U-Pb AND K-Ar SYSTEMATICS OF CATACLYSM AND PRECATACLYSM LUNAR IMPACTITES

F. Oberli, J. C. Huneke and G. J. Wasserburg, The Lunatic Asylum, Division of Geological and Planetary Sciences, Caltech, Pasadena, CA 91125

We report U-Pb and K-Ar measurements of a variety of lunar highland breccias, continuing our study of early crustal evolution [1]. Previous U-Pb data [2,3] of most highland rocks form a rather well defined linear array on a U-Pb evolution diagram which yields intersections with the concordia curve at ~4.45 and ~ 3.9 AE. Scatter of data points about this array was noted but could not clearly be attributed to sources other than analytical precision in most cases. There is excellent evidence that the lower intersection represents the time of crystallization or impact metamorphism, while the upper intersection was tentatively interpreted as the primary age of the lunar crust. It is important to establish whether a) there exist clear exceptions to this interpretation, and b) if the times of impact metamorphism are reliably reflected by both the U-Pb and the K-Ar systems. A connection between the two methods could permit the determination of early (or late) lunar events from a single U-Pb datum using a 2-stage model with the lower intersection being the outgassing age determined by K-Ar and the primary age being defined by the upper intersection. The existence of several U-Pb data points plotting substantially above the cataclysm isochron posed the questions whether part of the lunar crust was formed very early, at times prior to 4.5 AE, or whether these rocks were modified by events predating the terminal lunar cataclysm as suggested by K-Ar ages >3.9 AE. Based on isotopic data and petrological arguments, anorthositic breccia 67075 [4] and a group of breccias termed "early granulitic impactites" [5], 67955, 78155 [6,7], and 79215 [8] were selected for U-Pb and K-Ar analysis.

The results of U-Th-Pb total rock and Pb acid leaching experiments are shown in the Table and Fig. 1,3, and 4. The data for breccias 14305, 14311, 14321, as well as earlier data [1] for 73235, 73275 and two fragments of 66075 yield a precise line intersecting the concordia curve at 4.47±0.03 AE and 3.86±0.05 AE. Most previously published highland rock data plot on or very close to this array. The cataclysm array includes the "early impactite" 79215 [5]. A lithic clast and the matrix from this breccia yield ideal ^{40}Ar-^{39}Ar plateaus at ages of 3.91 and 3.90 AE with an absolute uncertainty of ±0.03 AE (Fig. 2). All ages cited in this paper are calculated using newly recommended decay constants [9]. ^{40}Ar-^{39}Ar plateau ages for other individual breccias plotting on the U-Pb cataclysm array range from 3.84 to 3.92 AE and suggest a number of distinct events. This range in ages is in excellent agreement with the lower intersection of the U-Pb data array at 3.86±0.05 AE.

Fragments of breccia 66075 which form part of the terminal cataclysm array were leached with dilute HNO_3 in order to establish if a precise secondary age could be determined consistent with the lower intersection. The Pb data on acid soluble Pb and the leached residue, including a total rock data point [1], are shown in Fig.3. The data form a linear array with an intercept corresponding to a $^{207}Pb/^{206}Pb$ age of 3.83(+10,-5)AE. The array strongly suggests a 2-stage U-Pb system composed of an inherited Pb fraction evolved in the interval from ~ 4.47 to ~ 3.83 AE and a radiogenic component produced by in situ U decay since 3.83 AE. A K-Ar age is not available for comparison. This $^{207}Pb/^{206}Pb$ age is consistent with the time of U-Pb fractionation defined by the U-Pb total rock array and the K-Ar ages. We may generalize this to infer that Ar was nearly totally outgassed at the time of major U-Pb fractionation. The excellent agreement of these independent dating techniques on metamorphic rocks stresses the existence of a major lunar time marker discovered by Tera, Papanastassiou and Wasserburg which has previously been assigned to a terminal lunar bombardment of the moon [2] and which has been applied to the whole inner solar system.

