EVIDENCE FOR WIDESPREAD MAGMATIC ACTIVITY AT 4.36 GA IN THE LUNAR HIGHLANDS FROM YOUNG AGES DETERMINED ON TROCTOLITE 76535. Lars Borg[1], James Connelly[2], William Cassata[1], Amy Gaffney[1], Richard Carlson[3], Dimitri Papanastassiou[4], Jerry Wasserburg[4], Erick Ramon[1], Rachael Lindval[1], and Martin Bizzarro[2]. [1]Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore CA 94550 USA. [2] Centre for Star and Planet Formation, University of Copenhagen, Denmark. [3]Department of Terrestrial Magnetism, Washington, DC 20015-1305 USA. [4]California Institute of Technology, Pasadena CA 91109 USA.

Introduction: Although geochemical evidence for crystallization and differentiation of the lunar magma ocean (LMO) is widespread and robust [e.g. 1-2], direct measurements constraining its age are not. Age estimates for magma ocean crystallization range from 4.57 to 4.38 Ga [3-4] and are based on: (1) crystallization ages determined on primary plagioclase–rich magma ocean cumulates (ferroan anorthosites; FANs), (2) ages of Mg-suite rocks thought to be intruded into FANs, (3) model ages for mare basalt sources, and (4) model ages for the last solidification products of the LMO (KREEP). We recently determined a young age of 4359±3 Ma for FAN 60025 that suggests that either some FANs are not products of the magma ocean or that the age of solidification of the LMO is significantly younger than previous estimates [5]. In order to test these two possibilities we have evaluated the reliability of published ages for highlands samples and found that the oldest ages are some of the least reliable [6].

One of the few apparently reliable old ages is a "whole rock" Rb-Sr age of 4.57±0.07 Ga determined on Mg-suite troctolite 76535 [7]. This ancient age, if correct, strongly supports the first scenario in which some FANs are not LMO crystallization products. Although numerous Sm-Nd and U-Pb ages determined on 76535 are younger and discordant, variation in these ages can be interpreted to reflect different closure temperatures of the three isotopic systems. In this scenario, the Rb-Sr age records the time when the rock was at higher temperatures. This is not unreasonable because the high Rb/Sr ratios in the olivine mineral fractions reflect the presence of melt inclusions which are more difficult to disturb by diffusion processes associated with slow cooling [7].

In order to evaluate this interpretation we reanalyzed 76535. Below we report Rb-Sr, Sm-Nd, and preliminary Pb-Pb ages that indicate the rock has indeed undergone slow cooling at 2-3 °C/Ma, but solidified no earlier than 4.37 Ga. The young age of 76535 is common in many lunar samples requiring a significant and relatively late moonwide magmatic event.

Analytical techniques: Mineral separates of 76535 ,11 were produced at Cal Tech as part of the original Rb-Sr investigation [7] and included ultra-pure plagioclase, olivine, pyroxene, and two dark mineral fractions consisting of mafic minerals with minor amount of plagioclase. Aliquots of the pyroxene, olivine, and one dark mineral fraction were analyzed for Pb-Pb. Analysis of Pb followed the procedure outlined in [5] in which the fractions were washed and then progressively digested. The remaining fractions were spiked with a 99.988% pure ^{150}Nd spike that allowed ^{146}Sm-^{142}Nd and ^{147}Sm-^{143}Nd chronometry to be applied to the same mineral fractions without need for correction of ^{142}Nd from the spike. Nd and Sm were run as metals at high intensity (>2.5V ^{144}Nd, and 1V ^{149}Sm) for long durations (up to 1080 ratios). The Sm isotopic composition of 76535 was determined on an unspiked plagioclase mineral fraction and was shifted to ε^{149}_{Sm} = -16.54±0.10 as a result of the capture of thermal neutrons. The measured ε^{149}_{Sm} value is consistent with the value of -15.3±0.8 determined by [8]. Both the measured ^{147}Sm/^{144}Nd and ε^{142}_{Nd} were adjusted slightly to account for neutron capture effects [9].

Results: The ^{147}Sm-^{143}Nd and ^{146}Sm-^{142}Nd isotopic data are plotted on isochron diagrams in Figures 1 and 2. The ^{147}Sm-^{143}Nd system records an age of 4293±11 Ma with an initial ε^{143}_{Nd} isotopic composition of -0.27±0.15. This age is concordant with the age of 4295^{+29}_{-36} Ma determined from the ^{146}Sm-^{142}Nd system. This isochron yields an initial ε^{142}_{Nd} of -0.03±0.05 relative to a terrestrial standard (JNdi).

The ^{146}Sm-^{142}Nd age was calculated using the traditional ^{146}Sm t½ = 103 Ma and an initial solar system

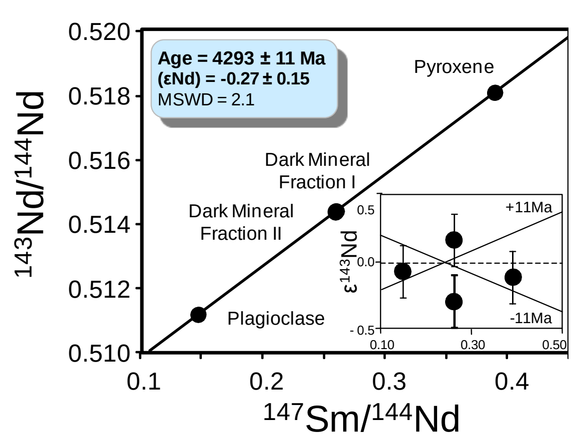

Figure 1. ^{147}Sm-^{143}Nd isochron plot of 76535. Inset represents deviation of individual mineral fractions from the isochron in epsilon units.

