LUNAR CRUSTAL HISTORY RECORDED IN LUNAR ANORTHOSITES. L. E. Nyquist [1], C.-Y. Shih[2], Y. D. Reese[3], J. Park[4,5], D. Bogard[1], D. Garrison[2], A. Yamaguchi[6]. [1]KR/NASA Johnson Space Center, Houston, TX 77058. E-mail: laurence.e.nyquist @nasa.gov. [2]ESCG Jacobs-Sverdrup, Houston, TX 77058. [3]Mail Code JE-23, ESCG/Muniz Engineering, Houston, TX 77058. [4]Lunar and Planetary Institute, 3600 Bay Area Blvd. Houston, TX 77058, [5]NASA-MSFC, Huntsville, AL 35812 & Univ. Alabama @ Huntsville, 35805, [6]National Institute of Polar Research, Tachikawa, Tokyo, 190-8518, Japan.

Introduction: Anorthosites occur ubiquitously within the lunar crust at depths of ~3-30 km in apparent confirmation of the Lunar Magma Ocean (LMO) hypothesis. [1]. We have dated lunar anorthosite 67075, a Feldspathic Fragmental Breccia (FFB) collected near the rim of North Ray Crater by the Sm-Nd and Rb-Sr techniques. We also have dated an anorthositic white clast (WC) in lunar meteorite Dhofar 908 by the ^{39}Ar-^{40}Ar technique and measured whole rock (WR) Sm-Nd data for a companion sample. We discuss the significance of the ages determined for these and other anorthosites for the early magmatic and bombardment history of the moon.

Concordant Sm-Nd and Rb-Sr Ages for 67075: Although ^{39}Ar-^{40}Ar ages of ~3.95-4.04 Ga have been reported for 67075 [2,3], our Sm-Nd and Rb-Sr ages for this anorthosite are 4.47±0.07 Ga and 4.49±0.07 Ga, respectively. Figure 1 shows the Sm-Nd isochron; the Rb-Sr isochron is not shown here.

Similarly old Sm-Nd ages have been determined for Apollo 16 anorthosites 60025 [4] and 67215 [5], but this is the first time that a well-defined Rb-Sr age that is concordant with the Sm-Nd age has been determined for a lunar anorthosite. Indeed among 12 analyses of bulk and mineral separates from 67075, several show some evidence of minor isotopic disturbance. Initial ^{87}Sr/^{86}Sr is 0.699045±12 from the isochron fit, where the 2█rror limits apply to the last digits. Initial ^{143}Nd/^{144}Nd determined from the Sm-Nd isochron corresponds to █$_{d,CHUR}$ = 0.3±0.5 compared to a Chondritic Uniform Reservoir [6] or █$_{d,HEDPB}$ = -0.6±0.5 compared to the initial ^{143}Nd/^{144}Nd of the HED Parent Body [7].

Sm-Nd data for Dho 908 WC: Fig. 2 shows the Sm-Nd data for Dho 908WC compared to data for Yamato 86032,133, an anorthositic clast in the 648 g Y-86032 lunar feldspathic highland breccia [7,8]. Independently determining an isochron for Dho 908 WC was impossible. However, the Dho 908 WC analysis lies precisely on the extension of an isochron fit to bulk (WR), plagioclase, and pyroxene-enriched samples from the white clast Y-86032,133 composed predominantly of An97 plagioclase [8]. Mg' of mafic minerals in these rocks are similar to those of typical ferroan anorthosites (FANs), with some extension towards higher values for Y-86032, 133 [8]. With the *assumption* that these anorthositic clasts in these two meteorites formed contemporaneously from (a) compositionally identical precursor(s) (the LMO?), the age of their formation given by the isochron fit is 4.31±0.07 Ga. For this isochron, initial ^{143}Nd/^{144}Nd corresponds to █$_{d,CHUR}$ = 1.2±0.4, and █$_{d, HEDR}$ = 0.3±0.4

^{39}Ar-^{40}Ar Age of Dho 908 WC: Like samples of most desert meteorites, Dho 908 contained a significant amount of terrestrial atmospheric Ar that degassed at low temperatures in a stepped temperature extraction. Fig. 3 shows the ^{39}Ar-^{40}Ar age spectra for the last 35% of the ^{39}Ar released (~98 ppm K). From a minimum of ~3.95 Ga, six extractions releasing 86-97% of the ^{39}Ar give nearly constant ages of 4.42±0.04 Ga, the best value for the formation age of

