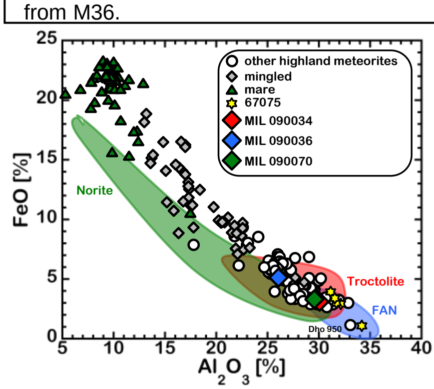
LATE BOMBARDMENT OF THE LUNAR HIGHLANDS RECORDED IN MIL 090034, MIL 090036 AND MIL 090070 LUNAR METEORITES. J. Park[1,4,5], L.E. Nyquist[2], C.-Y. Shih[3], G.F. Herzog[4,5], A. Yamaguchi[6], N. Shirai[7], M. Ebihara[7], F.N. Lindsay[4,5], J. Delaney[4,5], B. Turrin[8,5], C. Swisher III[8,5]. [1]Lunar Planet. Inst., Houston, TX 77058, [2]KR/NASA Johnson Space Center, Houston, TX 77058, [3]JE-23, ESCG/Jacobs Sverdrup, Houston, TX 77258-8477 [4]Dept Chem. & Chem. Biol, [5]Rutgers Univ., Piscataway, NJ 08854, [6]Antarctic Meteorite Research Center, Natl. Inst. Polar Research, Tokyo 190-8518, Japan, [7]Tokyo Metropolitan Univ., Hachioji, 192-0372, Japan, [8]Dept. Earth Planet. Sci.

Introduction: The Kaguya mission detected small but widespread outcrops of nearly pure ferroan anorthosite in and around large impact basins on the Moon [1]. Yamamoto et al [2] took these observations as evidence for a 50-km thick layer of once-molten anorthosite underlying much of the lunar surface (cf. [3]). Along with certain lunar rocks, highly feldspathic lunar meteorites such as MIL 090034 (M34), 090036 (M36), and 090070 (M70) may provide samples of this material. We have measured the $^{40}Ar/^{39}Ar$ release patterns and cosmogenic ^{38}Ar concentrations of several small (<200 µg) samples separated from M34,36, and 70. From petrographic observations [4] concluded that "some of the clasts and grains experienced generations of modifications," a conclusion that we examine in light of our data.

Fig.1. Among lunar meteorites, M34, M36, and M70 have the largest modal abundances of plagioclase. M34 & 70 differ from M36.



M34,36,70 are anorthositic regolith breccias [5]. The petrology and mineralogy of samples of the breccias allocated to us were reported by [6]. Fig. 1 and rare earth element abundances suggest pairing of M34 and M70, as also suggested by [7,8]. Yamaguchi et al. [6] interpreted M70 to be a crystalline melt breccia, whereas M34 and M36 are fragmental or regolith breccias. Mg-suite fragments, a rare feature in lunar highland meteorites, were found in M34[6]. Plagioclase mineral fragments in M70 were found to have a narrow compositional range, An_{93}-An_{98}, whereas plagioclase in M34 ranges from An_{82}-An_{99}, and in M36 from An_{64}-An_{98}. Mg' (molar Mg/(Mg+Fe) for olivines in M34 and M70 are similar to those in FAN. Some olivines in M36 have higher Mg' numbers. The range of Mg' in olivine and An in plagioclase imply a contribution of Mg-suite rocks to M36 as well as to M34. Molar Ti/(Ti + Cr) and Fe/(Fe + Mg) in some pyroxenes in M34 and M36 are similar to those of LT and VLT mare basalts, implying that these pyroxenes originated from mare basalts [6].

Experimental Methods for Ar-Ar Analyses:

Samples were separated by handpicking from 68 mg of M34,20,1,8; 129 mg of M36,16,4; and 43 mg of M70,17,21. Sugary, polycrystalline masses ranging from 53 to 330 µg were hand-picked and the elemental compositions confirmed as anorthositic by either EDX or x-ray fluorescence. The grains selected from M34 included darkly colored streaks, possibly impact melt. Samples were irradiated for ~80 h with Cd shielding at the USGS Triga reactor.

