LUTETIUM-HAFNIUM AND SAMARIUM-NEODYMIUM SYSTEMATICS OF APOLLO 17 SAMPLE 78236: AGE AND THE IMPORTANCE OF THERMAL NEUTRON FLUENCE ON THE LUTETIUM-HAFNIUM SYSTEM.

R. Andreasen[1], S. T. Simmons[1,2], M. Righter[1] and T. J. Lapen[1], [1]Department of Earth and Atmospheric Sciences, University of Houston, 312 Science and Research Building 1, Houston TX 77204, USA (randreas@central.uh.edu, tjlapen@uh.edu), [2]Statoil, 6300 Bridge Point Parkway, Austin TX 78730, USA.

Introduction: Apollo 17 sample 78236 is a highly shocked and nearly pristine Mg-suite norite [1]. Its major element chemistry compared to other Mg-suite samples places it near the Mg-rich end-member of the suite, potentially representing the end of the lunar magma ocean stage and the beginning of Mg-suite magmatism [2], and thus providing important age constraints on the early evolution of the Moon. The sample originated from the station 8 boulder that is described as small, ~ 0.5 m in diameter, and glass covered and was collected from atop the lunar regolith in the Sculptured Hills adjacent to the North Massif [3]. 78236 is composed of ~50% orthopyroxene and about ~50% plagioclase and contains trace amounts of clinopyroxene, Si-rich glass, phosphate minerals, potassium feldspar, baddelyite, zircon, troilite, ilmenorutile, ilmenite, chromite, and impact melt [4-5].

Methods: The glassy rind was removed from the allocated ~1 g sample of Apollo 17 78326,28 and the sample was gently crushed and separated into fractions of plagioclase, pyroxene, plagioclase with oxide inclusions, pyroxene with oxide inclusions, and whole rock. Trace element concentrations of representative grains from the sample aliquots were obtained by laser ablation ICP-MS at the University of Houston in order to calculate optimal spiking for Sm-Nd and Lu-Hf measurements. Samples of about 50 mg of each fraction were weighed, spiked, and dissolved. In addition to Sm-Nd and Lu-Hf, Gd was separated for investigating the neutron fluence of this particular sample; for the same purpose, unspiked whole rock was also analyzed. Isotope data were measured on a Nu Plasma II MC-ICP-MS at the University of Houston. Data reduction follows the methods outlined in [6-7].

Results & Modeling: The four mineral fractions and whole rock give a thermal neutron fluence corrected Sm-Nd age of 4448±32 Ma and an initial $^{143}Nd/^{144}Nd$ ratio of 0.507024±38 (Figure 1). The plagioclase, pyroxene, and pyroxene with oxide inclusions give an apparent Lu-Hf age of 4419±23 Ma and an apparent initial $^{176}Hf/^{177}Hf$ ratio of 0.279777±17. A significant anomaly in mass bias-corrected ^{180}Hf of about -1.8 ε units was observed for all samples, suggesting that the Hf isotopes are affected by thermal neutron capture. The unspiked whole rock has a ^{178}Hf anomaly of +1 ε unit. Using ^{149}Sm as a monitor for

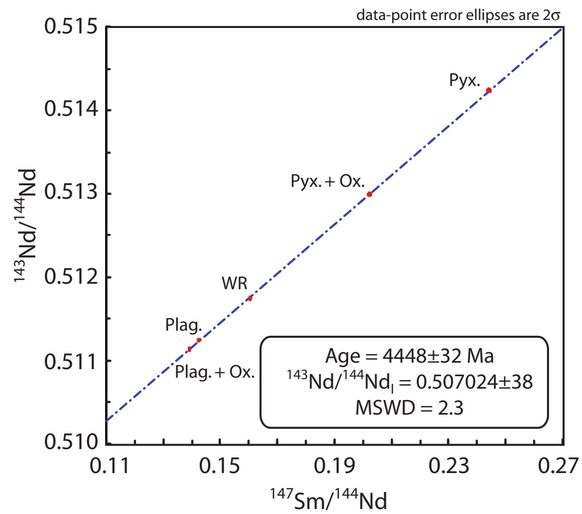

Figure 1: Five point Sm-Nd isochron, giving an age of 4448±32 Ma, and $^{143}Nd/^{144}Nd_I$ of 0.507024±0.000038.

