Implications for Lunar Crustal Evolution from Y-86032 and Dho 908. L. E. Nyquist [1,7], C.-Y. Shih[2], Y. D. Reese[3], J. Park[4,5], D. D. Bogard[1], D. H. Garrison[2], A. Yamaguchi[6,] and K. H. Joy[4,7,8]. [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. [7]Center for Lunar Science and Exploration, NASA Lunar Science Institute. [8]Mineralogy Department, The Natural History Museum London, Cromwell Road, London, SW7 5BD, UK.

Introduction:

We have studied anorthositic clasts in the Y-86032 and Dhofar 908 meteorites by the Rb-Sr, Sm-Nd, and ^{39}Ar-^{40}Ar techniques [1,2,3] combining isotopic studies with mineralogical/petrological studies of the same clasts. As a result of these studies, we conclude that the lunar crust is composed of a variety of anorthosites, at least some of which must have formed as plutons in the earliest formed ferroan anorthosite crust.

Sm-Nd data for lunar anorthosites:

Several of the anorthositic clasts that we have studied were too small to contain mafic minerals in sufficient abundance for determination of internal Sm-Nd or Rb-Sr isochrons. We combine bulk ("whole rock") Sm-Nd data with ^{39}Ar-^{40}Ar ages to estimate initial ^{143}Nd/^{144}Nd for them. It is widely assumed that ferroan anorthosites (FANs) formed as flotation cumulates on a global lunar magma ocean (LMO). A corollary is that all FANs are approximately contemporaneous and formed with the same initial ^{143}Nd/^{144}Nd ratio. Indeed, a whole rock isochron for selected FANs (and An93 anorthosite) [4] yields an isochron age of 4.42±0.13 Ga and initial ^{143}Nd/^{144}Nd, expressed in ε-units, of $\varepsilon_{Nd,CHUR}$ = 0.3±0.3 relative to the CHondritic Uniform Reservoir [5] or $\varepsilon_{Nd,HEDPB}$ =-0.6±0.3 relative to the HED Parent Body [6]. These values are in good agreement with the age (T) = 4.47±0.07 Ga, and $\varepsilon_{Nd,HEDPB}$ =-0.6±0.5 for FAN 67075 [1,4]. The old Sm-Nd age and concordant Rb-Sr age [1] updated to 4.47±0.07 Ga make 67075 an outstanding candidate to have been a magma ocean flotation cumulate [3,4].

Fig. 1 compares the whole rock Sm-Nd data for anorthositic clasts from Y-86032 and Dho 908 to the ~4.42 Ga isochron (dotted line) and whole rock Sm-Nd data for 67075. An isochron (solid line) is drawn through the data for whole rock (WR), plagioclase (Plag), and pyroxene (Px) separates for FAN clast Y86032,133 [2] plus WR data for Dho908, which fits well with the Y86032,133 data. Together they give an age of 4.31±0.07 Ga and $\varepsilon_{Nd,HEDPB}$ =0.3±0.4. The isochron thus formed lies above the reference ~4.42 Ga isochron, and excludes the data for two bulk samples of 67075, and also the data for Y86032,44 FAN and Y86032,28 LG An93 anorthosite that has initial Nd- and Sr-isotopic systematics that are identical to those for FANs [1,4].

The age and initial Nd-isotopic parameters are shown more clearly with the aid of a (T, ε_{Nd}) diagram (Fig. 2). This diagram shows that although much of the Sm-Nd data are consistent with evolution from $\varepsilon_{Nd,HEDPB}$ =0 at the beginning of the solar system 4568 Ma ago with chondritic ^{147}Sm/^{144}Nd (μ) = 0.1967 (shown by the ε_{Nd} =0 line), other data require either higher or lower values of μ. A simplified scenario for those data is (a) evolution from initial values (T, ε_{Nd}) = (4568 Ma, 0) to the 67075 values (4470 Ma, -0.6) (period of lunar formation followed by the LMO) with μ ~0.12, (b) formation of sources for anorthositic plutons in the early lunar crust with μ in the range ~0.12 – 0.33. Such μ-values are plausible extreme values and are similar to values for plagioclase and pyroxene crystallized from 67075.

