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^{40}Ar–^{39}Ar DATING OF LUNA 16 AND LUNA 20 SAMPLES

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Two fragments of Luna 16 mare basalt and two Luna 20 samples (one metaclastic fragment and a group of five anorthositic particles) from the Royal Society allocation have been dated by using the ^{40}Ar–^{39}Ar technique. The results of this work effectively double the chronological information available concerning these sites. The Luna 16 ages confirm that mare lavas were extruded in Mare Fecunditatis 3.4–3.5 Ga ago. Similarly, the age of the Luna 20 metaclastic fragment provides further support for a 3.9 Ga age for the Crisium basin and for the widespread cataclysmic bombardment of the moon between 4.05 and 3.85 Ga.

The presence of at least two isotopically distinct, non-radiogenic argon components in the Luna 20 anorthositic sample compromises an unequivocal age assignment but the simplest model leads to a plateau age of 4.40 ± 0.10 Ga and a minimum age of 4.30 ± 0.10 Ga.

There are now several lunar highland samples which are significantly older than 4.0 Ga and which give rise to a secondary age grouping in the interval 4.2–4.3 Ga. Depending on whether highland ages were primarily reset during the excavation of a large number of medium-sized craters or a small number of large basins, this secondary grouping implies either a significant peak in the cratering rate at 4.0 Ga or statistical fluctuations in a monotonically decreasing cratering rate.

INTRODUCTION

The combined analysis of a single basalt pebble from the Luna 16 landing site by the ^{40}Ar–^{39}Ar technique and by the Rb–Sr internal isochron method presently provides the only chronological clue to the ages of extrusion of basaltic lava flows in Mare Fecunditatis (Huneke, Podosek & Wasserberg 1972; Papanastassiou & Wasserburg 1972*a*). The ages calculated by the two methods, 3.45 ± 0.04 Ga and 3.42 ± 0.18 Ga respectively, fall between the ages of the young basalts from Mare Imbrium and Oceanus Procellarum (3.15–3.35 Ga) and the older titanium-rich basalts returned by Apollos 11 and 17 (3.6–3.9 Ga).

The Luna 20 mission returned highland materials from a region on the Moon far removed from the Imbrium and Orientale basins. The returned samples are therefore, of all lunar samples, probably the least contaminated with ejecta from these basins and most likely to contain pre-Imbrian crustal material. The proximity of the site of the Crisium and Fecunditatis basins, however, makes it probable that the chronology of Luna 20 materials will be dominated by events forming one or both of these basins.

The earliest, and only precise, measurements of Luna 20 rocks by Podosek, Huneke, Gancarz & Wasserburg (1973) were of two highly recrystallized polymict noritic breccias with relatively high potassium contents (0.12 and 0.18 %). Both samples gave well defined and identical ages of 3.90 ± 0.04 Ga. Podosek *et al.* noted the similarity of this age to those determined at all Apollo highland sites and considered a number of possible interpretations including the suggestion that they may be representative of either the Imbrium or Crisium basin forming events.

The analysis of a single 8.7 mg fragment of glassy and friable feldspar L2015, 3, 1 has been reported previously (Turner, Cadogan & Yonge 1973). The sample was an extremely unfavourable one for dating, containing only 50 p.p.m. K. An imprecise age of 4.0 ± 0.3 Ga was determined, the uncertainties arising from the small amount of sample gas and the large Ca and trapped ^{40}Ar corrections. Although this age is similar to those of other highland samples, including the potassium-rich metaclastic rocks from the Luna 20 site, it is far too imprecise to enable us to support or refute the possible age of 3.90 Ga for the Crisium basin. In this work the analysis of five small Luna 16 basalt fragments (L1627, 3, 2) five Luna 20 metaclastic fragments (L2015, 3, 10 and L2015, 3, 11D) and a group of five anorthositic fragments (L2015, 3, 6) was undertaken to investigate further the chronologies of the two landing sites. The samples were selected from the Luna 16 and 20 allocations to the Royal Society by Dr S. O. Agrell at the University of Bristol.

EXPERIMENTAL METHODS

The Luna 20 anorthositic sample consisted of five fragments (total weight 7.7 mg) of microcrystalline plagioclase from L2015, 3, 6, a 14.3 mg hand-picked fraction. Fragment L2015, 3, 6, 1 appears under binocular examination to be representative of this group of fragments and has been described in Eglinton *et al.* (1974). The particles appear to have been derived from an anorthositic source. The sample was packaged in 0.4 μm thick aluminium foil and vacuum encapsulated in a quartz tube before being irradiated with fast neutrons in the Herald reactor at Aldermaston. Also included in this irradiation, designated SH 31, were evacuated quartz tubes containing four samples of our hornblende monitor (Hb3gr). Argon analyses from the monitors enabled a mean J-value of 0.1295 to be calculated (table 1). The threefold higher potassium content of L2015, 3, 6 (180 p.p.m.) compared to L2015, 3, 1 (Turner *et al.* 1973), enabled gas extraction to be carried out in 12 heating steps.