The original U-Pb point of 67075(S) [4] plots in Fig. 1 far above the cataclysm array. ^{40}Ar-^{39}Ar measurements yielded ages of 3.98 AE [10] and 3.89

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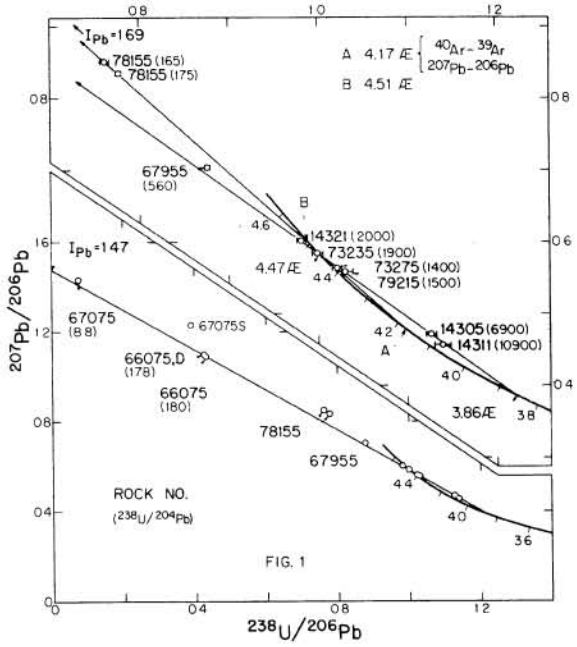

