**AGE RELATIONSHIP BETWEEN SLOWLY COOLED LUNAR CRUSTAL TROCTOLITE SAMPLE 76535 AND NORITIC ANORTHOSITE SAMPLE 60025.** L.E. Borg[1], W. Cassata[1], and A.M. Gaffney[1] [1]Lawrence Livermore National Laboratory, Livermore, CA, USA.

**Introduction:** The Lunar Magma Ocean (LMO) model provides a general petrogenetic framework for the differentiation of the Moon in which an initial molten body solidifies forming mafic mantle cumulates, plagioclase-rich crust, and incompatible element enriched trapped liquids known as urKREEP. Rocks of the Mg-suite contain a KREEPy geochemical signature and are thought to be intruded into the plagioclase-rich crust. This relatively simple model of lunar differentiation and crust formation predicts that the mafic and felsic cumulates produced during primordial differentiation will predate magmatism associated with the Mg-suite. However, despite numerous chronologic investigations, temporal support for this scenario is largely lacking. This is illustrated on Figure 1 where it is apparent that there is little chronologic distinction between plagioclase-rich crustal samples of the ferroan anorthosite suite (FAS) and Mg-suite rocks. The discrepancy between the petrogenetic models of crust formation and the results of chronologic investigations may reflect the inability of the models to accurately reflect the geologic complexity of the Moon or the inability to accurately determine ages of lunar highlands rocks. Another consideration is the role that variable cooling rates of deep seated crustal samples play in producing the observed spread, and therefore overlap, in the apparent crystallization ages of lunar samples. The goal of this investigation is to better understand the potential spread of crustal rock ages resulting from slow cooling in the deep lunar interior. To this end, data obtained from the Mg-suite troctolite 76535and from the ferroan suite noritic anorthosite 60025 are compared.

**Samples:** Troctolite 76535 is one of the slowest cooled lunar rocks and is therefore ideal to investigate the role slow cooling potentially plays in creating the temporal overlap in FAS and Mg-suite ages. It is a very coarse-grained cumulate with individual mineral grains up to 1 cm in size [1]. It has a granular texture with abundant 120 degree grain boundary intersections that indicate that it cooled extremely slowly. Estimated cooling rates for 76535 are based on texture and grain size and range from $1^0$C/Ma [2] to $5^0$C/Ma [3]. These cooling rates are slow enough that they are likely to influence age determinations completed using isotopic systems with different closure temperatures. Equilibrium temperature and pressure calculated from the symplectite mineral assemblage of olivine + orthopyroxene + clinopyroxene + Cr-spinel + plagioclase are 850 ± 50 $^0$C and 225 ± 25 MPa [4]. This corresponds to a depth of cooling of 45 ± 5 km which lies near the base of the lunar crust or in the upper mantle. McCallum et al. [5] have used Fe-Mg ordering states in orthopyroxene to determine that the last stages of cooling below 500 $^0$C were very rapid at ~$4x10^4$ $^0$C/Ma. This most likely reflects cooling in an ejecta blanket after exhumation from the lunar interior.

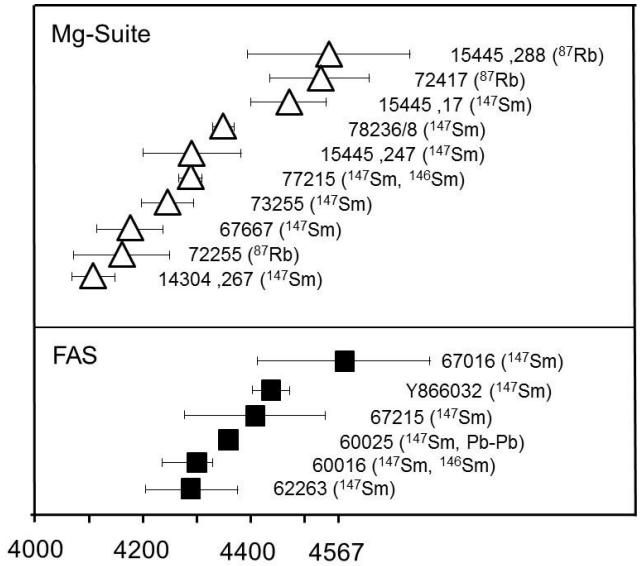


**Figure 1**. Compilation of lunar highland rock ages from [6].

Noritic anorthosite 60025 is a coarse-grained moderately shocked anorthosite. It contains ~90% shocked twinned plagioclase ($An_{94-98}$) that is up to 4 mm in length. Mafic minerals are ferroan in composition and irregularly distributed throughout the sample. Pyroxene is anhedral and generally less than 0.5 mm in size. Despite its relatively coarse-grained nature, the cooling rate of the sample, estimated from pyroxene textures, indicate that 60025 cooled fairly rapidly at a rate of ~18 °C/Ma [7].

