Proceedings of the Fourth Lunar Science Conference
(Supplement 4, *Geochimica et Cosmochimica Acta*)
Vol. 2, pp. 1889–1914

Argon selenochronology

GRENVILLE TURNER, PETER H. CADOGAN, and CHARLES J. YONGE

Department of Physics, Sheffield University, Sheffield, U.K.

Abstract—The K–Ar ages of samples from Apollos 15, 16, and 17 and Luna 20 have been determined by the Ar^{40}–Ar^{39} method. The age of an Apollo 17 basalt confirms evidence from Apollo 11 samples that extrusion of mare basalts began as early as 3.8 aeons ago. Ages of highland samples cluster in the interval 3.88 to 4.05 aeons and are taken to indicate that at least three and probably six of the major lunar basins formed in this period. The implications of this observation are discussed. Cosmic ray exposure ages have been determined using the Ar^{38}–Ar^{37} method and used to date North Ray (46 m.y.) and Camelot (90 m.y.) craters.

INTRODUCTION

THE K–AR AGES of samples from Apollo 15, 16, and 17 and Luna 20 have been determined by the Ar^{40}–Ar^{39} method using stepwise heating (Merrihue and Turner, 1966). Cosmic ray exposure ages have also been determined by the Ar^{38}–Ar^{37} technique (Turner *et al.*, 1971).

The samples analyzed were; 15382 an unmetamorphosed KREEP basalt from the Apennine Front, 67075 an anorthosite from the rim of North Ray Crater, 66095 a polymict anorthositic breccia, 62295 a metaclastic spinel bearing troctolite, two samples of 75055, an Apollo 17 subfloor basalt from the rim of Camelot Crater, two samples of 76055, an anorthositic gabbro from the base of the North Massif, and L2015 an 8 mg fragment of plagioclase from the Royal Society of London allocation of Luna 20.

EXPERIMENTAL PROCEDURE

Our analytical techniques for Ar^{40}–Ar^{39} work have been described elsewhere (Turner, 1971a; Turner *et al.*, 1973) and we shall comment here only on some aspects of the neutron irradiation.

The samples analyzed in the present work were irradiated as part of three separate irradiations: SH15 (15382), SH23 (62295, 66095, 67075, L2015), and SH24 (75055, 76055). The results of the measurements on the monitors included in these irradiations are summarized in Table 1. The analyses were typically performed on 15 mg splits of Hb3gr (Turner *et al.*, 1971) and the Ar^{40*}/Ar^{39*} ratios are seen to be reproducible to 0.2% for a given irradiation, indicating that any inhomogeneities within the monitor have a negligible effect on the age calculations. In contrast the (Ar^{37}/Ar^{39*}) ratios have a standard deviation of 4% and in view of the variations observed within a given irradiation this must reflect real K/Ca variations within the monitor, probably due to the presence of small amounts of biotite of identical age. There may be some additional variation resulting from spectral differences in the neutron flux between different irradiations but we are unable to separate this effect on the basis of our monitor measurements. We have therefore adopted a value of $\alpha = 0.55 \pm 0.02$ for the purpose of calculating K/Ca ratios and cosmic ray exposure ages (Turner *et al.*, 1971).

The integrated neutron flux for SH23 was rather large to enable us to make measurements on the

Table 1. Hb3gr monitor measurements.

Irradiation	Ar^{40*}/Ar^{39*}	Ar^{37}/Ar^{39*}	J^a	α^b
SH15	25.35±0.07	3.27±0.02	0.02985±0.0007	0.57±0.02
	25.38±0.08	3.15±0.02		
	25.32±0.12	3.2±0.02		
SH23 (Top)[c]	5.61±0.05		0.1349±0.003	0.54±0.02
	5.61±0.03	3.03±0.01		
SH23 (Bottom)[c]	5.72±0.04	2.93±0.02	0.1325±0.003	0.53±0.02
	5.69±0.03	3.02±0.02		
SH24	15.11±0.09	2.95±0.02	0.0501±0.001	0.55±0.03
	15.04±0.04	3.03±0.01		
	15.12±0.06	3.29±0.01		

[a] $J = (\exp(\lambda T) - 1)/(Ar^{40*}/Ar^{39*})$, $T = (1.062 \pm 0.02) \times 10^9$yr (Turner *et al.*, 1971) $\lambda = 5.305 \times 10^{-10}yr^{-1}$, $\chi_e = 0.585 \times 10^{-10}yr^{-1}$, $^{40}K/K = 0.0119\%$.