TABLE 1. SH31 HORNBLENDE MONITORS

sample mass/g	^{40}Ar/^{39}Ar	^{37}Ar/^{39}Ar	J†	α‡
0.0168	5.83	2.93	0.1297 ± 0.0005	0.52
0.0171	5.85	2.89	0.1293 ± 0.0007	0.51
0.0219	5.86	2.87	0.1292 ± 0.0006	0.51
0.0201	5.83	2.97	0.1299 ± 0.0005	0.53

† $J = (\exp(\lambda T) - 1)/(^{40}\mathrm{Ar}/^{39}\mathrm{Ar})$, $T = (1.062 \pm 0.020\ \mathrm{Ga})$, $\lambda = 5.305 \times 10^{-10}\ \mathrm{a}^{-1}$
$\lambda_e = 0.585 \times 10^{-10}\ \mathrm{a}^{-1}$, $^{40}\mathrm{K/K} = 0.000119$.
‡ $\alpha = (\mathrm{K/Ca})/(^{39}\mathrm{Ar}/^{37}\mathrm{Ar})$.

The Luna 20 metaclastic fragments and the Luna 16 basalt samples were cleaned of adhering dust by ultrasonic washing with acetone before being packaged individually in aluminium foil and encapsulated in a single evacuated quartz tube together with three samples of our terrestrial hornblende monitor, Hb3gr. The monitor results from this high fluence neutron irradiation (2×10^{19} neutrons cm^{-2}, designated SH34) yielded a mean J-value of 0.1549 ± 0.0010. After the irradiation the samples were repackaged in unirradiated aluminium foil before argon analysis. Of the samples analysed, only the largest single Luna 20 fragment (L2015, 3, 11D) and the two largest Luna 16 basalts contained sufficient ^{39}Ar for accurate measurements of ^{40}Ar/^{39}Ar ratios to be achieved and were sufficiently free of 'trapped' ^{40}Ar to enable meaningful ages to be obtained. Only the results from these three samples from irradiation SH34 will be reported here; one of the Luna 16 'basalts' was in fact a dark glass containing large quantities of trapped argon.

L2015, 3, 11D was a fine grained noritic metaclastic rock with minipoikilitic texture. It was similar in texture and composition to numerous Apollo 16 and 17 highland soil fragments which have been variously described as impact melts or recrystallized breccias. Electron microprobe analysis was carried out by Dr S. O. Agrell at the University of Cambridge and revealed the following major element composition: SiO_2 46.6 %, Al_2O_3 22.2 %, FeO 8.5 %, MgO 10.5 %, CaO 11.3 %.

Argon isotope ratios were corrected for interferences in the following sequence.

(1) Radioactive decay of ^{37}Ar ($\lambda_{37} = 0.01975 \pm 0.0010$ d^{-1}) and ^{39}Ar ($\lambda_{39} = 7.2 \times 10^{-6}$ d^{-1}) during and since the irradiation.

(2) Minor products of neutron reactions on potassium and calcium. Corrections employed were $(40/39)_K = 0.012$, $(38/39)_K = 0.011 \pm 0.001$; $(36/37)_{Ca} = 0.000272 \pm 0.000008$, $(38/37)_{Ca} = 0.000077 \pm 0.000010$ $(39/37)_{Ca} = 0.000671 \pm 0.000010$, $(40/37)_{Ca} = 0.0003 \pm 0.0003$.

(3) Previously determined atmospheric argon furnace blanks. These ranged from 10^{-9} cm^3 s.t.p. at 530 °C to 5×10^{-9} cm^3 s.t.p. at 1400 °C and were assigned uncertainties of ± 50 %.

Results and discussion

The argon isotope ratios and concentrations of ^{39}Ar from all samples discussed in this paper are given in tables 2 and 3 and in graphical form in figures 1, 2 and 3. In the case of the Luna 16 samples and the Luna 20 norite fragment the ^{40}Ar–^{39}Ar ages have been corrected for trapped ^{40}Ar on the basis of correlation plots of (^{36}Ar$_t$/^{40}Ar) against (^{39}Ar/^{40}Ar). In the case of the larger Luna 16 fragment this trapped correction corresponded to apparent age corrections of 0.06 Ga or less in all extractions. The calculated (^{36}Ar$_t$/^{40}Ar) ratio, 0.1 ± 0.1, was unusually low but should be viewed with caution in view of the relatively small amounts of trapped argon present. Corrections for cosmogenic ^{38}Ar and ^{36}Ar have been applied on the basis of the (^{36}Ar/^{38}Ar) ratios, assuming binary mixtures of cosmogenic argon, $(^{36}\mathrm{Ar}/^{38}\mathrm{Ar})_c = 0.63$ and trapped argon, $(^{36}\mathrm{Ar}/^{38}\mathrm{Ar}_t) = 5.35$. In figure 1 (^{38}Ar$_c$/^{37}Ar) ratios are plotted against fractions of ^{37}Ar released and in each case the onset of the apparent age plateau is indicated by means of arrows. Nominal exposure ages are based on a ^{38}Ar production rate of 1.4×10^{-8} cm^3 s.t.p. per g Ca per Ma.

