KREEP-rich samples...
represented some of the oldest rocks. Clustering of KREEP ages around 3.8-4.1 Ga [Fig. 2] even led to the hypothesis that KREEP volcanism was associated with basin formation during the cataclysm. However, the young age of NWA 773 demonstrated that KREEP volcanism has in fact spanned much of the time recorded by the ages of lunar basalts [Fig. 2].

Petrogenesis of basaltic meteorites. Several of the lunar meteorites have trace-element and isotopic compositions that differ significantly from the Apollo basalts. In Figure 3 crystallization age is plotted against the initial Nd isotopic composition. These data indicate that some of the meteorites derived from source regions more depleted in LREE relative to HREE than other basalts. This is particularly true for NWA 4898, which is derived from a source with a $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of $-0.36$. The $^{147}\text{Sm}/^{144}\text{Nd}$ ratio calculated for NWA 773 source region is equally fractionated, but in the opposite sense. Thus, the range of Nd isotopic variations observed among lunar basalts is defined by the meteorite data.

Finally, evidence suggests that the mechanisms by which some of the meteorites were derived from their sources differ from those responsible for production of the Apollo basalts. This is illustrated on Figure 4 in which the $^{147}\text{Sm}/^{144}\text{Nd}$ ratios of individual basalt sources calculated from their isotopic systematics are plotted against the $^{147}\text{Sm}/^{144}\text{Nd}$ of their bulk rocks. NWA 032 and NWA 4898 fall farthest from the 1:1 line. The most reasonable mechanism to account for this is generation by smaller degrees of partial melting. Conclusion: The compositional, chronological, and petrogenetic differences between the collected and meteorite basalts indicate that the Apollo and Luna samples do not encompass the full lithologic diversity of the Moon. Although the meteorite data can be fitted into generalized lunar evolution models based on Apollo samples, the models require some modification. Thus, we expect to significantly expand our knowledge of lunar geologic history through analysis of new samples during the next era of lunar exploration.