THREE-SYSTEM ISOTOPIC STUDY OF LUNAR NORITE 78238: RB-SR RESULTS. J. Edmunson[1], L.E. Borg[1], L.E. Nyquist[2], and Y. Asmerom[3], [1]Institute of Meteoritics, University of New Mexico, Albuquerque NM 87131 (edmunson@unm.edu), [2]Johnson Space Center, Mail Code SR, Houston TX 77058, [3]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque NM 87131.

Introduction: The duration of lunar magma ocean (LMO) crystallization is poorly constrained (Fig. 1). Three techniques employed to determine the age of LMO solidification are 1) dating ferroan anorthosites (FANs), thought to be primary cumulates from the LMO, 2) calculating model ages for KREEP, the most incompatible element enriched material that remained after ~99.5% of the LMO crystallized [1], and 3) constraining the age of the oldest KREEP-rich magnesium suite (Mg-suite) or alkali suite rock. Dating FANs is difficult because the samples are essentially monomineralic and contain low abundances of many elements used in isotopic dating. In addition, the young ages determined for some FANs may be related to impact metamorphism, potentially making FANs non-ideal for dating the age of LMO crystallization (e.g., [2]). Model ages for KREEP formation are dependent on the assumptions of the initial isotopic composition and parent/daughter ratio of the source. However, lunar rocks are susceptible to isotopic resetting and volatile element loss during shock, and are therefore unlikely to yield consistent model LMO crystallization ages (e.g., [3]). Rocks from the Mg-suite contain KREEP, indicating that they formed after LMO crystallization, and have old ages that indicate they formed almost immediately after the LMO crystallized (Fig. 1). Therefore, precisely dating the oldest Mg-suite rock is a promising way to constrain the age of LMO solidification.

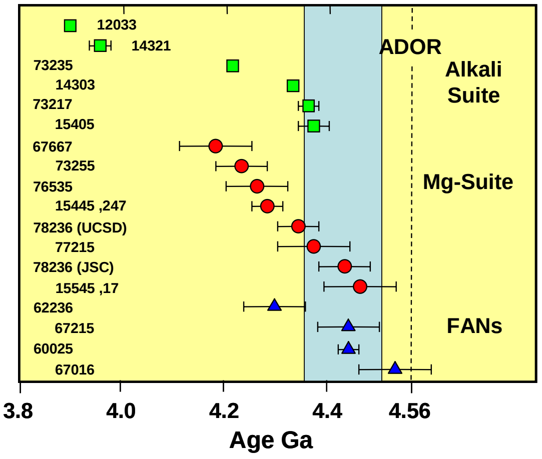

Figure 1: Overlap in ages between the ferroan anorthosites (FANs) and the oldest episodes of lunar magmatism (modified from [4]; see references therein). Shaded area indicates range of KREEP model ages from all isotopic systems (e.g., [3], [5]). Pb-Pb age from Angra dos Reis (ADOR) determined by [6].

Although the oldest Mg-suite age may provide a robust lower limit to the time of LMO crystallization, the same Mg-suite rocks have yielded inconsistent ages from different labs and different isotopic systems. For example, ages for 78235 and 78236, derived from the same norite boulder, range from 4.11±0.02 to 4.43±0.05Ga (Fig. 2). In order to further constrain the age of these samples, we have begun isotopic studies on one of the oldest Mg-suite rocks, 78238. Our goal is to determine precise Rb-Sr, Sm-Nd, and U-Pb ages for this sample, using the same high-purity mineral fractions, and thus potentially constrain the start of Mg-suite volcanism and the end of LMO crystallization. Here we present the Rb-Sr results from this study.