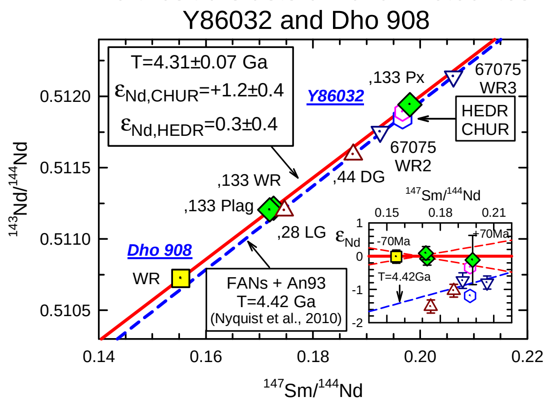

Fig. 1. Whole rock Sm-Nd data for anorthositic clasts in Y86032 and Dho 908 compared to those for FAN 67075.

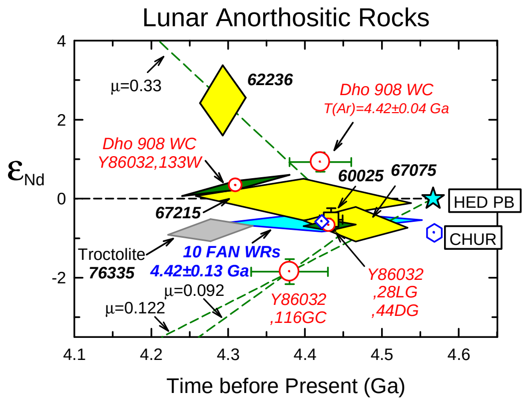

Fig. 2. (T, ε_{Nd}) diagram for lunar anorthosites, anorthositic clasts, and troctolite 76335.

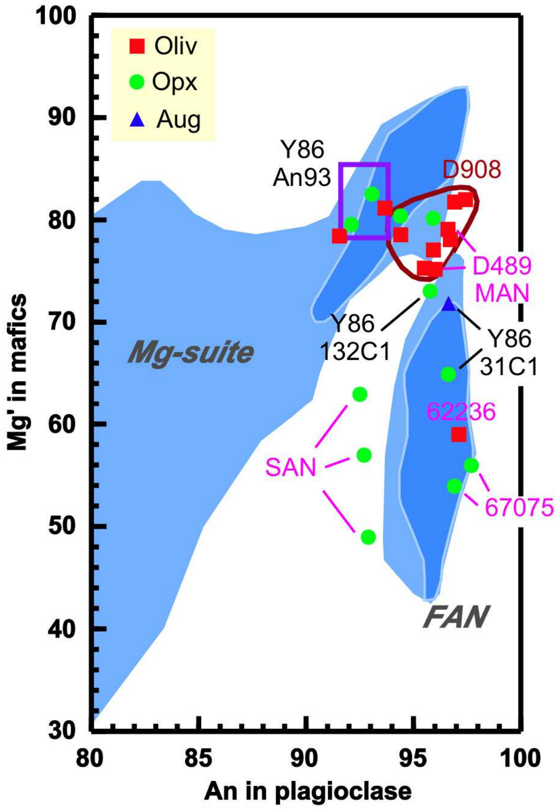

Fig. 3. Mg' vs. An for clasts in Y86032 and Dho 908. Adapted from [2]. Oval encloses new data for Dho 908, including a magnesian anorthosite, a troctolite (far left in oval), a spinel troctolite, and troctolitic anorthosites. K. Joy, analyst.

Mg' vs. An relationships for lunar anorthosites:

Fig. 3 illustrates that not only are the Nd-isotopic data for lunar anorthosites diverse, but their mineral compositions are diverse as well. It illustrates the composition of pristine FANs 67075 and 62236, pristine fragments of magnesian anorthosite [7] (MAN), the composition of some clasts in Y-86032 (labeled Y86NCn), sodic anorthosites [8] (SAN), and the reconstructed composition of An93 anorthosite [2] against the fields for lunar pristine rocks of the FAN and Mg-suites [2]. Also shown are new data for lithic clasts in PTSs P13288 and P13289 of Dho 908. These clasts range in size from ~100x120 μm to ~1.5x1.6 mm. They represent a suite of lunar crustal rocks including magnesian anorthosite (MAN), troctolitic anorthosites, a troctolite, and a spinel troctolite.

