THE AGE OF METAMORPHISM OF A HIGHLAND BRECCIA (65015) AND A GLIMPSE AT THE AGE OF ITS PROTOLITH

J. C. Huneke, E. K. Jessberger† and G. J. Wasserburg, the Lunatic Asylum, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91106

We report here an attempt to decipher the age of the protolith of breccia 65015 using the ^{40}Ar-^{39}Ar technique. Petrographic and Rb-Sr isotopic studies have shown the presence of clasts which have not been brought into chemical equilibrium with the recrystallized ground mass (1,2). Studies on such rocks are important in penetrating the time barrier at ~4.0 AE reflecting the terminal lunar cataclysm and are applicable to the characterization of the early lunar crust and the time scale for its evolution.

Ar analyses were made on a whole sample and mineral separates (two plagioclase, a pyroxene and a pyroxene with 4% whitlockite [Ph-A]), using 30-50 heating steps to provide high resolution in $^{40}Ar/^{39}Ar$ variations. It was anticipated this would allow the contributions from relict retentive phases to be isolated. Fig. 1 shows that the age spectra of all samples increase rapidly to a local maximum at ~600° C and then decrease. A low resolution experiment would not show this fine structure, but would give age plateaux at 3.9 to 4.05 AE for all samples between 500-900° C. Above 900° C, pyroxene, Ph-A and whole rock ages all decrease sharply, while both plagioclases show a rapid increase in apparent age. For plagioclase B, the highest age of ~4.5 AE is approached in a regular sequence of precise data. This increase in apparent age of the plagioclase is unusual. Plagioclase separates have typically exhibited well defined age plateaux, with the one exception of plagioclase from rock 68415 (3), where the ages increased to ~4.5 AE in a pattern very similar to that observed here. 68415 also contains large plagioclase relicts to which the age of ~4.5 AE in the last Ar release can be ascribed (4), although Sr isotopic equilibration with the matrix is indicated (5).

Of the K in 65015, 90% resides in an irregularly dispersed, very fine quintessence (1) which contributes a large fraction of the total ^{40}Ar at low temperatures, as demonstrated by the high K/Ca in these releases (cf. Fig. 2). Plagioclase B is ~99% pure, but an admixture of only 1.5% quintessence could account for two thirds of the K. In contrast, plagioclase has ~13% Ca whereas quintessence has only 2% Ca (1). Thus ^{37}Ar from the plagioclase samples is related almost entirely to release from the plagioclase, not high K-low Ca impurities, and a true plagioclase plateau should be associated with ^{37}Ar release. The data presented this way in Fig. 2 show the distinct peak at ~600° C in the high K/Ca regime which, instead of being interpreted as an intrinsic part of the plagioclase plateau, is identified in the ^{37}Ar plot as a minor contribution from an admixed high-K phase. There is a reasonably well defined plateau corresponding to a K/Ca of 0.005 appropriate to plagioclase and extending over 35% of the ^{37}Ar release. It is most reasonable to associate this plateau with plagioclase which has completely lost ^{40}Ar in a metamorphism at 3.98 AE and to associate the age peak at ~600° C with the crystallization of quintessence at the same time. About 15% of the ^{37}Ar release from plagioclase B and ~5% from plagioclase C can be related to high ages, in striking agreement with ~14% and ~8% inferred from Rb-Sr studies of the same separates (2). This provides a very important argument for the association of the ~4.5 AE age with unequilibrated plagioclase clasts, and it is thus plausible to correlate this age with the plagioclase clasts which have not been thoroughly equilibrated and outgassed during the metamorphism at 3.98 AE. These results support reports by other workers on evidence for more ancient lunar sample ages (6). The firm assignment of a precise time to a part of a ^{40}Ar-^{39}Ar release pattern requires a more complete understanding of the nature of $^{40}Ar/^{39}Ar$ variations. Spallation $^{38}Ar/^{37}Ar$ in plagioclase B was found to be 10% higher in the last 15% of ^{37}Ar release, indicating an older exposure age for the same plagioclase showing high ^{40}Ar-^{39}Ar ages. This suggests that the protoliths of many impact breccias may include material which resided for some time in the outer few meters of the lunar surface prior to the metamorphism.

Ar ages and trapped Ar compositions were measured for green glass and devitrified spheres hand-picked from the Apollo 15 breccia 15086 from Elbow crater. All of the spheres are presumed

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Fig. 1 Apparent age vs. extraction temperature for 65015 whole sample and mineral separates. All show a rapid increase to a local maximum at ~600° C corresponding to release from a high K/Ca phase, probably quintessence. Above 900° C, the plagioclases increase in age to ~4.5 AE, while the others decrease sharply.