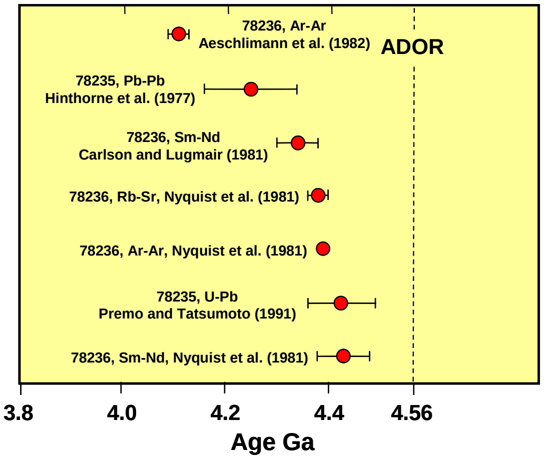

Figure 2: A compilation of ages determined for norites 78235 and 78236, paired with 78238 [7-11]. Note the variety of ages determined by different labs and isotopic systems.

Norite 78238: This sample was selected for isotopic dating because it is derived from the same boulder as 78235 and 78236, which have yielded old (>4.3Ga) ages (Fig. 1, 2; e.g., [12]). The samples were determined to be pristine, i.e. with no siderophile meteoritic contamination, by [13]. The boulder has a homogeneous cumulate texture (e.g., [12]). Although the petrology of 78238 has not been described in detail, 78235 contains roughly equal proportions of plagioclase and low-Ca pyroxene (e.g., [14]). Trace phases, found primarily in mesostasis, include silica, apatite, whitlockite, Fe-metal, diopside, chromite, troilite, ilmenorutile, zircon, and baddeleyite [14]. Impact melt glass may also be considered a major constituent of these norites, as it makes up approximately 20% of thin section 78235,51 [15].

Methods: Approximately 1.5g of 78238 was crushed with a sapphire mortar and pestle and sieved. The 100-200 mesh size fraction was selected for magnetic separation, from which six mineral fractions were obtained. These mineral fractions were meticulously hand-picked for the highest possible purity at ~95x magnification. Eight mineral fractions (including two reject fractions) and a whole rock were chosen for analysis. The mineral fractions were leached with 0.5M acetic acid, rinsed with 4x quartz distilled (QD) water, and leached with 4x QD 2N HCl at 25°C for 10 minutes. Samples were spiked with mixed $^{233\text{-}236}$U-^{205}Pb, ^{87}Rb-^{84}Sr, and ^{149}Sm-^{150}Nd tracers. Chemical separation procedures for U and Pb were performed at the Radiogenic Isotope Laboratory at the University of New Mexico. The Rb-Sr and REE cuts from the U-Pb columns were taken to the Johnson Space Center, where separation of Rb, Sr, Sm, and Nd was completed. The Rb-Sr data was obtained at JSC using the Finnigan MAT 261 thermal ionization mass spectrometer. Rubidium and Sr separates were loaded on double and single Re filaments, respectively, in TaO_5, HCl, and H_3PO_4. Rubidium and Sr blanks are 10pg and 40pg, respectively.

Results: The Rb-Sr isochrons obtained are illustrated in Figure 3. Two ages were determined with this method. One isochron is defined by the Plag 2, Wr-1, and Mg-Px fractions and has a slope corresponding to an age of 4366±53 Ma. This is interpreted to represent the crystallization age of the rock. This age is concordant with the ages determined for 78236 using the Sm-Nd isotopic system by [9] and [10]. A second isochron is defined by the Plag 1, Wr-1, Fe-Px rejects, GM, Fe-Px, and Int-Px fractions that has a shallower slope corresponding to an age of 4003±95 Ma (Fig. 3). The fact that several mineral fractions lie off the 4366 Ma isochron indicates a disturbance in the Rb-Sr isotopic system. The difference between the mineral fractions of the older and younger isochrons is the presence of mesostasis in the mineral fractions. The mesostasis contains magnetic phases, and is more abundant in the more magnetic separates (i.e., GM, Fe-Px, Int-Px). The Plag 1 fraction appears to have also re-equilibrated isotopically with the mesostasis during the shock event that converted it to maskelynite. Because the Wr-1 lies on both isochrons, it is likely that thermal resetting of the Rb-Sr system occurred in a closed system during a shock event. The thermal event would re-equilibrate the mesostasis and rotate the isochron about the whole rock point to a younger age. This style of disturbance has been documented by [16], who noted that the Sm-Nd isochrons of Apollo sample 15555 were rotated around the whole rock as a result of heating in an oven between 800 and 1000 °C. This interpretation is consistent with the observation that the young Rb-Sr isochron determined for 78238 is concordant with the Ar-Ar age of 78236 [7]. Therefore, provided the Rb-Sr isotopic system was completely reset in the mesostasis and isotopically re-equilibrated with the host mineral, the age of the disturbed isochron can be interpreted as dating the Serenitatis impact event [3].