Luna 16 *basalts*

The larger Luna 16 basalt fragment contained very little trapped ^{40}Ar and yielded a well-defined and precise plateau age of 3.50 ± 0.06 Ga which covered more than 76 % of the release of ^{39}Ar and 96 % of the ^{37}Ar release. The potassium-rich sites had apparently suffered appreciable argon loss. The apparent age plateau is paralleled by a relatively constant (^{38}Ar$_c$/^{37}Ar) ratio which corresponds to a nominal exposure age of 1000 Ma.

The ^{40}Ar/^{39}Ar release pattern from the smaller basalt fragment was dominated by argon release from potassium-rich sites, contained considerable trapped argon and was therefore relatively imprecise. The first two extractions accounted for 50 % of the ^{39}Ar release but only 6 % of the ^{37}Ar release. That recent gas loss from these sites has occurred is strongly suggested by the low (^{38}Ar$_c$/^{37}Ar) ratios in these first two extractions. The third and fourth extractions

TABLE 2. ARGON RELEASE PATTERNS FROM TWO LUNA 16 BASALTS AND ONE LUNA 20 METACLASTIC FRAGMENT

temp/°C	36/38	38/37	39/37	40/39	39	apparent age/Ga	(with cosmogenic and trapped corrections)
L1627, 3, 2 (basalt fragment 0.002 g; $(40/36)_t$ = 0.1±0.1)							
500	3.82±0.33	0.047±0.007	0.204±0.028	21.0±3.6	9	2.73±0.25	(2.72±0.25)
700	5.09±0.10	0.257±0.016	0.238±0.015	24.9±1.1	37	2.98±0.07	(2.95±0.07)
900	4.54±0.02	0.117±0.002	0.0427±0.0009	36.9±0.6	79	3.59±0.03	(3.53±0.06)
1050	3.29±0.04	0.0555±0.0012	0.0279±0.0007	35.2±1.3	36	3.51±0.06	(3.48±0.06)
1200	1.76±0.02	0.0287±0.0005	0.0149±0.0003	35.4±1.3	34	3.53±0.06	(3.50±0.06)
total	3.9	0.070	0.035	33.3	194	3.43	
L1627, 3, 2 (basalt fragment 0.0007 g; $(40/36)_t$ = 0.8±0.4)							
500	2.48±0.81	0.030±0.009	0.162±0.018	31.8±4.7	19	3.34±0.23	(3.34±0.23)
700	4.34±0.14	0.145±0.039	0.313±0.084	16.4±1.5	62	2.38±0.12	(3.23±0.14)
900	3.59±0.04	0.088±0.003	0.0392±0.0017	38.0±2.2	59	3.64±0.09	(3.36±0.17)
1050	1.97±0.05	0.052±0.003	0.0183±0.0017	33.9±7.4	21	3.46±0.34	(3.28±0.36)
1150	0.84±0.02	0.0382±0.0011	0.0031±0.0003	n.d.†	6	n.d.	
1350	0.95±0.19	0.0356±0.0017	0.010±0.004	n.d.	2	n.d.	
total	2.70	0.061	0.034	29.0	166	3.21	
L2015, 3, 11D (metaclastic fragment, 0.0049 g; $(40/36)_t$ = 0.75±0.75)							
500	3.30±0.32	0.058±0.007	0.076±0.018	72.0±18.0	2	4.7±0.4	
700	5.37±0.11	0.124±0.011	0.110±0.010	60.6±2.5	7	4.41±0.07	
900	4.37±0.01	0.114±0.002	0.0478±0.009	60.1±0.5	45	4.40±0.01	(4.13±0.27)
1000	3.04±0.02	0.0263±0.0005	0.0231±0.0004	46.4±0.6	34	3.96±0.02	(3.88±0.09)
1050	2.48±0.01	0.0217±0.0004	0.0195±0.0004	46.7±0.6	39	3.98±0.02	(3.91±0.06)
1150	3.51±0.04	0.0372±0.0008	0.0212±0.0005	52.0±2.7	12	4.15±0.09	(4.01±0.17)
1350	1.45±0.03	0.0174±0.0005	0.0108±0.0003	46.3±4.3	11	3.96±0.15	(3.91±0.16)
1500	1.13±0.11	0.0155±0.0005	0.0160±0.0007	n.d.	7	n.d.	
total	3.77	0.039	0.025	52.0	149	4.15	

† n.d., not determined.

TABLE 3. ARGON RELEASE PATTERN FROM L2015, 3, 6

temp./°C	36/38	38/37	38_c†/37	39/37	40/39	39‡
430	3.9±0.5	0.052±8	0.016±10	n.d.§	n.d.	n.d.
530	4.8±0.4	0.104±9	0.011±10	n.d.	n.d.	0.1
630	5.4±0.2	0.159±7	n.d.	0.012±4	386±123	0.5
720	5.18±0.02	0.164±2	n.d.	0.0050±8	465±74	0.9
800	4.86±0.03	0.123±1	0.013±1	0.0037±3	279±23	2.0
900	3.65±0.03	0.0323±4	0.0117±2	0.0035±1	99.3±4.7	2.8
990	2.88±0.02	0.0256±3	0.0135±1	0.0032±1	87.0±3.9	4.5
1080	2.66±0.03	0.0240±3	0.0137±1	0.0033±2	86.5±7.1	2.9
1170	1.43±0.01	0.0185±2	0.0154±2	0.0025±1	80.2±5.2	2.8
1240	0.67±0.03	0.0201±5	0.0200±5	0.0009±6	196±139	0.3
1340	0.71±0.03	0.0187±4	0.0185±4	0.0028±11	106±54	0.6
1450	0.49±0.23	0.0176±15	0.0176±15	n.d.	n.d.	0.1
total	3.67	0.039	0.014	0.0031	139	17.6