Fig. 2 Apparent age and K/Ca vs. ^{37}Ar release (top) and apparent age vs. ^{39}Ar release (bottom) from 65015 plagioclase B. Low temperature releases from high K, low Ca contaminant phases dominate the ^{39}Ar plot. A plateau at 3.98 AE and the subsequent rise to higher ages, which we associate with retentive relict plagioclase, includes a significant portion of ^{37}Ar release.

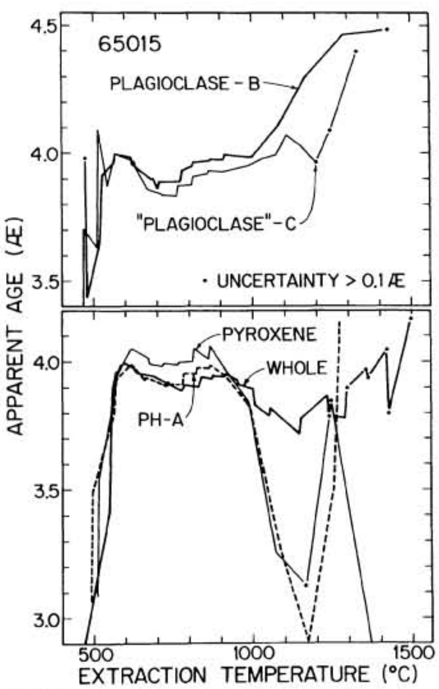

Fig. 1

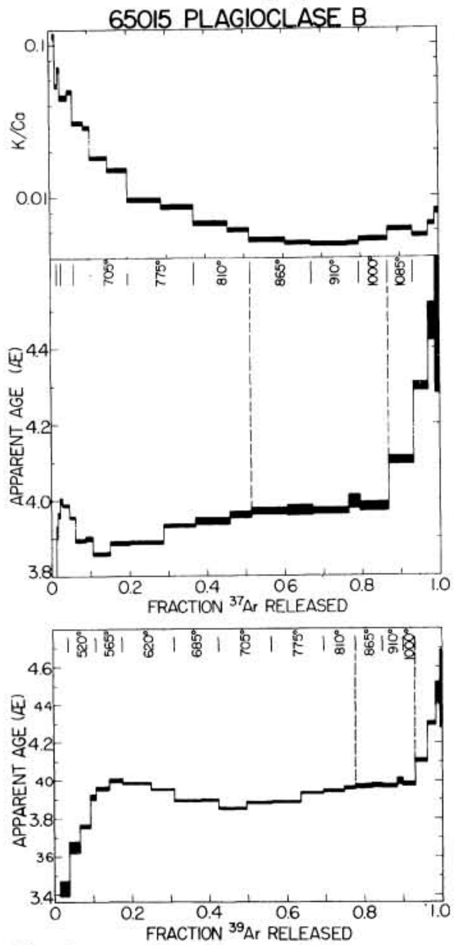

Fig. 2

Fig. 3 $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ for 15086 green glass and devitrified spheres. The data below 800° C shows the complex release of at least two trapped components. A general linear correlation between a K-derived Ar (abeissa) and a trapped Ar (ordinate) exists for the glass from 810-1320° C, but no well-defined trapped Ar is evident. The devitrified sphere data is generally shifted toward younger ages at high temperatures.

Fig. 4 Apparent age vs. ^{39}Ar release for 15086 green glass and devitrified spheres. A ratio of $^{36}Ar/^{40}Ar = 1.23$ was used to correct for trapped ^{40}Ar. For the green glass, an age of 3.29 ± 0.06 AE is estimated from the 17-60% ^{39}Ar release data (1075° C and 1195° C). The large apparent ages in the final releases are interpreted to reflect a redistribution of ^{40}Ar. For the devitrified spheres, the last 65% ^{39}Ar release gives an average age of 3.1 AE.