The Dho 908 White Clast (WC) analysed isotopically was metamorphosed, and Mg' could not be reliably obtained from sparse pyroxene inclusions within it which may be of metamorphic origin. The FeO contents of those pyroxenes suggest that the parent rock was a FAN, but that is uncertain. Among the small lithic clasts, none of the analysed mafics had Mg'<~75, characteristic of magnesian anorthosites (MAN, [7]). These data show that the lunar crust was quite magnesian where the Dho 908 meteorite came from. Its composition apparently corresponded to Mg' values intermediate to those of FANS and plutonic Mg-suite rocks.

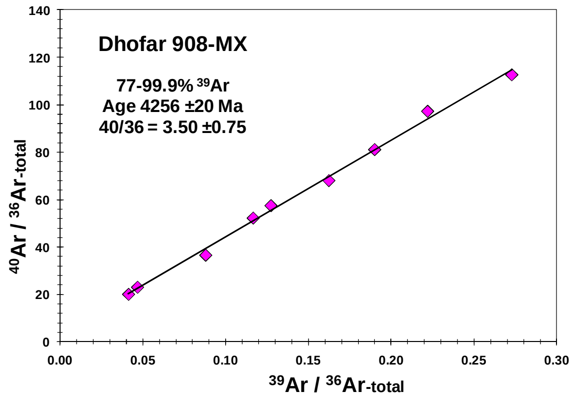

Fig. 4. ^{39}Ar-^{40}Ar isochron plot for Dho 908 matrix.

^{39}Ar-^{40}Ar age of Dho 908 matrix:

Fig. 4 shows an ^{39}Ar-^{40}Ar isochron plot for Dho 908 matrix. A precise age of 4256±20 Ma was obtained from the high-temperature extractions after correction for trapped solar wind Ar and lunar atmosphere ^{40}Ar with combined ^{40}Ar/^{36}Ar = 3.5±0.75. The presence of trapped Ar shows that the matrix had some exposure in the lunar regolith. The matrix is dominantly troctolitic, and the ^{39}Ar-^{40}Ar age obtained from it is typical of that of lunar troctolites (*cf.* 76335 in Fig. 2), further indication of a magnesian crustal composition.

Conclusions:

The crystallization ages and Nd isotopic compositions of the majority of FANs appear to be consistent with the LMO hypothesis if the lunar initial ^{143}Nd/^{144}Nd ratio was the same as for the parent body of the HED meteorites. However, our study of Y-86032 tells us that other anorthositic compositions satisfy this criterion as well, and having a FAN composition doesn't guarantee an LMO origin. Anorthositic plutons probably are present in the lunar crust. The earliest crust probably underwent complex petrogenetic processes. Further studies are needed to place the full array of lunar anorthosites into a comprehensive picture of lunar crustal evolution. Reliably determining the crystallization age and Nd-isotopic composition of magnesian anorthosites (MAN) could provide an important new constraint on lunar crustal evolution.

References: [1] Nyquist L. et al. (2006) *Geochim. Cosmochim. Acta*, *70*, 5990-6015. [2] Yamaguchi A., et al. (2010) *Geochim. Cosmochim. Acta*, in press. [3] Nyquist L. E. et al. (2010) *41st Lunar and Planetary Science Conference, Houston, TX, Abstract #1383.* [4] Nyquist L. E. et al. (2010) Papers presented to the Global Lunar Conf., Beijing, May 31-June 3, 2010. [5] Jacobsen S. B. and Wasserburg G. J. (1984) *Earth Planet. Sci. Lett. 67*, 137-150. [6] Nyquist L. E. et al. (2004) *Antarct. Met.* **XXVIII,** 66-67. [7] Takeda H. et al. (2006) *Earth Planet. Sci. Lett. 247*, 171-184. [8] Norman M.D. and Taylor S.R. (1992) *Geochim. Cosmochim. Acta 56*, 1013-1024.