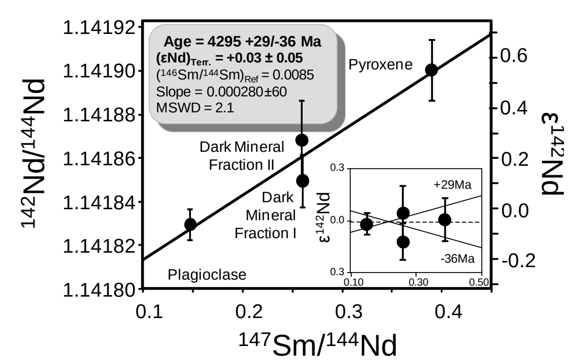

Figure 2. ^{146}Sm-^{142}Nd isochron plot of 76535. Inset represents deviation of individual mineral fractions from the isochron in epsilon units. The age is calculated assuming t½= 103 Ma, and $^{146}Sm/^{144}Sm = 0.0085$.

$^{146}Sm/^{144}Sm$ of 0.0085 [10]. Using the recently published ^{146}Sm t½ = 68 Ma and $^{146}Sm/^{144}Sm$ of 0.0094 [11] yields an age 4378^{+19}_{-25}. This age is clearly discordant from the ^{147}Sm-^{143}Nd isochron age suggesting that either the new t½ value or initial $^{146}Sm/^{144}Sm$ ratio is incorrect.

The Rb-Sr isotopic data are plotted in Figure 3. These data demonstrate clear evidence of isotopic disturbance. Nevertheless, a two point tie-line regressed through the plagioclase and olivine data points yields a slope corresponding to an age of 4308±45 Ma, and an initial $^{87}Sr/^{86}Sr$ isotopic ratio of 0.699105±12. This age is concordant with the Sm-Nd ages and suggests that only the mineral fractions containing pyroxene

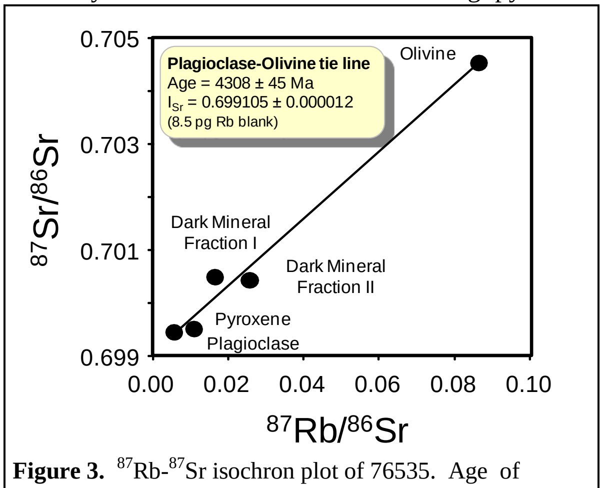

Figure 3. ^{87}Rb-^{87}Sr isochron plot of 76535. Age of plagioclase-olivine tie line calculated using t½ = 4.94 Ga ($\lambda = 1.402 \times 10^{-11} a^{-1}$) [12].

are disturbed. Shock disturbance of Rb-Sr in pyroxene fractions is common in highlands rocks [E.g. 6].

Finally we have determined a preliminary Pb-Pb age of 76535 from multiple leachates of olivine, mafic mineral, and pyroxene mineral fractions. Although the Pb-Pb system is also disturbed, a preliminary age of 4375±1 Ma is defined by the three last digestion steps in pyroxene. This age is discordant from the Sm-Nd and Rb-Sr ages by ~75 Ma.

Discussion: The ages reported here are in good agreement with some of those reported in earlier studies [e.g., 8, 13, 14], but have smaller uncertainties associated with modern procedures. This allows, previously irresolvable age differences between the various systems to be evaluated in the context of slow cooling in the Moon's lower crust. The cooling history of 76535 is constrained using the ages reported in this study, the Ar-Ar age of 4195±24 Ma [15; racalculated using λ½ = $5.531e^{-10}a^{-1}$ of [16]), and closure temperatures for the isotopic systems. A good estimate of the closure temperature of the Ar-Ar system in 76535 is ~450ºC [17], whereas the closure temperature of the Sm-Nd system in plagioclase is ~600ºC [18]. The closure temperature for the Pb-Pb system is poorly constrained but may be best represented by the crystallization temperature of 850ºC defined by thermobarometric calculations for late stage symplectites [19] that contain high U/Pb assessory phases such as baddeleyite. An initial cooling rate of 3ºC/Ma is calculated between 4375 and 4295 Ma, and slows to 1.5ºC/Ma between 4295 and 4195 Ma. This cooling rate agrees with cooling rates estimated from petrographic observations [20] and accounts for the slight discordancy between Pb-Pb and Sm-Nd ages reported in this study.

Despite the range of ages determined for 76535, there is no evidence for equilibrium of isotopic systems before 4375 Ma. Similar ages are observed in numerous lunar samples including: the ^{147}Sm-^{143}Nd KREEP model age (4398±48 Ma), one FAN (4359±3 Ma), the ^{146}Sm-^{142}Nd mare basalt source age (4342±23 Ma), the A17 zircon population (4335±10 Ma), and the oldest reliably dated Mg-suite norite (4334±34 Ma). The preponderance of lunar ages at 4357±10 Ma (the weighted average of listed ages) suggests that the Moon experienced a widespread melting event at this time, or that the LMO solidified around this time.

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