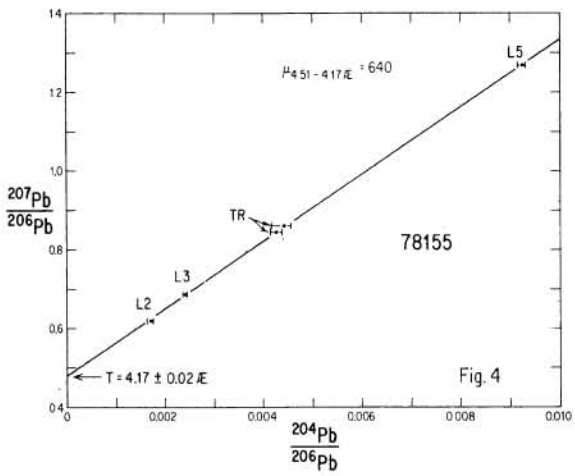

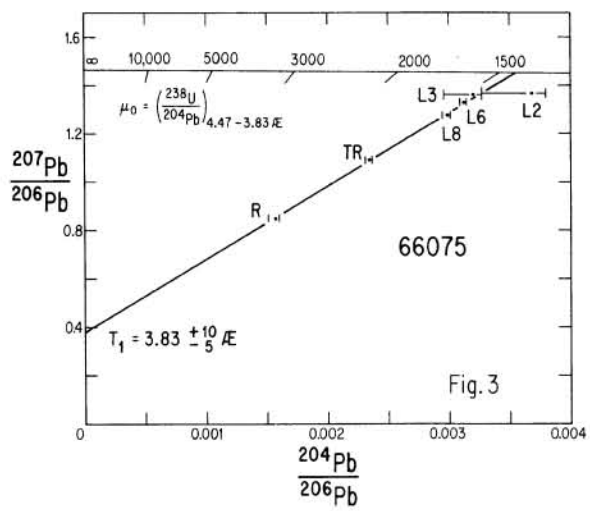

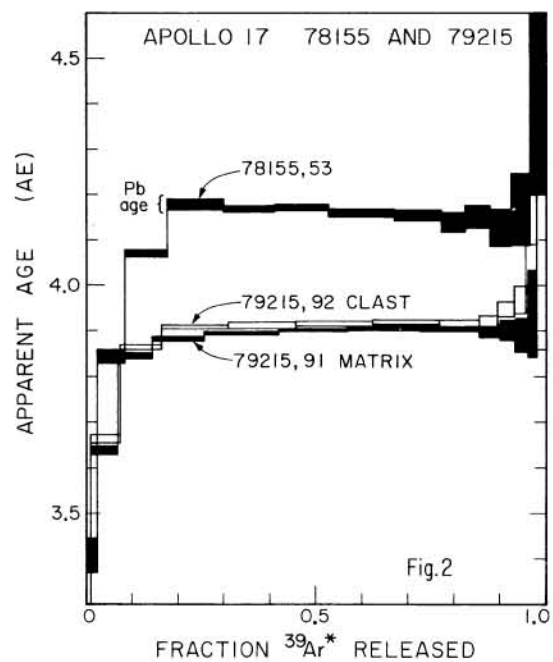

Fig.1 U-Pb evolution diagram for lunar highland breccias from the present work and [1]. The data are corrected for primordial Pb [12]. Error bars reflect overall uncertainty of $^{238}U/^{206}Pb$ ratios. Most points lie precisely on the cataclysm array intersecting the concordia curve at the primary age of 4.47±0.03 AE and the time of terminal cataclysm at ~3.86 AE. Line A-B joining 78155 with the concordant metamorphic age of 4.17 AE (Fig.2, 4) yields a similar primary age of 4.51±0.04 AE. Data point 67075S is from [4].

Fig.2 Apparent ages vs. ^{39}Ar release for breccias 78155 and 79215. The age spectra are ideal, rising rapidly from initially young ages to very well-defined age plateaus at 3.90 AE and 3.91 AE for 79215, 91 and 92 and 4.17 AE for 78155. The age of 78155 is in excellent agreement with the Pb age (Fig.4).

Fig.3 Internal isochron for breccia 66075, which is part of cataclysm array in Fig.1. The $^{207}Pb/^{206}Pb$ age of 3.83 AE is in good agreement with the age of lower intersection of the U-Pb data array. The isochron is based on acid leach fractions L6, L8, residue (R), and total rock (TR) [1]. Error bars show overall uncertainty of $^{204}Pb/^{206}Pb$ ratios. The age uncertainties reflect the most extreme lines through the data points.

Fig.4 Internal Pb isochron yielding a precataclysm age of 4.17±0.02 AE (2σ) for breccia 78155, which is not part of the cataclysm U-Pb array in Fig.1. The line is based on three acid leach fractions and two total rock points. This age is well corroborated by the K-Ar results (Fig.2).

AE [11], typical for members of the cataclysm array. Taken together these U-Pb and K-Ar results suggested a distinctive older primary age. The result of our new analysis plots only slightly above the cataclysm data array near the ordinate intercept and shows the earlier determination to be in error. The position of the new data point now appears compatible with the cataclysm array and with the ^{40}Ar-^{39}Ar ages and thus compatible with the primary age of 4.47 AE. The slight offset from the cataclysm line, also shown by 67955, is beyond error limits and implies minor variations in the times of U/Pb fractionation.

Earlier U-Pb data of breccia 78155 [6] plotted substantially above the cataclysm array. ^{40}Ar-^{39}Ar measurements yielded an age of 4.15±0.04 AE [7], distinctly older than 3.9 AE. These data prompted us to carry out extensive U-Pb studies and to confirm the Ar analysis. Again an almost perfect ^{40}Ar-^{39}Ar plateau was obtained corresponding to an age of 4.17±0.03 AE (Fig.2). U-Pb analyses on a lithic clast and on the friable matrix yielded two data points plotting close to each other (Fig.1) again above the cataclysm array, confirming the incompatibility of the data with this array. An acid leaching experiment analogous to 66075 was carried out. The Pb isotopic data of the analyzed fractions shown in Fig.4 yield a precise linear array with a $^{207}Pb/^{206}Pb$ age of 4.17±0.02 AE, in perfect agreement with the Ar data. This clearly demonstrates that the high K-Ar age of 4.17 AE cannot be ascribed to incomplete degassing of ^{40}Ar or to the presence of trapped ^{40}Ar. We note that this breccia is the only sample of the group of "early impactites" retaining isotopic evidence of a precataclysm history.

Taking the concordant K-Ar and Pb ages of 4.17 AE to indicate a time of major U/Pb fractionation (A) by (impact) metamorphism and using a 2-stage model to explain the U-Pb evolution of 78155, we obtain an upper intersection (B) corresponding to an age of 4.51±0.04 AE (Fig.1). This result is indistinguishable from the primary model age of 4.47±0.03 AE defined by the cataclysm array. We note that this is the first demonstration of a primary age consistent with the primary age of cataclysm U-Pb systematics obtained from a highland rock which is not part of the ~ 3.9 AE cataclysm breccia population. This coincidence of primary model ages by two distinctly different subsystems of a planetary crust is strongly suggestive of major lunar differentiation at 4.47-4.51AE.