[b] $\alpha = (K/Ca)/(Ar^{39*}/Ar^{37})$.

[c] Samples for SH23 were irradiated on two levels separated by a distance of 4 cm. Ni flux wires and Hb3gr monitors indicated a 2.5% difference in flux for the two levels.

small fragment (8 mg) of potassium poor (50 ppm) calcium rich plagioclase from Luna 20. We therefore attempted in that irradiation to determine the extent of interference due to the production of Ar^{40} from Ca^{43} (n, α) Ar^{40} reactions. A stepwise heating experiment was performed on fragments of zone-refined CaF_2 included in the irradiation. Because of atmospheric Ar^{40} contamination it is not possible to determine the extent of Ca derived Ar^{40} unambiguously but we were able to place an upper limit to the $(Ar^{40}/Ar^{37})_{Ca}$ ratio of 6×10^{-4}. This is a factor of 7 less than the upper limit determined previously (Turner, 1971a) and a factor of 5 less than a value of 3×10^{-3} estimated on the grounds of nuclear systematics (Turner, 1971b). On the basis of this measurement we conclude that Ca derived Ar^{40} is unlikely to present a serious analytical problem for the analysis of lunar anorthosites even when unusually large neutron doses are employed.

ANALYTICAL RESULTS

The concentration of potassium derived Ar^{39*} and argon isotope ratios for the argon released in each temperature step from the nine specimens analyzed are given in Tables 2 and 3. The radiogenic Ar^{40*} has been corrected for extraction system atmospheric blanks (typically 1–5 $\times 10^{-9}$ ccSTP) but not for contributions from cosmogenic or trapped Ar^{40}. The effect of these contributions will be discussed later for the individual samples where they are significant.

Ar^{39}, Ar^{38}, and Ar^{36} have been corrected for contributions from neutron induced reactions on Ca using the following correction factors determined by measurements on irradiated CaF_2; $(Ar^{39}/Ar^{37})_{Ca} = (6.7 \pm 0.3) \times 10^{-4}$; $(Ar^{38}/Ar^{37})_{Ca} = (1.3 \pm 0.3) \times 10^{-4}$ (SH23); $(Ar^{38}/Ar^{37})_{Ca} = (0.8 \pm 0.2) \times 10^{-4}$ (SH15, SH24); $(Ar^{36}/Ar^{37})_{Ca} = (1.1 \pm 0.2) \times 10^{-4}$ (SH23); $(Ar^{36}/Ar^{37})_{Ca} = (2.0 \pm 0.3) \times 10^{-4}$ (SH15, SH24). Ar^{38} has been corrected for contributions from neutron induced reactions on K assuming $(Ar^{38}/Ar^{39*})_K = 0.011 \pm 0.002$ (Turner, 1971a).

The Ar^{40*}/Ar^{39*} ratio for each stage of the gas release has been converted to an apparent K–Ar age, t, using the expression

$$t = 1.885 \ln [1 + J . (Ar^{40*}/Ar^{39*})] \text{ aeons} \qquad (1)$$

Table 2. Argon release patterns from Apollo 15 and 16 and Luna 20 samples.