† (^{38}Ar$_c$/^{37}Ar) was calculated assuming that ^{38}Ar originates from cosmogenic argon. (^{36}Ar/^{38}Ar)$_c$ = 0.63 and trapped argon (^{36}Ar/^{38}Ar)$_t$ = 5.25.

‡ Amounts in units of 10^{-8} cm s.t.p. per g.

§ n.d., Gas quantities too low for accurate isotope ratio determination.

accounted for nearly 60 % of the ^{37}Ar release and yielded apparent ages which were similar within the large analytical uncertainties (3.35 ± 0.15) Ga. The final three extractions yielded a (^{38}Ar$_c$/^{37}Ar) 'plateau' which corresponds to a nominal exposure age for this fragment of 1600 Ma. The high apparent ^{40}Ar/^{39}Ar age in the first extraction cannot be due to trapped ^{40}Ar because of the high ^{40}Ar/^{36}Ar ratio, but may be due to atmospheric argon which was adsorbed onto the sample. Although the age is imprecise it is consistent with that obtained from the larger fragment.

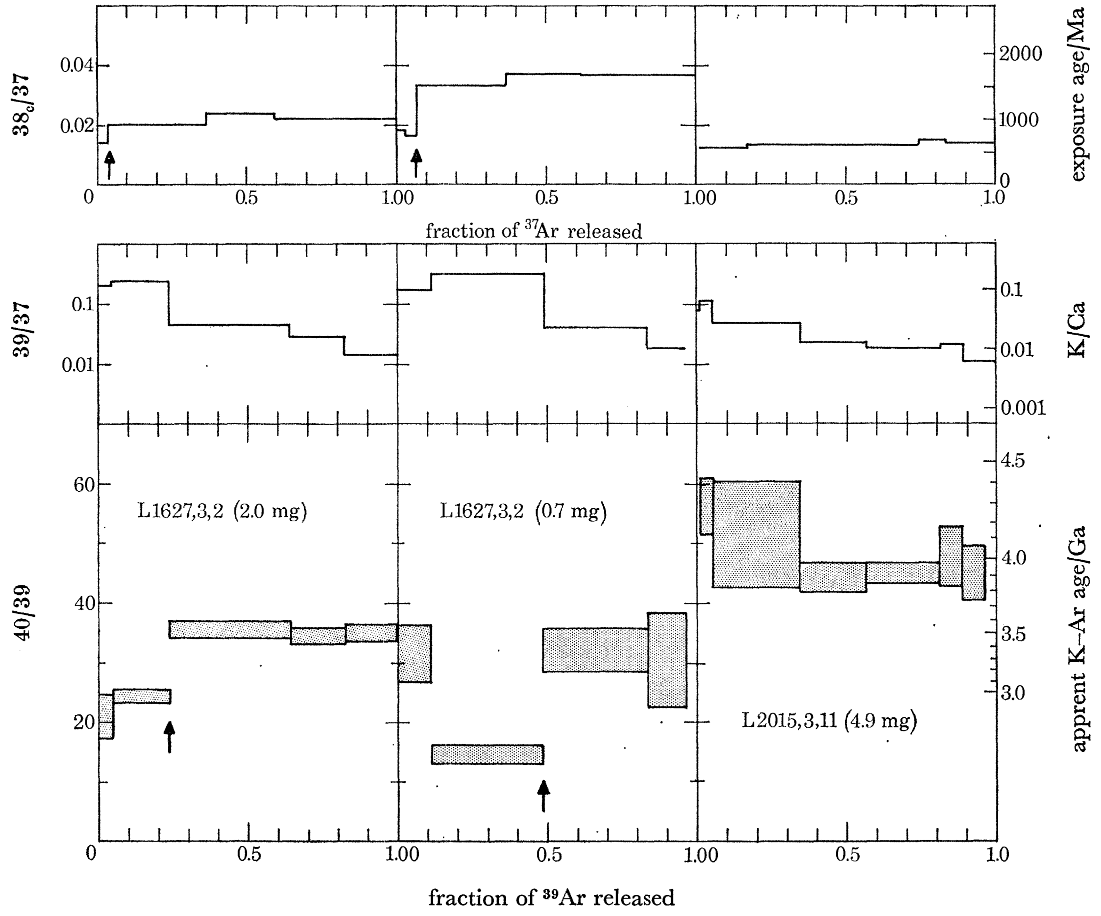

Figure 1. Argon release patterns from two Luna 16 basalts and one Luna 20 metaclastic fragment. The ages are corrected for trapped ^{40}Ar on the basis of correlation plots. The arrows indicate the onsets of the ^{40}Ar/^{39}Ar plateaux.

