Rb-Sr, Sm-Nd AND Lu-Hf ISOTOPE SYSTEMATICS OF NORITE 77215: REFINING THE AGE AND DURATION OF LUNAR CRUST FORMATION.

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Introduction: Direct attempts to determine the age range of lunar crust formation focus on the plagioclase-rich rocks of the ferroan anorthosite (FAN) and high-Mg suite highland groups. Petrologic studies of these two groups have been interpreted to indicate that the FANs formed as direct floatation cumulates from the lunar magma ocean [1] whereas the high-Mg suite are from later bodies intruded into preexisting crust whose parental magmas were derived by melting of the lunar interior [2]. The age ranges obtained for both high-Mg suite samples and the few FAN's that have been dated are both large and overlapping [3,4] with some ages approaching the age of the Solar system and others, particularly in the high-Mg suite, extending down to quite young ages (e.g. 4.18 Ga for 67667 [5]). Deciding whether this circa 500 Ma range reflects the true age range of crust formation on the Moon or instead dating inaccuracy is critical to such basic questions as the age of the Moon and the mechanism of formation of its plagioclase-rich crust.

In order to better constrain the time of initiation and duration of lunar crust formation, we have been producing new age dates for lunar crustal rocks using modern approaches that offer the potential of higher age precision and the ability to compare ages obtained from more than one radiometric system on exactly the same material. In this work, we report the results for the 77215 norite clast from the Apollo 17 Station 7 boulder. Previous age dating of this sample [6] produced discordant Rb-Sr (4.52 ± 0.04 Ga using a ^{87}Rb decay constant of 1.402 x 10^{-11} yr^{-1}) and Sm-Nd (4.37 ± 0.07 Ga) ages and an unexpectedly low initial ^{143}Nd/^{144}Nd (ε^{143}Nd = -2.8 ± 0.2 when the data are fractionation corrected to ^{146}Nd/^{144}Nd = 0.7219). To compare 77215 with other high-Mg samples, whole rock splits were analyzed for three other high-Mg samples, feldspathic lherzolite 67667, cataclastic Mg-anorthosite 76335, and norite 78238. 78238 was previously dated at 4334 ± 34 Ma [7,8] and 76335 at 4278 ± 60 Ma, both using Sm-Nd [9].

Analytical Procedure: A small chip of 77215 was gently crushed in an agate mortar. Fractions enriched in plagioclase and pyroxene were then hand-picked from the crushed rock. These fractions were then ground again and sieved to produce a size fraction of 106-250 μm. A "whole rock" fraction (42 mg) was taken from the <106 μm fraction while the larger grain size fractions were magnetically separated and then hand-picked to yield plagioclase (15 mg) and pyroxene (11 mg) fractions. Samples were total spiked for Rb, Sr, Sm, Nd, Lu, and Hf concentration and isotopic composition determinations. A 99.988% pure ^{150}Nd spike was used that led to minimal spike corrections to ^{142}Nd, thereby improving the accuracy of these measurements. An unspiked aliquot of Sm from the 77215 whole rock was measured at LLNL and found to show only minimal neutron capture on ^{149}Sm. Significant neutron exposure necessitated corrections to Sm concentration and the measured ^{142}Nd and ^{176}Hf isotopic compositions for 76335 and 78238. Sm and Nd were run as metal ions using double Re filaments on the DTM Triton. Lu and Hf were analyzed on the DTM Nu-Plasma MC-ICPMS.

Results: The 77215 minerals and whole rock define precise isochrons for the ^{146,147}Sm-^{142,143}Nd and Lu-Hf systems. The ^{147}Sm-^{143}Nd (4296 ± 20 Ma) and Lu-Hf (4244 ± 78 Ma; λ^{176}Lu = 1.867 x 10^{-11} yr^{-1}) ages are concordant within error, and with the previous Sm-Nd age determination [6]. The initial ^{143}Nd/^{144}Nd is subchondritic (ε^{143}Nd = -0.78 ± 0.08), but higher than the very low value reported by [6]. The initial ^{176}Hf/^{177}Hf (εHf = -2.0 ± 0.6) also is slightly subchondritic. The data show only a very small range of 22 ppm in ^{142}Nd/^{144}Nd. The best fit line through the ^{146}Sm-^{142}Nd data corresponds to an initial ^{146}Sm/^{144}Sm ratio of 0.0019 ± 0.0009. Using 103 Ma for the half-life of ^{146}Sm and a Solar system initial ^{146}Sm/^{144}Sm = 0.0085 [10], this slope translates to an age of 4348 (+57, -96) Ma, overlapping the ^{147}Sm-^{143}Nd and Lu-Hf ages. Using the new half life (68 Ma) and adjusted Solar system initial ^{146}Sm/^{144}Sm = 0.0094 [11], the ^{146}Sm-^{142}Nd age of 4411 (+38, -63) Ma is older than the ^{147}Sm-^{143}Nd age. The initial ε^{142}Nd calculated at the ^{146}Sm-^{142}Nd ages are +0.03 and +0.39 relative to average ordinary chondrite [12], using the new and old decay constants, respectively. The latter is inconsistent with the negative initial ε^{143}Nd determined for 77215 and the former would require an initial ^{142}Nd/^{144}Nd closer to terrestrial than chondritic. Using the more precise ^{147}Sm-^{143}Nd age of 4296 Ma, the initial ε^{142}Nd using either decay constant is -0.17 compared to average ordinary chondrite, which would require a source