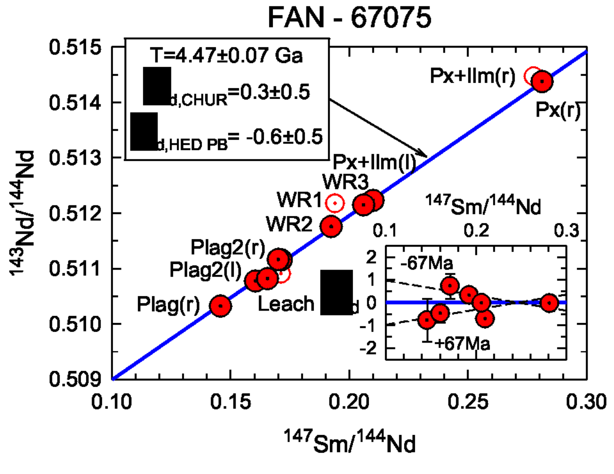

Figure 2. Sm-Nd isochron for 67075.

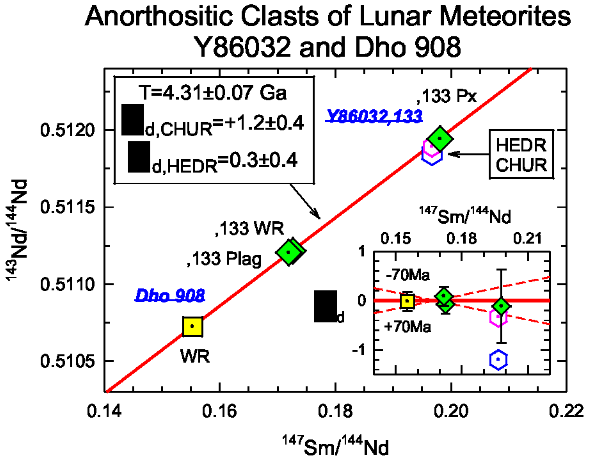

Figure 1. Sm-Nd data for Dho 908 WC compared to bulk, plagioclase and pyroxene-enriched samples of Y-86032 [8].

the clast. (A higher age for the last 3% of the ^{39}Ar is discounted.)

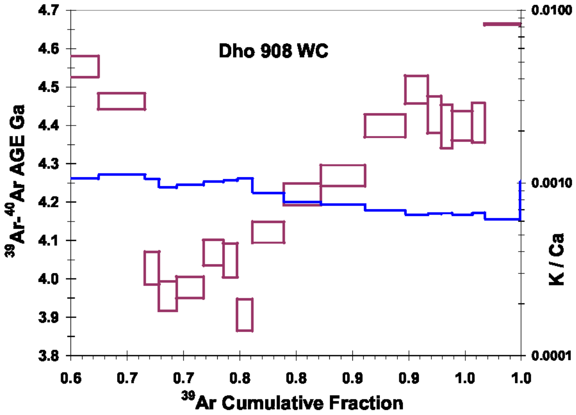

Figure 3. Ar-Ar age spectra for Dho 908WC anorthosite.

Discussion: Two other measured ^{39}Ar-^{40}Ar ages for FANs are 3.93±0.08 Ga for 67215 [5], and 4.15±0.12 Ga for 60025 [9, Bogard,unpublished]. These ages are reset and show that these anorthosites were exposed to secondary heating that also could have perturbed the other chronometers. In contrast, anorthositic clasts in two lunar meteorites, Yamato 86032 and Dhofar 908, retain older ^{39}Ar-^{40}Ar ages up to ~4.35 Ga [7, this investigation], consistent with Sm-Nd ages of the clasts.

Lunar Meteorites Retain "High" Ar-Ar Ages. On the basis of the few currently available analyses, it appears that the anorthositic clasts in lunar highland meteorites are less likely to have been reset by secondary heating events than anorthosites returned during the Apollo program. The upper portion of Fig. 4 shows Ar-Ar ages measured in the JSC lab for anorthositic clasts from Y-86032 [7], the magnesian anorthosite (MAN) clast from Dhofar 489 [10], as well as Dho 908WC. Also shown are the ages of an impact melt vein in Y-86032 [7] and the matrix of Dho 908 [11]. Only the impact melt (Y-86032,30) has an Ar-Ar age consistent with the nominal ~3.8-4.0 Ga period of the putative lunar impact cataclysm, a hint that "cataclysmic" impacts were on average less energetic in the source regions of these meteorites than on the lunar nearside.

