ARGON-39-ARGON-40 AGES OF LUNAR HIGHLAND ROCKS AND METEORITES.

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The Problem: The magma ocean model for the moon envisions formation of an early flotation crust primarily composed of Ca-rich feldspar. Yet, ages of most lunar highland rocks are considerably younger than the ~4.5 Ga formation time for the moon as a whole. For example, ^{39}Ar-^{40}Ar and Rb-Sr ages of highland rocks from Apollo sites 14, 16, and 17 commonly show values of ~3.7-4.1 Ga (e.g. Fig. 6 in [1]), and considerable evidence exists for widespread volatilization of lunar Pb (thus resetting of Pb-Pb ages) ~3.9 Ga ago. The common explanation for these younger highland rock ages is that they were totally or partially reset during heating by large impacts. Two explanations of this impact resetting have been offered. One is that it represented the tail end of a long lunar accretion and was preceded by even more intense bombardment [2]. The other is that the reset ages represent a time period in which the rate of impacts increased dramatically, i.e., an impact cataclysm [3]. It has been suggested that much of the mass impacting the moon late in the bombardment was concentrated in a few large objects which formed the nearside basins [4]. Several of these basins are believed to be 3.8-4.0 Ga old, and many of the returned highland rocks probably were incorporated into these basin ejecta.

Clearly an understanding of the early impact history of the moon also gives insight to the early impact histories of the terrestrial planets and large asteroids [1]. This requires dating of lunar rocks not thermally affected by the large basins [5]. Yet, even lunar rocks showing old Sm-Nd ages often show younger Ar-Ar ages, several ~3.9 Ga. A different perspective to the problem may be gained through those few lunar meteorites originating from the lunar highlands. The probability is high that they were ejected from back-side and other lunar locations not affected by the large lunar basins. Below we report recent ^{39}Ar-^{40}Ar data on a few lunar highland samples and lunar meteorites which address these issues.

Lunar Highland Rocks: Lunar ferroan anorthosite **62236** has a Sm-Nd isochron age of 4.29 ±0.06 Ga, but its ^{39}Ar-^{40}Ar age of 3.93 ±0.04 Ga and Rb-Sr isochron age of 3.84 ±0.31 Ga give evidence of resetting by impact [6]. The Ar-Ar age is slightly older than the age generally accepted for the Imbrium and Serenitatis basins, but may be consistent with ages of the Crisium and Nectaris basins. Another ferroan anorthosite **67215** has a Sm-Nd isochron age of 4.40 ±0.11 Ga, but shows disturbance of its Rb-Sr system ~3.93 Ga ago [7]. A plagioclase separate from 67215 suggests Ar-Ar degassing at ~3.93-4.00 Ga and probably represents incomplete K-Ar resetting from a basin impact ~3.93 Ga ago. Like several previous old highland rocks, both of these ferroan anorthosites appear to have experienced significant heating by large nearside basin ejecta.

Lunar Highlands Meteorites: Lunar meteorite **MAC88105** contains a large clast, W1, which is a coarse-grained anorthositic impact melt breccia composed of ~85% plagioclase [8]. The ^{39}Ar-^{40}Ar age spectrum for W1 is shown in Fig. 1. Nearly all extractions released pure cosmogenic ^{36}Ar with a ^{36}Ar/^{38}Ar ratio of ~0.66, so no solar ^{36}Ar or lunar atmosphere ^{40}Ar were present. The K/Ca ratio is approximately constant at ~0.0013 across 90% of the ^{39}Ar release and suggests most of the K resides in a single mineral. The Ar-Ar age increases uniformly with extraction temperature and shows the classic shape of a partial Ar degassing profile. Five extractions releasing the last 31% of the ^{39}Ar define an age of 4.07 ±0.04 Ga. This may be a lower limit to the Ar degassing age, as a modest amount of ^{40}Ar could have been lost later by diffusion from these high temperature lattice sites.