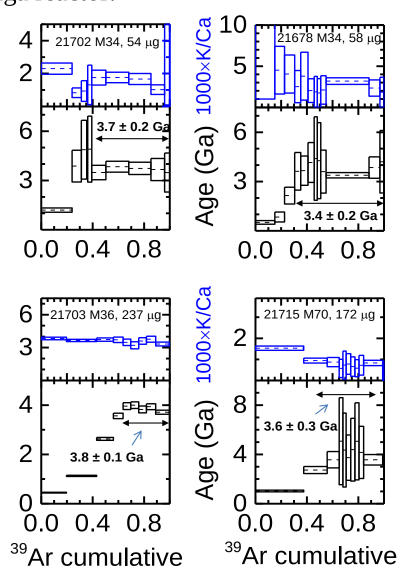


Fig. 2. Apparent Age spectra and K/Ca ratios of M34, M36 and M70.

Results: *Argon release patterns and ages.* Figure 2 shows our four best Ar age spectra without corrections for trapped ^{40}Ar. All release patterns are disturbed at low fractional ^{39}Ar release (<0.2) and relatively flat at high ones (>0.6), although with large uncertainties because of low K concentrations. For M34, 36, and 70, the respective weighted mean ages (Ga) calculated for the high-temperature ages (Ga), which we take to indicate the time of the last major re-settting, are 3.4±0.3 (M34, n=5), 3.80±0.12 (M36, n=5), and 2.62±0.17 (M70; n=6) or 3.5±0.7 (n=4, excluding 2 analyses). These results suggest but do not prove lower ages for M34 and M70 than for M36.

Isochrons. Isochrons for $^{40}Ar/^{36}Ar$ vs. $^{39}Ar/^{36}Ar$ were plotted for the high-temperature data after removing a small cosmogenic ^{36}Ar component ($^{36}Ar_c$) calculated using the relation $^{36}Ar_c = 0.65\times{}^{38}Ar_c$. The isochron age for M36 is 3.54±0.04 Ga (Fig. 3a), about 2σ less than the high-temperature weighted average above. For M34 we obtain 3.23±0.31 Ga, and for M70 3.05±0.59 Ga (Fig. 3b). The isochron ages cannot be clearly distinguished because of the relatively large uncertainties for the M34 and M70 ages. Nevertheless, the ages of M34 and M36 agree only at the limits of uncertainty, a strong hint that M34, and problably M70 as well because of its strong compostional pairing with M34, experienced a major outgassing event more recently than did M36. Incorporation in the laboratory of 0.5-1.8×10^{-8} cm^3 STP/g of at-

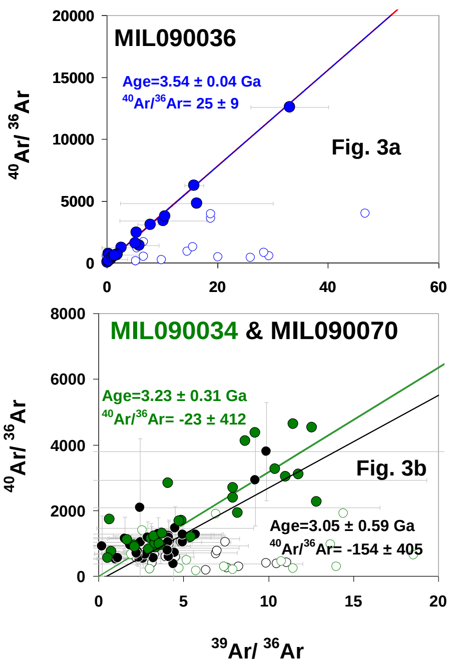


Fig. 3. $^{40}Ar/^{36}Ar$ vs. $^{39}Ar/^{36}Ar$ isochrons for M36 (a) and M34 plus M70 (b). Low temperature data shown by open symbols were excluded from the regressions.

mospheric ^{40}Ar [9] would have raised the apparent ages of some release steps, especially ones with low $^{39}Ar/^{40}Ar$ ratios. Data points in the lower left-hand corner of Figure 3 probably indicate atmospheric Ar in several fractions of M34 and M70, but not of M36.