thermal neutron fluence, following the equations of [8], a model for the effect of thermal neutron capture on the Lu-Hf isotope system was created [7]. As ^{176}Lu has a large thermal neutron capture cross section and, contrary to Hf is a strong non-1/v nuclide, there are significant temperature and parent-daughter ratio dependencies for thermal neutron capture in the Lu-Hf system. Figure 2 shows the mass bias-corrected (i.e. internally normalized to a $^{179}Hf/^{177}Hf$ = 0.7325) ^{178}Hf and ^{180}Hf anomalies for the unspiked whole rock data and modeled isotopic shifts based on the neutron flux estimated from ^{149}Sm. The exposure temperature of 78236 is not well known but it is apparent from the model that the shifts in Hf isotopes follow the pattern predicted by Sm. The measured ^{149}Sm anomaly is +29.4 ε units, however the neutron flux predicted from this anomaly is too low to explain the observed Hf isotope anomalies. Neutron fluxes predicted from isotope anomalies of Gd in 78236 (^{155}Gd is +10.8 ε and ^{157}Gd is +48.2 ε units) underestimate the required neutron flux more than Sm even at the upper limits for realistic Lunar surface temperatures.

Epithermal neutron capture will generate anomalies in ^{180}Hf that are about -7 times those of ^{178}Hf, this is not consistent with the observed pattern, and although a small epithermal contribution cannot be ruled

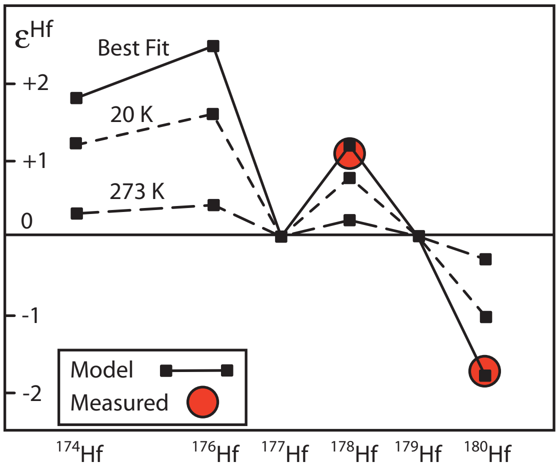

Figure 2: Stable Hf isotopic shifts for unspiked whole rock with models of thermal neutron effects based on the on shift in ^{149}Sm for temperatures of 273 K & 20 K, and a best-fit thermal neutron model for Hf in 78236.

out given the uncertainty in the data, the observed pattern is fully consistent with thermal neutron capture.

Neutron capture effects on Lu-Hf isochrons. Neutron capture will lead to a clock-wise rotation of the Lu-Hf isochron [9,10] as the positive shift in ^{176}Hf is relatively higher for samples with low Lu/Hf ratios. Higher Lu/Hf ratios have a greater relative input from ^{176}Lu into ^{177}Hf and will keep the ^{179}Hf/^{177}Hf ratio closer to normal and thus create a smaller shift in ^{176}Hf due to improper mass-bias correction. This results in apparent Lu-Hf ages that are too young and initial ^{176}Hf/^{177}Hf ratios that are too high. For Apollo 17 sample 78236,28 these corrections are significant. Using the neutron flux estimated internally from the unspiked Hf isotope data, the pyroxene with the highest ^{176}Lu/^{177}Hf ratio has a correction on ^{176}Hf/^{177}Hf of -1.8±0.5 epsilon units, due to thermal neutron fluence, for the pyroxene with oxide inclusions with intermediate ^{176}Lu/^{177}Hf ratio the correction on ^{176}Hf/^{177}Hf is -2.4±0.5 epsilon and for the plagioclase with the lowest ^{176}Lu/^{177}Hf ratio the correction on ^{176}Hf/^{177}Hf is -2.8±0.5 epsilon. This results in a corrected three-point isochron with an age of 4446±23 Ma and an initial ^{176}Hf/^{177}Hf ratio of 0.279692±17 (Figure 3). This bring the Sm-Nd and Lu-Hf ages of 78236,28 in complete agreement and changes the initial ^{176}Hf/^{177}Hf by -3.0 epsilon units. The initial ^{176}Hf/^{177}Hf of 78326 is now substantially sub-chondritic relative to [11] and only +0.3±0.9 ε units higher than the Solar System initial value of [12] suggesting that 78236 is derived from a reservoir that has seen very early enrichment and was not subjected to any irradiation events that may have increased the chondritic ^{176}Hf/^{177}Hf value from Solar System initial (*e.g.* [13]).