These results confirm that igneous activity occurred in Mare Fecunditatis between 3.5 and 3.4 Ga ago. The ages of the Luna 16 basalts help to fill the hiatus which separates the old, titanium-rich basalts in Mare Tranquillitatis and Mare Serenitatis (3.6–3.9 Ga) from those in the Western maria, Mare Imbrium and Oceanus Procellarum (3.15–3.35 Ga). They do not however support a smooth decrease in mare ages across the visible lunar hemisphere from east to west. As yet there is no evidence for an extended period of basaltic lava extrusion in Mare Fecunditatis.

Luna 20 *metaclastic fragment*

After applying the correction for trapped ^{40}Ar, the ^{40}Ar/^{39}Ar release pattern from L2015, 3, 11D yielded a plateau corresponding to a gas retention age of 3.90 ± 0.10 Ga in good agreement (within the experimental uncertainties) with the ages determined for two other metaclastic fragments from the Luna 20 mission, 22006 and 22007 (Podosek *et al.* 1973). Sample L2015, 3, 11D yielded argon from sites with similar K/Ca ratios to 22006 and 22007, its total potassium content was very similar (0.14 %) and it also had an unusually high exposure age (600 Ma). Very high exposure ages for soil fragments are common at both the Luna sites and might imply that the regolith at these two locations is unusually thin. The corrections for trapped ^{40}Ar were greatest for the third extraction from which the apparent age was reduced by (0.3 ± 0.3) Ga. The fourth and fifth extraction contained the least trapped ^{40}Ar and, for these the reduction in apparent age were only (0.10 ± 0.10) Ga. The 3.90 Ga plateau age provides further support for a 3.90 Ga age for the Crisium basin and for the intense bombardment of the moon at around 4.0 Ga.

Luna 20 *anorthositic fragments*

Although the interpretation of the results from the Luna 20 anorthositic fragments is not, in the first instance, limited by analytical precision, there remains the problem of trapped ^{40}Ar. Its existence is necessary to account for the impossibly high apparent ages based on the uncorrected (^{40}Ar/^{39}Ar) ratios. These ages define an upper limit to the argon release pattern in the conventional plot (figure 2).

In an attempt to correct for trapped ^{40}Ar, the results have been plotted on a three isotope correlation diagram of (^{36}Ar$_t$/^{40}Ar) against (^{39}Ar/^{40}Ar) in figure 3. The *measured* (^{36}Ar/^{40}Ar) ratios are indicated by solid circles. The open circles represent the (^{36}Ar/^{40}Ar) ratios after correction for cosmogenic ^{36}Ar. It is assumed that cosmogenic ^{40}Ar is negligible in samples of anorthositic composition, due to their low Fe and Ti contents. On this diagram, pure trapped argon would plot on the axis $(^{39}\text{Ar}/^{40}\text{Ar}) = 0$, whereas pure potassium derived argon would plot on the axis $(^{36}\text{Ar}/^{40}\text{Ar}) = 0$. As the experimental points are not all co-linear the gas fractions must be complex mixtures of at least three end members. A minimum of one radiogenic argon component and two isotopically distinct trapped components (one with a (^{36}Ar/^{40}Ar) ratio $\leqslant 0.1$) are required to explain the data. This can be seen most clearly in the conventional argon release diagram shown in figure 2. The $(^{40}\text{Ar}/^{36}\text{Ar})_t$ ratio required to account for *all* of the ^{40}Ar in the 800 °C extraction is 1.8. But this value is still too low to make the apparent ages from lower temperature fractions less than the generally accepted age for the solar system. Despite this necessary existence of at least two trapped components, however, several important statements about the chronology of L2015, 3, 6 may be made.

The four high-temperature (900–1170 °C) extractions account for 77 % of the total ^{39}Ar released (figure 2). Within analytical uncertainty the points corresponding to these gas fractions are co-linear on the isotope correlation diagram (figure 3) and thus, after correction for trapped argon, can define a plateau on the conventional plot. If a simple binary mixture is responsible for this correlation, the two end members must be a trapped argon component with $(^{40}\text{Ar}/^{36}\text{Ar})_t = 0.8 \pm 0.2$ and a single potassium derived component corresponding to a K–Ar gas retention age of (4.4 ± 0.1) Ga.

It is possible that the co-linearity of these four points is fortuitous. In this case, the next most simple assumption is that the 800–1170 °C fractions contain a single trapped component but