Cosmic-ray exposure. We calculated the concentration of cosmogenic ^{38}Ar from the relation $^{38}Ar_c$=(5.35×^{38}Ar–^{36}Ar)/(5.35-0.65) . Average total $^{38}Ar_c$ concentrations (cm^3 STP/g) over total ^{37}Ar concentrations (cm^3 STP/g), a measure of total cosmic-ray exposure in Ca-rich and K- and Cl-poor material, are as follows: M34 (7.8±2.2)×10^{-4} (n=5); M36, (2.0±0.3)×10^{-2} (n=5); M70 (7.0±1.3) ×10^{-4} (n=6). Thus, the average cosmogenic $^{38}Ar_c$ concentration is ~25 times larger for M36 than for M34 and M70. The difference is even larger if we consider high-temperature $^{38}Ar_c/^{37}Ar$ ratios, from which apparent cosmic ray exposure (CRE) ages can be calculated (Figure 4). A lower bound on the total duration of irradiation can be estimted from an upper bound

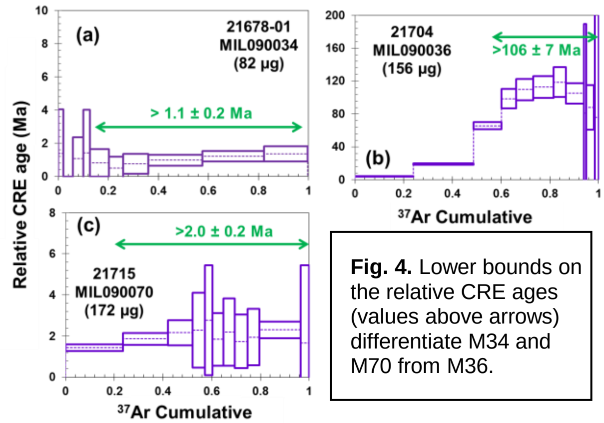


Fig. 4. Lower bounds on the relative CRE ages (values above arrows) differentiate M34 and M70 from M36.

on the production rate of $^{38}Ar_c$, P_{38} = 0.22 × 10 ^{8} cm3 STP/(g-Ma) [9], based on a Ca concentration of ~12 wt% in MIL meteorites [10]. The results (Ma) are: 1.3±0.6 (M34) (n=5); 50±10 (M36) (n=5) and 1.6±0.3 Ma (M70)(n=6). (The relative CRE ages in Fig. 4 show individual data). The apparent CRE ages for M34 and M70 are short and agree well within their error limits, suggesting that they were excavated to (or from) the lunar surface at the same time. Also, values of "4-π" CRE ages for lunar meteorites rarely exceed 5 Ma [11], suggesting that M36 was excavated to the lunar surface much earlier.

Discussion and Conclusions: The high-temperature Ar/Ar ages of M34, M36, and M70 are much younger than the anorthositic protolith from which they were formed. The ages fall within the range of ages for impact melt clasts from other lunar feldspathic regolith breccias, which indicate a broad Ar/Ar age peak between 3.0 and 3.5 Ga [12]. M34 and M70 are compositionally similar to Apollo 16 FANs; M36 to Apollo 16 soils. One large Apollo 16 FAN (60015) has a similarly young Ar-Ar age [13]. Also, from an Ar/Ar study of 7 'rocks' extracted from Apollo regolith sample 63503, [14] inferred a major impact event in the Cayley plains ~3.3 Ga ago and perhaps a broader bombardment of the Moon at that time. Orbital geochemical data (*cf*. [1,2]), show central-peak craters in the lunar highlands to be suitable sources for highly aluminous M70 and M34, but higher trace element abundances in M36 suggests an origin in the vicinity of the Procellarum KREEP terrain (PKT).

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