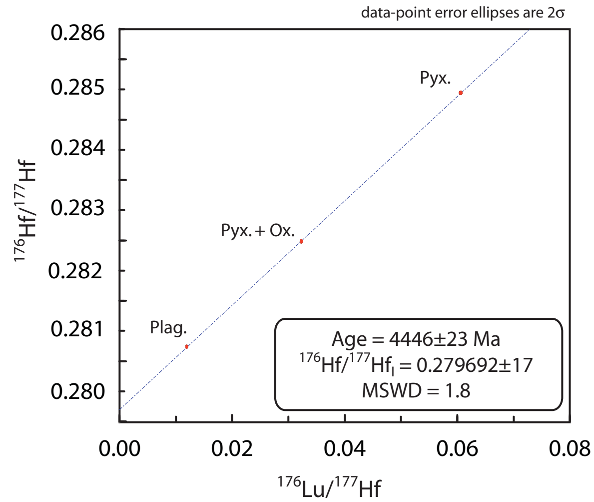

Figure 3: Three point Lu-Hf isochron corrected for thermal neutron fluence, giving an age of 4446±23 Ma, and a ^{176}Hf/^{177}Hf$_I$ of 0.279692±0.000017.

Conclusions: Apollo 17 sample 78236,28 give neutron fluence corrected Sm-Nd and Lu-Hf ages of 4448±32 and 4446±23 Ma, these are older than some Sm-Nd ages [2,14], but are in agreement with the Sm-Nd age of [15] and the U-Pb age of [16], and are not consistent with a young formation age of the Moon of 4360 Ma [17]. The Lu-Hf systematics of lunar surface samples are significantly affected by thermal neutron fluence. Using neutron dosimeters like ^{149}Sm, ^{155}Gd, and ^{157}Gd will result in an underestimation of the effective neutron flux affecting the Lu-Hf isotope system.

Acknowledgements: We wish to thank CAPTEM for the allocation of 78236. Funding was provided by the NASA Lunar Science Institute.

References: [1] Blanchard D. P. (1982) *LPI*, 49. [2] Edmunson J. et al. (2009) *GCA*, *73*, 514-527. [3] Jackson E. D. et al. (1975) *GSAB*, *86*, 433–442. [4] Sclar C. B. and Bauer J. F. (1975) *LPS VI*, 799-820. [5] Dymek R. F. et al. (1975) *LPS VI*, 301-341. [6] Lapen T. J. et al. (2004) *G^3*, *5*, Q01010. [7] Simmons S. T. (2012) *M.Sc. Thesis* UH. [8] Hidaka H. et al. (2000) *MAPS*, *35*, 581-589. [9] Sprung P. et al. (2010) *EPSl*, *295*, 1-11. [10] Sprung P. et al. (2012) *LPSC XXXXIII*, 2194 [11] Bouvier A. et al. (2008) *EPSl*, *273*, 48-57. [12] Bizzarro M. et al. (2012) *G^3*, *13*, Q03002. [13] Thrane et al. (2010) *ApJ*. *717*, 861-867. [14] Carlson R. W. and Lugmair G. W. (1981) *EPSL*, *52*, 227-238. [15] Nyquist L. E. et al. (1981) *LPSC XII*, 67-97. [16] Premo W. R. and Tatsumoto M. (1991) *LPSC XXI*, 89-100. [17] Borg L. E. et al. (2011) *Nature*, *477*, 70-72.