CAN GRANULITE METAMORPHIC CONDITIONS RESET ^{40}AR-^{39}AR AGES IN LUNAR ROCKS? B. A. Cohen, Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI 96822; now at Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131 (bcohen@unm.edu)

Introduction: Granulitic lithologies occur as hand samples, rake samples, and breccia clasts in all Apollo highlands sites, as well as in lunar highlands meteorites. Lunar granulites are extensively recrystallized, fine-grained cataclasites, impact melt rocks, or polymict fragmental breccias with chemistries similar to the bulk lunar highlands [1, 2], though their texture and composition varies [3, 4]. Their bulk composition is approximately anorthositic norite, with 70-80% modal plagioclase and a variety of mafic minerals. Granulitic textures arise during geologically rapid solid-state metamorphism at intermediate temperatures, probably in or near large (at least 30-90 km) impact craters [3]. The granulitic rocks and breccia clasts that have been dated fall into a relatively narrow range of ages, around 3.9-4.2 Ga. These degassing ages have been interpreted to result from a variety of geologic processes, including original mineral crystallization, metamorphism, excavation, and incorporation of clasts into breccias. It is not fully understood whether granulite ages should reflect the time of impact metamorphism, as do impact-melt rocks, or whether granulite metamorphism causes only incomplete degassing of ^{40}Ar.

Diffusion modeling: New experimental determinations of diffusion constants of Ar in plagioclase (J-A. Wartho, pers. comm.) show that plagioclase has a low closure temperature relative to other common minerals (Figure 1). The closure temperature (T_c) is the point at which the system is closed to Ar diffusion and is generally a function of cooling rate and grain (or subgrain) size. At cooling rates appropriate for granulites (left-hand shaded area in Fig. 1), plagioclase T_c (for grains 8 μm in diameter, the initial grain size in granoblastic rocks; [3] is in the range 300-400°C. The low T_c implies that plagioclase is sensitive to even low-grade metamorphism and may be easily reset by such conditions.

An impact-melt rock of the same grain size undergoes cooling by radiation (such as the top of a lava flow), at rates of degrees per hour (Fig. 3). At these cooling rates, T_c for plagioclase is higher (right-hand shaded area in Fig. 2), but for small grain sizes, is still effective in degassing ^{40}Ar and resetting the rock age. However, larger (≥50 μm) clasts may not have time to fully degas and care must be takes with clast-laden samples. In contrast, rocks cool by conduction after passage of a shock wave at rates of hundreds of degrees per hour (Fig 3). At these rates, T_c is quite high, preventing significant ^{40}Ar diffusion. This expectation is borne out in experiment, where passage of a shock wave up to 60 Gpa does not reset the ^{40}Ar-^{39}Ar age of a rock [5].

To examine theoretical ^{40}Ar loss experienced by granulites, the program MacArgon [6] was used to model the stepwise degassing profile of a rock subjected to the range of thermal histories suggested by [3]. The model results (Fig. 4) show that the high temperatures and moderate cooling rates experienced by granulites are sufficient to fully degas plagioclase. The argon release spectrum may exhibit evidence of further loss in the slow-cooling case but should cool below T_c within a few years of the metamorphic event. Thus, the age of the granulite should be an effective indicator of the impact age, within a few years (time it takes to cool to T_c).

Results: The results of the MacArgon model and the T_c calculations imply that the conditions undergone by lunar granulites should be sufficient to completely outgas the small grain-size regions of the rock and reset them to the time of metamorphism. Their ages should thus reflect large impact events on the Moon, unless subsequently overprinted by a later event. Nearly all lunar granulites exhibit loss of ^{40}Ar in low-temperature degassing steps, which is due to ^{40}Ar diffusion at low temperatures because of the low closure temperature of anorthite to ^{40}Ar. Many granulites also have high apparent ages in their high-temperature degassing steps. Often, this has been attributed to retention of ^{40}Ar from an older event, such as original crystallization of the precursor rock. The plagioclase diffusion data suggest that ^{40}Ar retention in these cases may be due to inclusion of large clasts where diffusion takes more time, a faster cooling rate than those suggested, or possibly ^{40}Ar retention in a different mineral phase, such as pyroxene, which isn't so easily reset. In cases where evidence of older ages persists, high-resolution degassing profiles may be able to separate the older age from the metamorphic age.

References: [1] Korotev, R.L., et al. (2003) Geochim. Cosmochim. Acta, submitted. [2] Taylor, S.R. (1982) Planetary Science: A Lunar Perspective, Houston, TX: Lunar and Planetary Institute. 481 p. [3] Cushing, J.A., et al. (1999) Meteorit. Planet. Sci., 34, 185-95. [4] Lindstrom, M.M. and D.J. Lindstrom (1986) J. Geophys. Res., 91, D263-76. [5] Deutsch, A. and U. Schärer (1994) Meteoritics, 29, 301-22. [6] Lister, G.S. and S.L. Baldwin (1996) Tectonophysics, 253, 83-109.