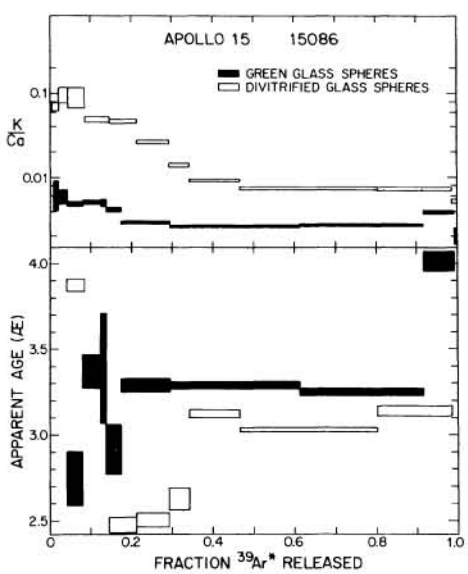

Fig. 4

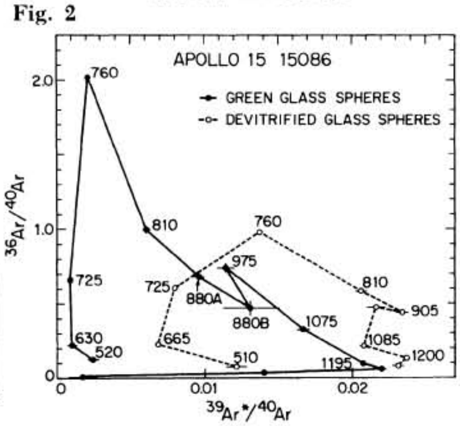

Fig. 3

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cogenetic. Electron probe measurements of green glass and devitrified spheres show very similar compositions (A. Albee, private communication). The devitrified spheres have 595 ppm K, compared to 175 ppm K in the green glass. Since K is very low, only a few high K particles are necessary to significantly effect the total pattern. An effort was made to avoid such contamination, which may nonetheless have occurred.

^{40}Ar must be separated into trapped and radiogenic contributions, which is attempted here using isotope correlations in a differential thermal release experiment. The data are shown in Fig. 3, corrected for Ar derived from neutron interactions on Ca during the irradiation and for cosmic-ray spallation Ar contributions. Trapped Ar compositions lie along the ordinate and K-derived Ar compositions along the abcissa. Mixtures of a trapped with a K-derived Ar lie along a line joining the two compositions. The compositional variation trajectories observed are complex. The low temperature releases are dominated by the consecutive release first of an ^{40}Ar-rich, then an ^{36}Ar-rich trapped Ar. No precise trapped Ar composition in the green glass is defined by the correlation of more than a few consecutive data points. Except for the two highest temperature releases, the data above 760° C form a roughly linear array which intersect the ordinate at nearly the total trapped Ar composition. The array is not precise, and no constant trapped Ar composition is clearly established. The two highest temperature releases are well outside this correlation, trending in the direction of excess ^{40}Ar. The reason for this, whether it is indicative of inherited ^{40}Ar, a redistribution of ^{40}Ar or K, or possibly an experimental artifact, is not established. The trajectory of green glass compositions is strikingly similar in its major features, including the high temperature trend, to that observed for 74220 orange glass, the only other glass measured in comparable detail (3).

Compositional variations in Ar released from the devitrified spheres (Fig. 3) are also complex. The trapped Ar variations at low temperature are similar in both samples. Higher temperature data scatters, but tends to converge with the K-derived $^{39}Ar/^{40}Ar$ of the green glass. Several measured $^{39}Ar/^{40}Ar$ of the devitrified spheres are larger than the extrapolated $^{39}Ar/^{40}Ar$ of the green glass, giving younger apparent ages for those releases. This observation is not sensitive to the assumed trapped Ar composition. Ar compositions from the devitrified spheres do *not* trend to exceptionally low $^{36}Ar/^{40}Ar$ and $^{39}Ar/^{40}Ar$ in the high temperature release as observed in the glasses.

Ages of both green glass and devitrified spheres, corrected for trapped ^{40}Ar using a trapped ratio of $^{36}Ar/^{40}Ar = 1.23$ are shown on Fig. 4. The data which are highly uncertain in K-derived Ar composition due to large trapped Ar contributions involve only the first 17% of ^{39}Ar release. These data characterize the trapped Ar. An age of 3.29 ± 0.06 AE is inferred for the green glass from the 1075° C and 1195° C points, which contain 45% of the ^{39}Ar release and relatively small amounts of trapped Ar. Inclusion of the subsequent 1320° C release would reduce the age by only 0.02 AE. This age for the green glass confirms the age of 3.38 ± 0.06 AE previously reported (7) and more firmly establishes the time of origin of the green glass during Imbrium mare flooding and a probable origin in volcanic activity during this period. For the devitrified spheres, the last 65% of ^{39}Ar release yields an average age of 3.1 AE, only slightly younger than the age of the green glass.

These analyses serve to illustrate the complexity in trapped Ar compositions. This problem must be seriously addressed in any ^{40}Ar-^{39}Ar analysis of samples exposed to solar wind. The systematics of $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ variation are somewhat better defined in the glasses compared to the devitrified spheres, and future studies should recognize both this and the decreases in apparent age which seem to be associated with the devitrification.

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