Sample	Weight mg	Lunar Pb[a,b] ^{208}Pb	^{207}Pb	^{206}Pb	^{204}Pb	α[c]	^{204}Pb[a] blank	^{238}U[b] picomoles	^{232}Th[b] picomoles
Total Rock U-Th-Pb									
14305, 66	41.1	704.8	356.6	755.2	0.1227	5950	0.0161[d]	849.4	3133
14311, 72	39.9	1046.1	504.8	1104.2	0.1148	7516	0.0322	1257	-
14321, 161	23.5	492.3	317.2	524.8	0.2515	2018	0.0086	512.2	2017
67075, 34	101.4	26.91	37.38	26.56	0.2097	116.2	0.0227[e]	1.852	13.67
67955, 30	85.2	150.16	99.33	139.98	0.2221	585.2	0.0177	120.75	543.6
78155, 55[f]	33.3	48.61	42.51	49.36	0.2181	212.0	0.0163	35.96	136.4
78155, 55[g]	80.2	109.2	94.37	111.60	0.4760	224.5	0.0233	83.25	312.8
79215, 91	90.3	146.06	117.63	209.20	0.1413	1358	0.0129[d]	214.1	559.0
Acid Leaching Experiments									
66075, 11	529.2 mg							Yield[h] % ^{206}Pb	
L1: H_2O,cold		0.0605	0.1142	0.0788	0.0	31.9	0.00630[j]	0.003	
		0.1217	0.1392	0.1095	0.00159	31.9	0.00471	0.005	
L2: 0.01M HNO_3,cold		13.93	19.16	14.03	0.0515	245.9	0.0060	0.6	
L3: 0.05M HNO_3,cold		25.57	35.19	25.88	0.0827	291.0	0.0067	1.1	
L6: 1.0M HNO_3,cold		197.90	268.6	202.4	0.6333	316.4	0.0069	8.9	
L8: 2.0M HNO_3,hot		281.5	352.0	276.1	0.8272	328.3	0.0148[e]	12.2	
Residue		743.5	746.2	879.6	1.395	614.5	0.0380[i]	38.8	
78155, 55	614.2 mg								
L1: 0.05M HNO_3,cold		15.782	5.995	9.644	0.0186	410.1	0.00514	1.1	
L2: 0.2M HNO_3,cold		109.54	38.49	62.10	0.1066	556.5	0.00514	7.3	
L3: 1.0M HNO_3,cold		149.22	63.37	92.12	0.2226	404.9	0.00514	10.8	
L5: 2.0M HNO_3,hot		103.92	126.57	99.73	0.9225	107.4	0.0076[e]	11.7	

a) Picomoles. b) Corrected for blank with α = 19.36-19.73, β = 15.77-16.15, and γ = 38.59-39.13; ^{238}U: 0.083 pm; ^{232}Th = 0.025 pm. c) Corrected for spike cross contamination only. d) Estimated blanks; total procedure blanks were measured for each of the other analyses. e) Measured blanks adjusted for low Pb yields (yields: 67075, 66%; 66075,L8, 47%; 78155,L5, 55%. f) Coherent breccia component. g) Friable component. h) Pb yields in acid leaches given relative to total rock ^{206}Pb concentrations in 66075,11 [1] and 78155,55g. i) Blank for total residue; blank in 47% aliquot is 0.0180 pm ^{204}Pb. j) ^{204}Pb all blank.

REF.: 1.Lunar Sci. IX (1978)832; 2. EPSL 22(1974)1; 3. Proc.5th(1974)1571; 4.Lunar Sci.IV (1973)672; 5.Proc. 8th(1977)2051; 6. Proc.6th(1975)1431; 7.Proc.6th(1975) 1509; 8.Lunar Sci. IX(1978)720; 9. EPSL 36(1977)359; 10.Proc.4th(1973) 1889; 11.Lunar Sci. VIII(1977)481; 12. Science 180(1973) 1279. Ack: Work supported by NASA under grant NGL 05-002-188.