$^{147}Sm/^{144}Nd$ = 0.183 from 4.568 to 4.296 Ga. This source Sm/Nd ratio would produce an initial $\varepsilon^{143}Nd$ (4.296 Ga) = -0.5, consistent with that determined from the ^{147}Sm-^{143}Nd isochron for 77215. The Rb-Sr data for 77215 show considerable scatter with a best fit line corresponding to an age of 4.4 ± 0.7 Ga.

Lu-Hf data for whole rock splits of high-Mg samples 78238 and 76335 fall close to the 77215 mineral isochron. Indeed, a line fit to the 4 whole rock points (2 measurements of 77215 WR, one at DTM, one at LLNL) provides an isochron of 4295 ± 53 Ma (MSWD = 1.1). This age overlaps the Sm-Nd mineral isochron ages for 77215, 78238 [8], and 76335 [9]. The data for 67667 plot substantially above the Lu-Hf line defined by the other high-Mg samples as might be expected given its substantially younger crystallization age [5]. After correcting for neutron capture effects, the ^{146}Sm-^{142}Nd data for 78238 and 76335 lie along the line defined by the 77215 data, with the data for 67667 displaced just slightly above this line. The ^{147}Sm-^{143}Nd data for 78238 and 76335 lie off of the 77215 isochron, show only a limited range in Sm/Nd ratio, which coupled with considerable scatter about any best fit line, leads the whole rocks to define an extremely imprecise age of 4.5 ± 0.6 Ga. All high-Mg whole rocks measured here have subchondritic initial $\varepsilon^{143}Nd$ ranging from -0.6 (67667) to -1.1 (78238). These initial $\varepsilon^{142}Nd$ and $\varepsilon^{143}Nd$ could be achieved with a source $^{147}Sm/^{144}Nd$ = 0.184 if the source was 4.568 Ga old. If the high-Mg source has a $^{147}Sm/^{144}Nd$ (0.169) as low as proposed by [13], and similar to the Sm/Nd ratio measured in KREEP [14], then the high-Mg source must have formed after 4.50 Ga in order to match the initial $\varepsilon^{142}Nd$ and $\varepsilon^{143}Nd$ given by the 77215 Sm-Nd data. This result provides additional support for the idea that Moon formation occurred relatively late in Solar system history, most likely through a late collision between a large planetesimal and the proto-Earth.

References: [1] Wood, J.A. et al. (1970) Proc. Apollo 11 Lunar Sci. Conf. 965-988. [2] Norman, M.D. and G. Ryder (1980) Proc. 11th Lunar Planet. Sci. Conf. 317. [3] Carlson, R.W. and G.W. Lugmair (1988) Earth Planet. Sci. Lett. 90, 119-130. [4] Borg, L.E. et al. (2012) Nature 477, 70-73. [5] Carlson, R.W. and G.W. Lugmair (1981) Earth Planet. Sci. Lett. 56, 1-8. [6] Nakamura, N. et al. (1976) Proc. 7th Lunar Sci. Conf. 2309-2333. [7] Carlson, R.W. and G.W. Lugmair (1981) Earth Planet. Sci. Lett. 52, 227-238. [8] Edmunson, J. et al. (2009) Geochim. Cosmochim. Acta 73, 514-527. [9] Edmunson, J. et al. (2007) LPSC 38, abs. [10] Boyet, M. et al. (2010) Earth Planet. Sci. Lett. 291, 172-181. [11] Kinoshita, N. et al. (2012) Science 335, 1614-1617. [12] Carlson, R.W. et al. (2007) Science 316, 1175-1178. [13] Nyquist, L.E. et al. (1979) Proc. 10th Lunar Planet. Sci. Conf. 77. [14] Lugmair, G.W. and R.W. Carlson (1978) Proc. 9th Lunar Planet. Sci. Conf. 689-704.