We have completed chronologic investigations on both 76535 and 60025. Ages determined by Ar-Ar, Rb-Sr, $^{147}$Sm-$^{143}$Nd, and $^{146}$Sm-$^{142}$Nd for 76535 are 4320 ± 20 Ma, 4279 ± 52 Ma, 4307 ± 11 Ma, and 4299 $^{+29}/_{-35}$ Ma, respectively [8-9]. Likewise, $^{147}$Sm-$^{143}$Nd, $^{146}$Sm-$^{142}$Nd, and Pb-Pb for 60025 are 4360 ± 2 Ma, 4367 ± 11 Ma, and 4318 $^{+30}/_{-38}$ Ma, respectively [10].

**Cooling Rate:** The age recorded by a mineral isochron records the time when isotopic exchange between minerals comprising a rock ceased. For quickly cooled samples this is generally assumed to be the solidus temperature of the rock. However, because diffusion between adjoining minerals can occur at temperatures substantially below the solidus, slow cooling can result in ages that differ significantly from the solidus age. For example, the solidus temperature for 76535 is calculated from the bulk composition of the parental Mg-suite magma [11] using the pMELTS algorithm [12] at approximately 50 km depth [5] and is found to be 1125 ± 25 °C, whereas the closing temperature for Sm-Nd is generally assumed to be around 800 $^{0}$C. Cooling rates for 76535 vary from 1 to 5 $^{0}$C/Ma [2-3] and would thus result in a Sm-Nd age that is 325 Ma to 65 Ma younger than the solidus age. Thus, constraining the cooling rate of a slowly cooled sample is critical for the interpretation of isochron data.

The cooling rate of 76535 can be estimated from the chronometry and the estimated closure temperatures of relevant isotopic systems. The closure temperatures of the Rb-Sr, Sm-Nd, and Pb-Pb isotopic systems in plagioclase and orthopyroxene from 76535 have been calculated using equations first proposed by [13-14] and modified by [15], using the Arrhenius relations obtained by [16-19]. The closure temperature estimated for the Pb-Pb system in plagioclase from 76535 is estimated to be 624 ± 9 ºC, the closure temperature estimated for the Rb-Sr system is 649 ± 15 ºC, and the closure temperature for Sm-Nd is 825 ± 15 ºC. The Ar-Ar age records the onset of rapid cooling that began at ~500 ºC [5]. The cooling rate for 76535 is estimated in Figure 2 to be 3.9 ± 1.2 ºC/Ma.

**Solidus ages of 76535 and 60025:** A cooling rate of ~4 ºC/Ma for 76535 from Figure 2. This results in a shift in the Sm-Nd age of 76535 of ~77 Ma from 4307 ± 11 to 4384 ± 24 Ma. Likewise, a cooling rate of 18 ºC/Ma estimated for 60025 only shifts the Sm-Nd age by 16 Ma from 4367 ± 11 Ma to 4383 ± 17 Ma. Note the increased error estimates on the solidus ages reflecting uncertainties in the cooling rates of 76535 and 60025. Despite cooling at significantly different rates Mg-suite troctolite 76535 and ferroan suites noritic anorthosite 60025 have solidus temperatures that are within uncertainty of one another. This implies that FAS and Mg-suite magmatism was contemporaneous on the Moon. If FAS samples, such as 60025, are products of the LMO, then Mg-suite magmatism must be associated with its solidification. On the other hand, if FAS samples are not products of LMO solidification, then melting in the lunar interior produced bimodal magmatic suites. In this case petrogenetic models to account for the silmultaneous production of Ca and Fe-rich FAS magmas and Mg- and KREEP-rich Mg-suite magmas need to be further developed.

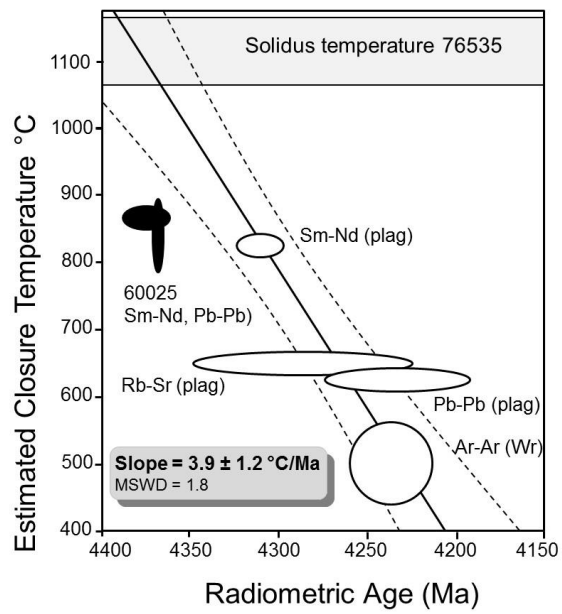


**Figure 2.** Age versus closure temperature of various isotopic systems in 76535 (open symbols) and 60025 (filled symbols).

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