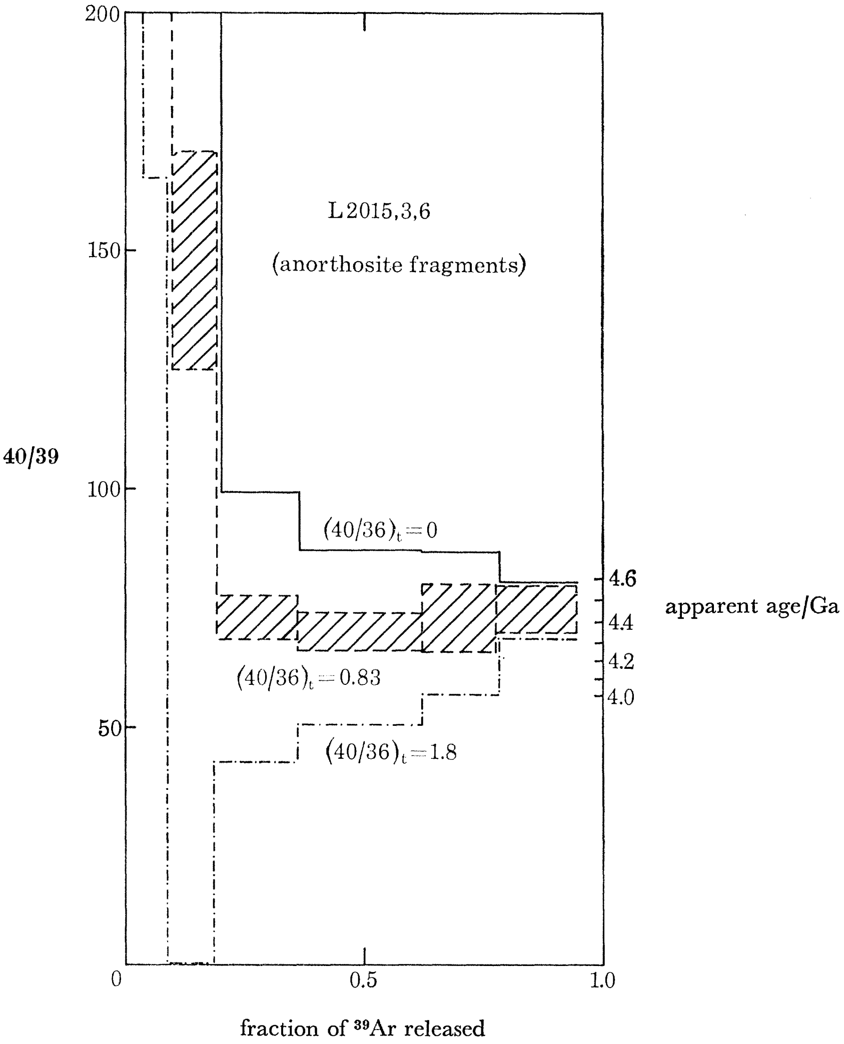

FIGURE 2. ^{40}Ar/^{39}Ar release patterns from L2015, 3, 6. A 'best plateau' age of 4.4 ± 0.1 Ga and a 'minimum' age of 4.3 ± 0.1 Ga are based on the assumption that the high temperature extractions only contain one trapped argon component. The upper limit to the release patterns results from ignoring the non-radiogenic ^{40}Ar component(s).

have variable (^{39}Ar/^{40}Ar) ratios as a result of natural losses of radiogenic argon. In this model a *lower limit* for the apparent age associated with each of these heating steps can be calculated on the basis of the (^{36}Ar/^{40}Ar)$_t$ ratio (0.56) required to account for *all* of the ^{40}Ar in the 800 °C extraction. It is interesting to note that this value is similar to the high temperature trapped ratio in Luna 20 metaclastic fragment 22007 (0.47 ± 0.05, Podosek *et al.* 1973). This *minimum* release pattern is also shown in figure 2. Even in this extreme case however, the apparent age for the 1170 °C extraction is still (4.3 ± 0.1) Ga. The only way by which this age can be further reduced is for the (^{36}Ar/^{40}Ar) ratio in the trapped component to decrease again at high temperatures. The apparent age can only be reduced to 4.0 Ga if the (^{36}Ar/^{40}Ar)$_t$ ratio falls to (0.27 ± 0.04). No evidence for a decrease in this trapped ratio at high temperatures was found from other Luna 20 soil samples which were analysed in a similar manner (Podosek *et al.* 1973). It is therefore difficult to avoid the conclusion that L2015, 3, 6 has a *minimum* age of (4.3 ± 0.1) Ga.