This study demonstrates that the age of both crystallization and impact metamorphism can be gleaned from the Rb-Sr isotopic system through the analysis of extremely pure mineral fractions. Additional Sm-Nd and U-Pb analyses will be completed on these mineral fractions in the near future and are expect to better define the crystallization age of 78238.

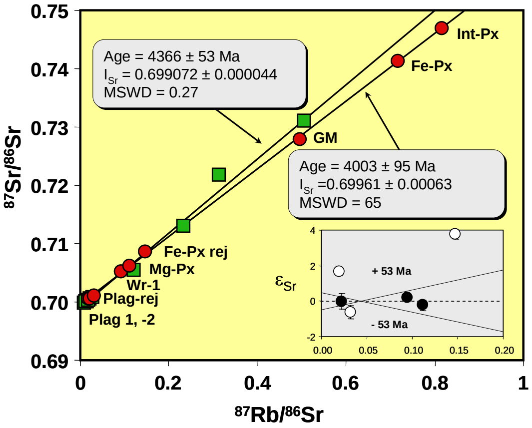

Figure 3: Rb-Sr isochrons for 78238, calculated using Isoplot [17], indicating ages of 4366±53 Ma and 4003±95 Ma. See text for a list of points that define each isochron. The younger isochron is likely a result of rotation of the older isochron about the whole rock due to resetting of the Rb-Sr system by isotopic re-equilibration of mesostasis during a post-crystallization heating event. Plag = plagioclase and maskelynite, Px = pyroxene, Int-Px = Mg-Fe pyroxene, GM = Glass and Melt, Wr = whole rock, rej = reject fraction. Also plotted is Rb-Sr data from the analysis of 78236 by [10] (squares). Inset diagram illustrates the position of the mineral fractions in epsilon Sr units relative to the isochron. Solid circles indicate points used in the isochron calculation.

References: [1] Snyder G. A. et al. (1992) *GCA, 56,* 3809-3823. [2] Shearer C. K. et al. (2002) *LPS XXXIII,* Abstract #1517. [3] Nyquist L. E. and Shih C.-Y. (1992) *GCA, 56,* 2213-2234. [4] Borg L. E. et al. (1999) *GCA, 63,* 2679-2691. [5] Lugmair G. W. and Carlson R. W. (1978) *Proc. LPSC IX,* 689-704. [6] Lugmair G. W. and Galer S. J. G. (1992) *GCA, 56,* 1673-1694. [7] Aeschlimann U. et al. (1982) *LPS XIII,* 1-2. [8] Hinthorne J. R. et al. (1975) *LS VI,* 373-375. [9] Carlson R. W. and Lugmair G. W. (1981) *EPSL, 52,* 227-238. [10] Nyquist L. E. et al. (1981) *Proc. LPSC XII, b,* 67-97. [11] Premo W. R. and Tatsumoto M. (1991) *Proc. LPSC XXI,* 89-100. [12] Jackson E. D. et al. (1975) *Geol. Soc. Amer. Bull., 86,* 433-442. [13] Warren P. H. and Wasson J. T. (1977) *Proc. LSC VIII,* 2215-2235. [14] McCallum I. S. and Mathez E. A. (1975) *Proc. LSC VI,* 395-414. [15] Dymek R. F. et al. (1975) *Proc. LSC VI,* 301-341. [16] Nyquist L. E. et al. (1991) *LPS XXII,* 985-988. [17] Ludwig K. (2001) Isoplot v. 2.49, Berk. Geoc. Cent. Sp. Pub. 1a.