Lunar $^{40}Ar/^{39}Ar$ data does not indicate a ca. 3.9 Ga impact episode. P. Boehnke[1], M. T. Heizler[2], T. M. Harrison[1], O. M. Lovera[1] and, P. H. Warren[1] [1]Department of Earth, Planetary, and Space Sciences, UCLA, Los Angeles, CA (pboehnke@gmail.com), [2]New Mexico Bureau of Geology & Mineral Resources, Socorro, NM.

While the original discovery of the Late Heavy Bombardment came from U-Pb and Rb-Sr data [1], the confirming evidence was drawn largely from interpretations of disturbed $^{40}Ar/^{39}Ar$ step-heating data in terms of "apparent" plateau ages. Despite the popularity of such an approach, the foundation of this practice is flawed in both theory and application. Here we both critically review published interpretations of lunar $^{40}Ar/^{39}Ar$ analyses and show how robust thermochronological data can be extracted from Apollo 16 samples and used to place quantitative constraints on reheating histories.

Simply put, the designation of a plateau age is limited to undisturbed samples. Essentially all Apollo samples do not meet this criterion and therefore cannot be usefully assessed in this fashion. Causes for open system behavior include mixing of different aged clasts, recoil redistribution during irradiation, and, most importantly, diffusive loss during heating events. While both mixing and recoil effectively prevent recovery of impact ages, minimum estimates of the timing of reheating can in some cases be made. However, the effects of diffusive ^{40}Ar loss on the age spectrum can be effectively recovered by modeling data derived from step-heating experiments using a multi-phase, multi-diffusion domain model [2].

Unfortunately, virtually all whole-rock lunar step-heated $^{40}Ar/^{39}Ar$ measurements utilize a simple, monotonic heating schedule [c.f., 3] which prevents unique recovery of sample specific Arrhenius parameters. This analytical deficiency precludes reconstructing the time and temperature of reheating events from the vast archive of published data. Fortunately, use of temperature cycling and isothermal duplicates [4] during laboratory heating permits recovery of thermal history information. Our results suggest that the majority of Apollo 16 samples are amenable to this form of multi-diffusion-domain (MDD) modeling.

Our systematic assessment of the timing of ^{40}Ar loss from the published literature (Fig. 1) shows a consistent decline from an apparent peak at ~3.7 Ga. If interpreted as the timing of reheating due to impacts, this broad bombardment history appears inconsistent with a discrete LHB type event at ~3.85 Ga [1] but instead supports a continual decline in impact frequency [5]. The apparent decline in frequency at ages >3.7 Ga is unlikely to be real but instead reflects the low retentivity of the early heating steps compounded by impact saturation of the lunar surface.

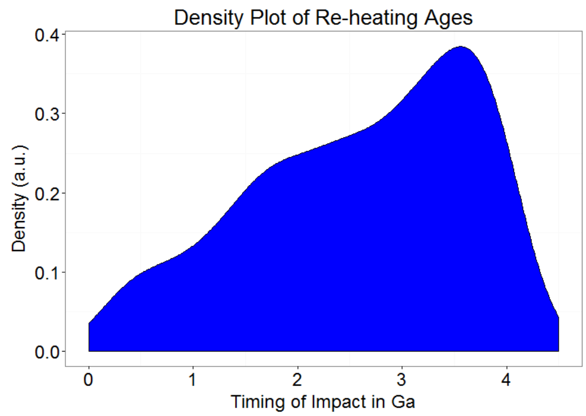

Figure 1. A compilation of initial minimum ages of Apollo $^{40}Ar/^{39}Ar$ step-heating analyses shows a broad distribution from a ca. 3.7 Ga peak.

Alternatively, using the maximum age attained in each age spectrum, we find that the peak ages for our Apollo 16 samples combined with previous data [6,7] yields a peak at ≥4 Ga (Fig. 2) rather than at ca. 3.85 Ga. Note, however, that this is still a minimum estimate of the timing of complete impact resetting.

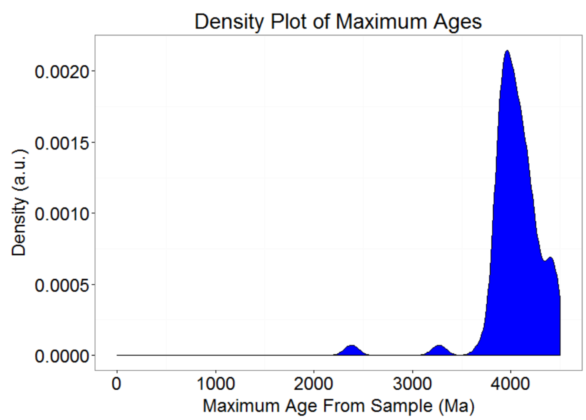

Figure 2. Maximum apparent ages for Apollo 16 samples. Note the peak is at ≥4 Ga and there is a gradual decline to ~3.5 Ga.