Lunar Anorthosites: From Diverse Sources. Fig. 5 summarizes (T, [redacted]$_d$) values for highland rocks analyzed in the JSC lab. Lunar anorthosites tend to have [redacted]$_d$ > 0 when compared to a chondritic reference value, i.e., CHUR [6], apparently inconsistent with derivation from a single lunar magma ocean. This problem is partially resolved if lunar initial ^{143}Nd/^{144}Nd is taken equal to HEDR for the HED parent body [7], but enough variability remains among the anorthosite data alone to suggest that lunar anorthosites do not derive from a single source, i.e., they are not all products of the LMO. Orbital geochemical studies confirm variability in lunar crustal composition [1, 13].

References: [1] Ohtake M. et al. (2009) *Nature 461,* 236-241. [2] Turner G. et al. (1973) *PLSC4*, 1889-1914. [3] Huneke J. C., et al. (1977) *Lunar Sci. VIII*, 481-483. [4] Carlson R. W. and Lugmair G. W. (1988) *Earth Planet. Sci. Let. 90,* 119-130. [5] Norman M. D. et al. (2003) *Meteoritics & Planet. Sci., 38,* 645- 661. [6] Jacobsen S. B. and Wasserburg G. J. (1984) *Earth Planet. Sci. Let. 67,* 137-150. [7] Nyquist L. et al. (2006) *GCA 70,* 5990-6015. [8] Yamaguchi A. et al (2010), submitted. [9] Schaeffer O. A. and Husain L. (1974) *PLSC5,* 1541-1555.. [10] Takeda H. et al. (2006) *Earth Planet. Sci. Let. 247,* 171-184. [11] Park J., et al. (2009) unpub. [12] C. Meyer, [redacted] [13] Cahill J. T. S. et al. (2009) *JGR 114*, E09001.

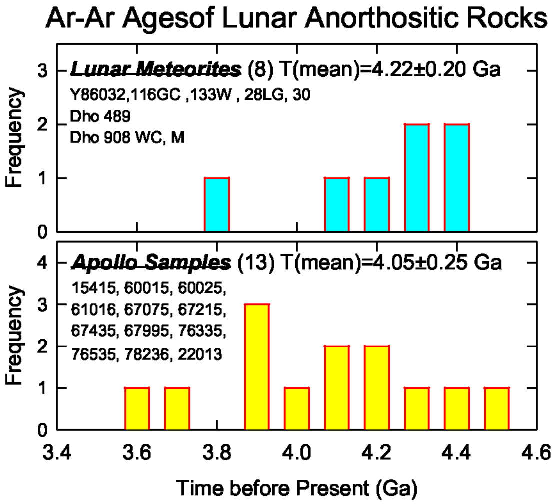

Figure 4. Ar-Ar ages. Lunar meteorites: see text. Apollo samples: New data for 15415 and 60015 [11]; literature data from Lunar Sample Compendium [12].

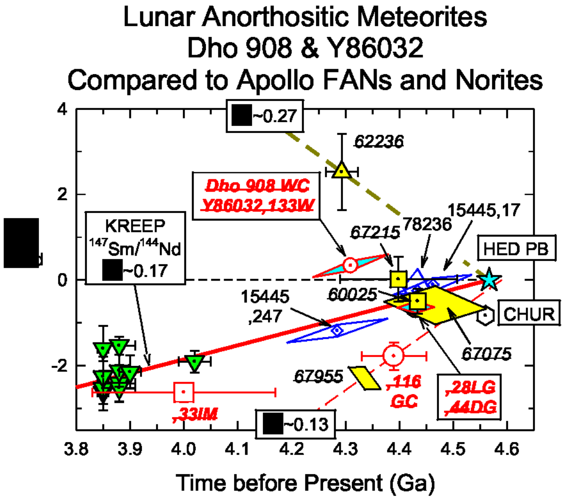

Figure 5. Summary of (T,[redacted]$_d$) values for highland rocks as determined at JSC.