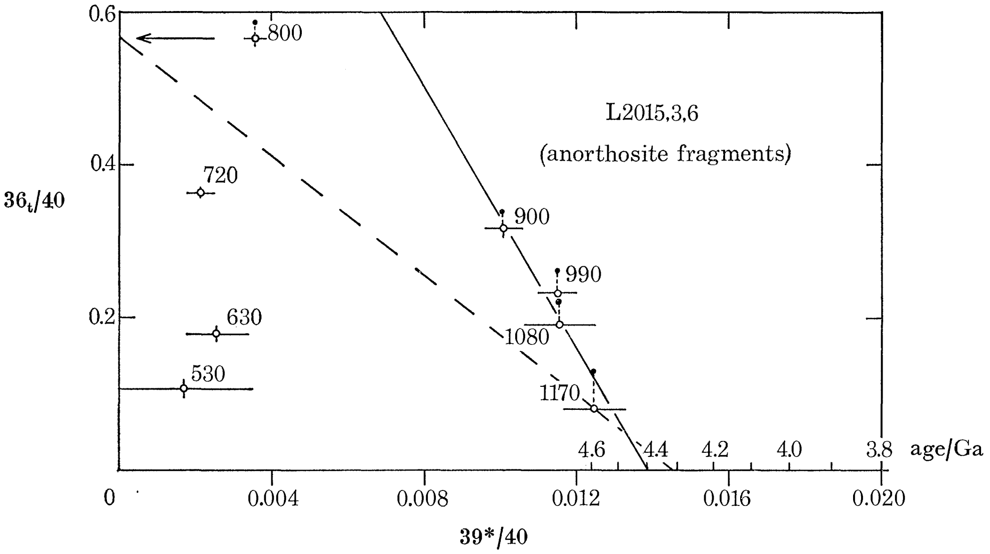

FIGURE 3. Three isotope correlation plot (^{36}Ar/^{40}Ar) against (^{39}Ar/^{40}Ar), lunar sample L2015, 3, 6. The extraction temperature is indicated in °C. The solid black circles indicate the (^{36}Ar/^{40}Ar) ratio before applying the correction for cosmogenic ^{36}Ar. Because the samples are anorthositic, cosmogenic ^{40}Ar is assumed to be negligible. The low temperature points indicate unambiguously that the (^{36}Ar/^{40}Ar) ratio of trapped gas increases with increasing extraction temperature to 800 °C. The four high temperature extractions represent 80 % of the radiogenic argon release and, on the assumption that they are a binary mixture of trapped and radiogenic argon of fixed composition, indicate a K–Ar age of 4.4 ± 0.1 Ga (solid mixing line). The somewhat weaker assumption that the trapped $(^{40}\text{Ar}/^{36}\text{Ar})_t$ ratio for the high temperature points is greater than or equal to that of the 800 °C extraction implies that the apparent age for the final extraction is not less than 4.3 ± 0.1 Ga (dashed line shows limiting case).

It is important to note that the uncertainty quoted here is a measure of analytical precision; the age value is model dependent. More accurate isotope ratio measurements would not only have decreased this analytical uncertainty but would also have enabled the choice of model to be made with greater confidence. This age is considerably greater than the age proposed for the Crisium basin of 3.90 Ga (Podosek *et al.* 1973) and suggests the presence of the Luna 20 site of anorthositic crust which was unaffected by this impact event. It should of course be stressed that these measurements were carried out on a mixture of anorthositic fragments with presumably different histories.

At temperatures ⩾ 800 °C the (^{39}Ar/^{37}Ar) ratios are relatively constant and correspond to a K/Ca ratio of 0.0017. As the sample contains 180 p.p.m. potassium this result is consistent with its anorthositic mineralogy. This potassium content is an order of magnitude lower than that of the samples analysed by Podosek *et al.* and the rock types are thus chemically quite distinct. The higher (^{39}Ar/^{37}Ar) ratios in the low temperature (630, 720 °C) extractions indicate the existence of low retentivity, potassium-rich sites which frequently occur in lunar rocks. It is these extractions which must contain an additional trapped argon component, which could conceivably be pure ^{40}Ar. This excess low-temperature argon corresponds to 14 % of the total ^{37}Ar released, compared to 20 % of the total ^{39}Ar. Calcium is presumably distributed relatively uniformly through the sample and therefore the low temperature trapped component is restricted to 14 % of the sample by volume. If this trapped component is surface concentrated, as suggested by its preferential release at low temperatures, this volume corresponds to a surface film 23 μm thick in particles *ca.* 1 mm in diameter.

The cosmogenic (^{38}Ar/^{37}Ar) ratio in L2015, 3, 6 shows variations which reflect the different exposure histories of the various fragments. The variations correspond to exposure ages in the range 400–700 Ma.

Ancient highland ages

Although the majority of dated rocks from the lunar highlands have ages in the range 3.85–4.05 Ga, several Apollo 16 and 17 samples have yielded ^{40}Ar–^{39}Ar ages as high as 4.3 Ga. These samples include: Apollo 16 coarse fines (Schaeffer & Husain 1973; Eberhardt *et al.* 1976), Apollo 17 coarse fines (Kirsten & Horn 1974), a cataclastic anorthosite, 60025 (4.19 ± 0.06 Ga), (Schaeffer & Husain 1974), clasts from the Apollo 17 consortium breccia 73215 (Jessberger, Kirsten & Staudacher, 1976) and a crushed anorthositic gabbro from the Sculptured Hills, 78155 (4.22 ± 0.04 Ga) (Turner & Cadogan 1975). A troctolite from Apollo 17, 76535, yielded a K–Ar age of 4.34 Ga (Bogard *et al.* 1974) and ^{40}Ar–^{39}Ar ages of 4.28 and 4.23 Ga (cited by Husain & Schaeffer 1975; Huneke & Wasserburg 1975). Samples have also been found which were involved in reheating episode(s) around 4.0 Ga which retained evidence of an earlier existence. This evidence is in the form of incomplete strontium isotope homogenization and high ^{40}Ar–^{39}Ar ages in the high-temperature gas release (Jessberger *et al.* 1974, 1976; Papanastassiou & Wasserburg 1972*b*; 76315, Turner & Cadogan 1975). Rb–Sr systematics of Apollo 12 breccia 12013 also showed incomplete homogenization at 4.0 Ga of a 'granitic' component originally formed about 4.5 Ga ago. An Rb–Sr mineral isochron from a dunite, 72417, yielded an age of 4.55 ± 0.10 Ga (Papanastassiou & Wasserburg 1975). To this list must now be added the anorthositic material from Luna 20 which is reported herein.