Lunar meteorite **Yamato-86032** is a fragmental feldspathic breccia which was described as containing almost no regolith component [9]. We made ^{39}Ar-^{40}Ar analyses of part of a gray clast set in a darker matrix (Fig. 2). The K/Ca ratio is constant across nearly the entire extraction, but the K concentration is only half that of MAC88105. A single 1400^{O}C extraction released 38% of the total ^{39}Ar and gives an apparent age of 4.39 ±0.06 Ga. Younger ages for lower temperature extractions releasing ~15-62% of the ^{39}Ar indicate some diffusion loss of ^{40}Ar. However, most extractions of Y-86302 give ^{36}Ar/^{38}Ar ratios of 1-2, with a ratio of 1.18 for the 1400^{O}C extraction. This observation, plus the apparent high Ar-Ar ages at <15% ^{39}Ar release, imply the presence of trapped Ar consisting of solar ^{36,38}Ar and lunar atmosphere ^{40}Ar. We can use the ^{36}Ar/^{38}Ar ratio to divide ^{36}Ar into cosmogenic and trapped components. Trapped Ar in the lunar regolith has ^{40}Ar/^{36}Ar ratios of ~0.4-8, with most samples showing ratios of ~0.5-2. If we correct the 1400^{O}C data for trapped ^{40}Ar assuming trapped ^{40}Ar/^{36}Ar ratios of 1 and 10, the corrected Ar-Ar age becomes 4.39 Ga (i.e., no change) and 4.35 Ga, respectively. Thus, we conclude the minimum K-Ar degassing age for Y-86302 to be 4.35 Ga, with a good possibility that this age is as old as 4.40 Ga. This Ar-Ar age is similar to other radiometric ages obtained on a few lunar rocks, e.g., 78236, 60025, 77215, and 15445 [5]. This argues that Y-86302 escaped K-Ar age resetting by the large near-side basins.

Lunar meteorite **Dar al Gani 400** is an anorthositic highland regolith breccia [10], which shows evidence of extensive terrestrial weathering. The $^{36}Ar/^{38}Ar$ ratio increases with extraction temperature from 3.2 to 5.1, and demonstrates that all extractions released trapped ^{36}Ar in greater abundance than cosmogenic ^{36}Ar. Detailed examination of the Ar-Ar age spectrum (Fig. 3) and variations in isotopic composition and rate of Ar release with temperature suggest the following. Between 0-16% of the ^{39}Ar release mostly terrestrial Ar is released, probably from weathering products. However, above ~16% ^{39}Ar release, most of the trapped Ar represents solar ^{36}Ar and lunar atmosphere ^{40}Ar. Those lattice sites releasing 0-45% of the ^{39}Ar have extensively lost radiogenic ^{40}Ar, and those sites releasing 45-100% of the ^{39}Ar have partially lost ^{40}Ar. We examined all these data in an inverted isochron plot [11] to determine possible mixtures of trapped and radiogenic Ar components. Derivation of the Ar-Ar age from those extractions giving >70% of the ^{39}Ar release depends on the trapped lunar $^{40}Ar/^{36}Ar$ assumed. For trapped $^{40}Ar/^{36}Ar$ of 0.5, 1.0, 2.0, and 5.0 this high temperature age becomes ~3.8 Ga, 3.7 Ga, 3.4 Ga, and 2.3 Ga, respectively. Thus, DaG-400 indicates an Ar-Ar age no higher than ~3.8 Ga, which could represent resetting during the impact cataclysm.

Nyquist et al. [12] reported whole rock Sm-Nd and Rb-Sr isotopic data for MAC88105 and Y-86302. Sm-Nd isotopic data for both are similar to lunar norites and lie on a 4.56 Ga reference isochron defined by whole rock data for several lunar highland rocks. The Rb-Sr data lie on the mixing line common to lunar crustal rocks and passing through initial $^{87}Sr/^{86}Sr$ ~0.69908, typical of lunar anorthosites like 60025. The Rb/Sr ratio is ~1/2 the crustal average [9] suggesting the absence of a KREEP component. The Pb-Pb isotopic data resembles that of lunar anorthosite 60025 [13]. These data are consistent with an overall crustal affinity of the two samples, consistent with the ~4.4 Ga Ar-Ar age of Y86032 and the $\geq$4.1 Ga age of MAC88105.

Implications: The widespread existence of younger Ar-Ar ages (and some Rb-Sr ages) of lunar highland rocks relative to the likely formation time of the upper lunar crust >4.4 Ga ago and relative to the measurement of older Sm-Nd ages for a few lunar rocks, argues that essentially all such highland rocks returned by Apollo experienced significant heating by impact. Whereas Apollo-returned rocks may have been reset by near-side basin-forming events, lunar meteorites may derive from areas of the moon far removed from major basins. However, only one of the three highland meteorites dated indicate an Ar-Ar age significantly older than ~4.0 Ga. The other two meteorites may have been reset by near-side basins. Additional analyses of highlands meteorites are needed to determine whether they record a different cratering history than the Apollo samples.

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