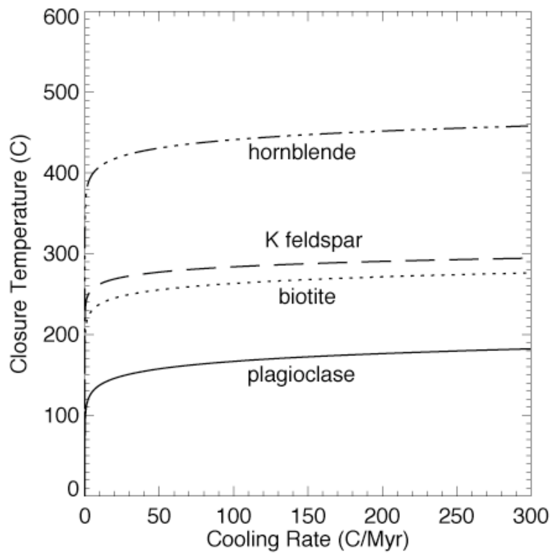

Figure 1. Closure temperature as a function of cooling rate (linear scales) showing that plagioclase has the lowest retentivity of common K-bearing minerals. The range of cooling rates shown is for common terrestrial metamorphic cooling rates. The effective diffusion domain is 4 µm (radius) for all minerals.

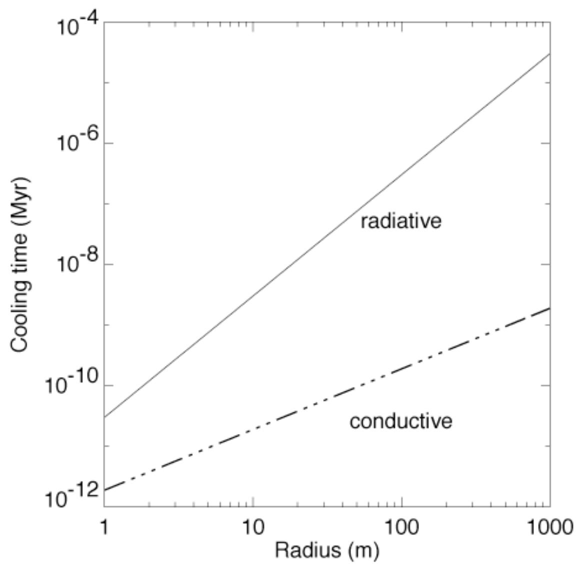

Figure 3. Cooling times as a function of radius of the rock. Igneous quenching occurs by radiative cooling while conduction is more appropriate for a rock buried in the regolith (if the surrounding rock is an ideal heat sink). Radiation can produce cooling rates 1-10°C/hr, for rock 1-10 m in radius. Conduction into cold country rock can allow cooling rates up to 100-1000°C/hr for rocks of the same size.

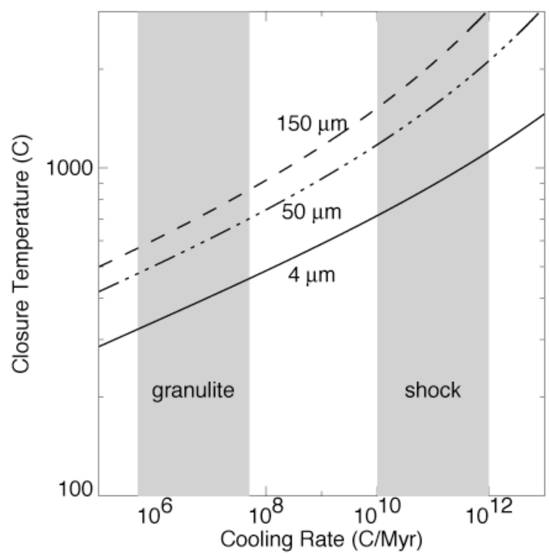

Figure 2. Plagioclase closure temperature (log scales) at different effective diffusion domain sizes (radius). Effective diffusion domain may be defined by grain size or, if applicable, subgrain size. Granulites had an original subgrain size of 4 µm [3]; larger clasts may have been as large as 50 µm. The left-hand shaded area shows the range of cooling rates for the granulites (0.5-50°C/yr). The right-hand shaded area shows cooling rates more appropriate for faster cooling, such as quenching of a melt pool (lower bound) or passage of shock wave (upper bound) (Fig. 3).

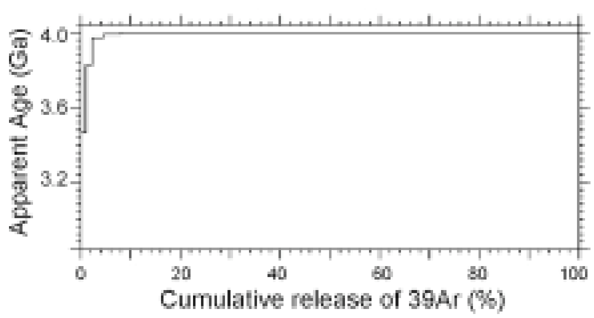

Figure 4. Modeled age spectrum for a plagioclase rock (grain size = 4 µm radius) heated to 1000°C at 4.0 Ga and cooled at 0.5°C/yr. Because of the low Tc of plagioclase, the rock degasses all its 40Ar under these conditions and records the metamorphic age of 4.0 Ga. In addition, the slow cooling rate allows further diffusion from the least-retentive sites, causing the low apparent ages in the low-temperature steps. In cases where higher temperatures are followed by faster cooling rates (1300°C; 50°C/yr), the rock is also fully degassed, reset to 4.0 Ga, and no diffusive loss in the low-temperature degassing steps is observed.