The interpretation of lunar highland ages, in all but the most general terms, poses a severe problem. It is usually assumed, with some justification, that the ages represent the effects of major argon loss during high-energy impact events and therefore provide an indication of the times of these impacts. Difficulties arise when attempts are made to determine which events have been responsible for argon loss in specific samples or groups of samples, and two simplifying but extreme assumptions have been made.

Several authors (see for example Turner *et al.* 1971, 1973; Jessberger, Kirsten & Staudacher 1974; Schaeffer & Husain 1974) have made the assumption that, to a first order, the age distribution of the rocks, at the sites sampled, is dominated by a relatively small number of major basin forming events, specifically the impacts which produced the Imbrium, Serenitatis and Nectaris basins, and, at the Luna 20 site, the Crisium basin. The justification for this assumption is to be found in the proximity of most of the landing sites to one or more of the impact basins and in the extent to which the local geological features are the direct result of the basin forming events.

A consideration of the observed distribution of ages, subject to the above assumption, has led to the hypothesis (Turner *et al.* 1973; Jessberger *et al.* 1974) that several basins (Orientale, Imbrium, Crisium and Serenitatis) were found in the restricted interval between 4.05 and 3.85 Ga. On stratigraphic grounds it is further argued that the Humorum and Nectaris basins were also formed in this interval. Schaeffer & Husain (1974) arrive at a somewhat different assignment of ages and regard the older basins (Nectaris and Serenitatis) as being formed prior to 4.2 Ga. The implications of the more restricted 4.05–3.85 Ga time scale is that at least six major asteroidal-sized objects collided with the Moon in a very narrow time interval of 0.2 Ga while in the succeeding 3.85 Ga no further major collisions occurred. Tera, Papanastassiou & Wasserburg (1974) infer the existence of a widespread lunar event, or events, at 3.9–4.0 Ga on the basis of Pb-U-Th isotope data. They have referred to it as the lunar cataclysm, or, more cautiously, the terminal lunar cataclysm.

An alternative interpretation of the lunar cataclysm (by which is implied the clustering of ages around 4.0 Ga) regards the age distribution as reflecting the effects of the large number of impacts which produced the medium-sized highland craters and erased the evidence of older events (Kirsten & Horn 1974). In this view it is not possible to assign sample ages to specific events. The distribution of ages must therefore be interpreted in a statistical way and can for example be used to infer a crater-production-rate half-life of around 170 Ma (Neukum, Konig, Storzer & Fechtig 1974). Arguments, which the present authors tend to accept, *against* such an interpretation relate to the non-random nature of the sampling of the lunar surface, which, as stated earlier, has been biased towards sites dominated by proximity to the major basins. At the Apollo 17 site, for example, half of the ages relate to samples from Massif boulders and many yield indistinguishable ages. It is conceivable that they date a *single* large geological unit at the Apollo 17 site, in which case it is clearly inadmissable to assume random sampling of many events. Nevertheless a small number of samples have been dated (60015 Schaeffer & Husain 1974; Apollo 16 coarse fines Eberhardt *et al.* 1976) which have well defined ages younger than the oldest mare basalts, implying that they were completely outgassed in recent, and therefore relatively minor, impact events. This being the case, it is also clear that the much larger number of medium-sized cratering events prior to 3.8 Ga must have affected the observed age distribution to some extent. The actual situation is presumably somewhere between the two extreme viewpoints just described.

The observation of a significant and growing number of highland samples with ages around 4.2–4.3 Ga has implications for both viewpoints. If the peak in the histogram at 4.2–4.3 Ga is real then the assumption that the distribution reflects large numbers of medium-sized cratering events would lead inevitably to the conclusion that the cratering rate prior to 3.8 Ga did not decline monotonically but fluctuated, going through a local maximum (a cataclysm) at around 4.0 Ga. This follows since the number of rocks retaining evidence of outgassing in a given time interval will be proportional to the product of two terms: (1) the cratering rate at that time (which determines how many rocks are outgassed per unit time interval) and (2) a survival factor which will presumably be an exponentially decaying function of the time integral of the cratering rate since that time. Whatever the form of term (1), (2) must be a monotonically decreasing function of time and therefore the presence of *two* or more local maxima in the age distribution implies *one* or more local maxima in the cratering rate.

The only other interpretation of local maxima in the age distribution must be a statistical one, namely that the apparent cratering rate has fluctuated because the number of *events* dominating the age distribution is very small. This is just the situation anticipated if the age distribution reflects the large basin forming events. In this case, because the number of dated events is small it is not possible to determine whether the *average* cratering rate shows a local maximum, due to some cataclysmic event, or alternatively a rapid monotonic decrease, possibly representing the closing stages of solar system accretion. As stated earlier, the present authors tend to prefer, on geological grounds, to interpret the ages in terms of a relatively small number of events, and therefore conclude that there is as yet no clear evidence to decide between a peak in the cratering rate at 4.0–3.9 Ga and a 3.9 Ga termination of accretion.

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