We illustrate the problematic nature of the "plateau" age approach to assigning impacts ages using a random sampling of data from Apollo age spectra where the "plateau" ages are compared with the maximum age from individual heating steps. Our results indicate that 50 to 70% of samples have a significant difference between the claimed "plateau" and maximum age that defines a distribution with a peak bias of ~550 Ma (Fig. 3). This discrepancy again underscores the subjective nature in assigning "plateau" ages to disturbed samples.

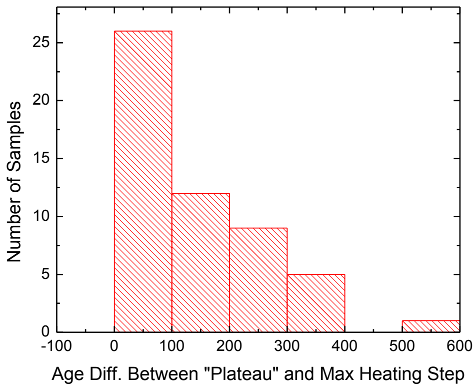

Figure 3. The difference between the "plateau" age and maximum age of any heating step. Note the one sided nature of the bias, the plateau ages are always younger.

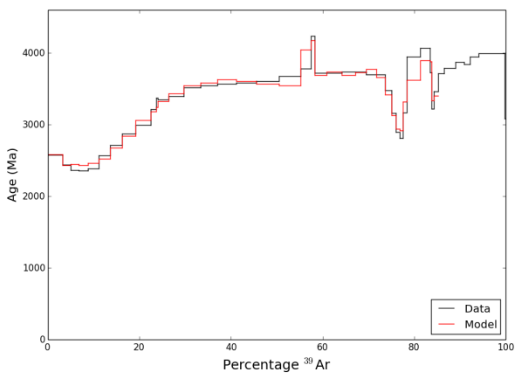

Figure 4. Age spectra for Apollo sample 67514,43. Note the dip in age which is evidence of multi-*E* behavior.

The majority of Apollo samples we have analyzed show clear evidence for multi-activation energy (*E*) behavior. For example, the age spectrum for intensely brecciated ferroan anorthosite 67514,43 (Fig. 4) shows a dip in age at a ^{39}Ar fraction release of ~75% which, coupled with the kinetic data shows a diagnostic characteristic of the presence of multiple activation energies. Our Arrhenius fits yield two *E*'s of ~39 and 95 kcal/mol, consistent with the degassing of plagioclase and pyroxene. A unique fit using sample specific kinetic parameters is obtained for a heating of ~3,800 K for 2 µsec, interpreted to represent a shock heating event [10]. An appropriate model fit indicates a reheating event at ~2.1 Ga and an age of last complete resetting at >4 Ga. For most "plateau" age criteria, an interpreted age of reheating of ~3.5 Ga would have been assigned despite clear evidence for older ages. Furthermore, given the demonstrated presence of multiple *E's*, the age spectrum itself is a function of the lab heating schedule [11]. That is, a different choice of laboratory heating durations would not yield the apparent ~3.5 Ga age. In other words, apparent "plateau" ages are analytical artifacts rather than a record of thermal events in the sample's history.

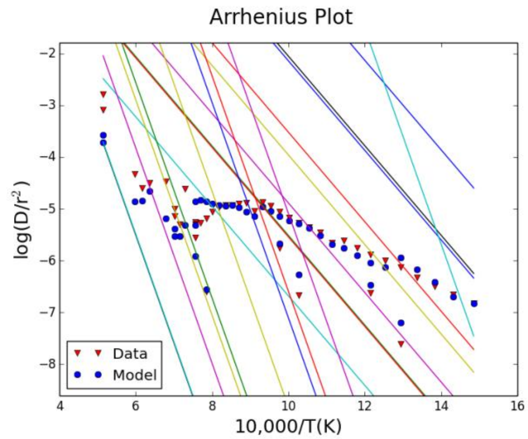

Figure 5. Arrhenius plot and model fit for sample 67514,43. The model needs two activation energies for a good fit.

Evaluating both our new Apollo 16 ^{40}Ar/^{39}Ar data together with previous lunar analyses in a quantitative thermochronological framework does not indicate a bombardment spike at ca. 3.85 Ga. Indeed, the basis of the interpretation that largely drove this hypothesis (i.e., arbitrarily assigned "plateau" ages) is shown to yield highly biased results. Instead, we argue that the data supports a protracted impact history.

References:

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