CHRONOLOGIC CONFUSION IN THE LUNAR HIGHLANDS. L. E. Borg[1], A. M. Gaffney[1], and C. K. Shearer[2] [1]Chemical Sciences Division, Lawrence Livermore National Laboratory, 7000 East Avenue L-231 Livermore CA USA (borg5@llnl.gov).[2] Institute of Meteoritics, University of New Mexico NM USA.

Introduction: In the absence of detailed stratigraphic information, radiometric age determinations of lunar highland rock suites are the primary mechanism used to elucidate their temporal relationships, as well as to constrain the origin and evolution of their sources [e.g. 1-2]. However, despite their tremendous power, results of radiometric age investigations are often ambiguous because the ages are not reproducible, have large uncertainties, or have internal inconsistencies that suggest they do not represent geologic events [3]. Below we explore the mechanisms for these disturbances and examine the criteria that can be used to define reliable igneous crystallization ages.

Disturbances: The most common chronometers used to date crystallization of highlands rocks are Rb-Sr, Sm-Nd, and U-Pb. In order to account for inherited daughter isotopes, ages are calculated by plotting isotopic data from multiple fractions on isochron diagrams. The slope (or the y-intercept for Pb-Pb) of the isochron defines the age of the sample. Linearity of the fractions on the isochron is the basis for calculating the age uncertainty and is ultimately the main criteria by which the reliability of the age is evaluated.

The isotopic systematic of lunar highlands rocks are strongly disturbed by the late heavy bombardment [e.g. 4]. Experimental investigations of shocked and heated lunar samples demonstrate that Sm-Nd is least mobile during shock metamorphism and therefore is the most reliable recorder of igneous events [4]. In contrast, Ar-Ar, Rb-Sr, and U-Pb systems are more easily disturbed, accounting for the wide range of ages reported for highlands samples [Fig. 1]. However, replicate Sm-Nd ages on single samples are usually discordant. For example, average Sm-Nd ages determined on FANs 60025 and troctolite 76535, are 4.38±0.12 Ga and 4.34±0.18 Ga respectively (see refs in [1]; uncertainties are 2 stdev of ages).

Much of the disturbance to the Sm-Nd isotopic system is likely to reflect the fact that the Moon is a relatively small, water-poor body and consequently crystallizes only a limited number of phases that contain REE. These phases include: plagioclase, pyroxene, olivine, and phosphates. Many rocks contain only two REE-bearing phases so that isochrons produced from these samples are in essence mixing lines. These lines can have chronologic significance, provided fractions are in isotopic equilibrium. The presence of minor amonts of extraneous minerals, however, can produce highly linear "isochrons" (i.e. with small age uncertainties) that have do not temporal significance. Furthermore, the extraneous mineral phases can have very similar mineralogical characteristics to the indegeneous minerals and are therefore very difficult to detect. is difficult to detect [5]. Note that such mixing lines will have inappropriate initial isotopic compositions. ***Thus, isochron linearity is necessary but not sufficient to demonstrate isotope equilibrium.***

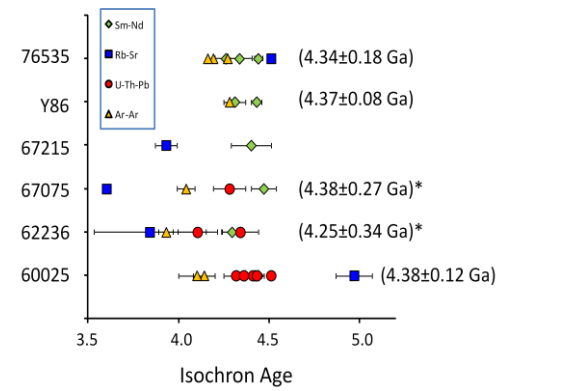

Figure 1. Ages of highlands samples that have been dated multiple times. Ages in parentheses are average Sm-Nd ages. * denotes average Sm-Nd and U-Pb ages.

Criteria: Samples that yield concordant ages from multiple isotopic systems almost certainly record a crystallization event. Ages determined by single chronometers should be considered with caution especially if: (1) multiple isotopic systems yield discordant ages on the same fractions, (2) ages are not reproducible between replicate analyses, and (3) initial isotopic compositions are inconsistent with petrogenetic models for the origin of the samples.

Conclusion: To our knowledge there are only three FAN and Mg-suite rocks that yield concordant ages from multiple isotope systems. These are FANs 67075 (4.47±0.07 Ga, [6]) and 60025 (4.359±0.003 Ga, [1]) and norite 78238 (4.344±0.037, Ga [7]). Clearly, the paucity of reliable ages does not permit the temporal relationship of these highland rock suites to be evaluated rigorously. Furthermore, the existing data indicate that the age distinctions are likely to be small (~50 Ma) between rock suites. Therefore in order to reliably elucidate the temporal relationships between highland samples the application of higher precision chronometers currently being developed will be required.

References: [1] Borg. et al. (2011) *Nature, 477,* 70-2. [2] Carlson & Lugmair (1988) *EPSL. 90,* 119-30. [3] Borg et al. (1999) *GCA. 63,* 2679-91. [4] Gaffney et al. (2011) *MAPS 46,* 35-52. [5] Shearer et al. (2012) LPSC #1421. [6] Nyquist et al. (2010) LPSC #1383. [7] Edmunson et al. (2009) *GCA 73,* 514-27. Prepared by LLNL under Contract DE-AC52-07NA27344.