Temp. °C	36/38	38/37	38_c[a]/37	39*/37	40*/39*	39*[b]	Apparent age (aeons)	(c)
15382 (KREEP basalt, 25.1 mg)			J = 0.02982	K = 0.44%				
500	1.12±0.18	0.15±3	0.13±3	1.65±3	52.4±1.0	4.9	1.77±0.02	
600	1.27±0.04	0.080±4	0.069±4	1.07±1	86.5±0.3	15.9	2.40±0.01	
700	1.66±0.05	0.0675±19	0.0525±19	0.600±3	154.5±0.9	19.1	3.25±0.01	
750	2.02±0.05	0.0502±12	0.0351±12	0.269±1	195.3±0.5	19.5	3.62±0.01	
800	1.42±0.03	0.0394±7	0.0327±7	0.111±1	223.2±1.7	11.3	3.84±0.01	
850	0.97±0.02	0.0314±4	0.0291±4	0.0558±4	233.6±1.8	11.6	3.91±0.01	
950	1.05±0.02	0.0344±6	0.0313±6	0.0439±4	217.4±2.2	7.5	3.79±0.02	
1070	1.05±0.03	0.0351±4	0.0319±4	0.0216±7	218.9±8.2	3.0	3.81±0.06	
1370	0.69±0.04	0.0315±3	0.0311±3	0.0189±3	202.0±18.5	5.5	3.68±0.14	
Total	1.10	0.0367	0.0328	0.0947	172.9	98.3	3.43	
67075 (Crushed anorthosite, 63.9 mg)			J = 0.1385	K = 0.010%				
800	2.11±0.09	0.00163±6	0.0011±5	0.00203±4	42.88±1.66	0.68	3.65±0.06	(3.60)
900	1.56±0.03	0.00136±2	0.00108±2	0.00151±2	54.50±1.40	1.41	4.05±0.04	(4.02)
1000	0.99±0.03	0.00116±2	0.00108±2	0.00145±2	54.92±1.43	1.83	4.06±0.04	(4.05)
1250	1.52±0.04	0.00138±2	0.00111±2	0.00136±1	55.34±1.42	2.99	4.07±0.04	(4.04)
1500	1.30±0.03	0.00136±2	0.00116±2	0.00122±1	58.5±5.2	3.28	4.16±0.15	(4.14)
Total	1.40	0.00134	0.00111	0.00138	55.2	10.2	4.07	(4.05)
62295 (Spinel troctolite, 91.5 mg)			J = 0.1385	K = 0.06%				
800	0.698±0.018	0.00755±10	0.00745±10	0.0201±3	48.03±0.58	27.5	3.84±0.02	
900	0.703±0.015	0.00761±11	0.00750±11	0.0110±2	50.33±0.81	12.6	3.91±0.03	
1000	0.673±0.021	0.00748±13	0.00742±13	0.0112±2	49.18±1.16	8.2	3.88±0.04	
1100	0.635±0.028	0.00793±14	0.00792±14	0.0142±2	43.93±1.61	5.3	3.69±0.06	
1270	0.652±0.024	0.00765±17	0.00762±17	0.0100±2	42.1±3.1	3.7	3.62±0.12	
1420	0.647±0.021	0.00792±9	0.00790±7	0.0094±1	40.9±3.1	5.8	3.58±0.12	
Total	0.680	0.00764	0.00757	0.0138	47.31	63.1	3.81	
66095 (Polymict anorthositic breccia, 174 mg)			J = 0.1348	K = 0.14%				
500	0.039±0.004	0.189±1		0.357±2	5.28±0.10	7.6	1.01±0.01	
800	1.20±0.02	0.00557±7	(0.00488±7)	0.0583±2	33.7±0.07	36.9	3.23±0.01	
900	3.54±0.07	0.00213±4	0.00078±4	0.0249±3	44.82±0.5	32.3	3.68±0.02	
1000	1.87±0.05	0.00152±4	0.00111±4	0.0197±1	47.69±0.23	26.0	3.78±0.01	
1100	1.48±0.03	0.00205±4	0.00167±4	0.0211±2	43.64±0.40	24.1	3.64±0.01	
1250	0.717±0.052	0.00078±3	0.00076±3	0.0120±1	43.77±0.31	6.3	3.64±0.01	
1420	0.303±0.064	0.00073±4		0.0158±29	44.5±8.0	9.2	3.67±0.29	
1500		0.00074±19		0.0115±2	28.1±14.6	1.1	2.95±0.77	
Total	1.25	0.0028		0.0264	39.9	143.5	3.49	
L2015 (Luna 20, anorthosite fragment, 8.7 mg)			J = 0.1330	K = 0.005%				
800	2.92±0.13	0.0211±10	0.0107±10	0.0045±9	59.0±15.0	1.0	4.1±0.4	(3.5)
1300	0.92±0.01	0.0091±1	0.0085±1	0.00059±5	62.0±10.0	4.8	4.2±0.3	(4.0)
1470	0.66±0.02	0.0087±1	0.0086±1	0.00037±3	—	1.0	—	
1550	0.72±0.13	0.0087±8	0.0086±8	0.0045±2	—	—	—	
Total	1.04	0.0095	0.0087	0.00069	—	6.8	—	

[a](Ar^{38}_c/Ar^{37}) was calculated assuming that Ar^{38} originates solely from cosmogenic argon, $(Ar^{36}/Ar^{38}_c) = 0.63$, and trapped argon, $(Ar^{36}/Ar^{38})_t = 5.25$. Where no figure is given, or where the ratio is in parentheses, other sources for Ar^{38} are suspected.

[b]Amounts in units of 10^{-8} ccSTP/g.

[c]The figure in parentheses shows the effect of applying a correction for trapped Ar^{40} on the basis of $(Ar^{40}/Ar^{36})_t = 1$. This correction is significant only for 67075 and L2015.

Table 3. Argon release patterns from Apollo 17 samples.

Temp. °C	36/38	38/37	38_c[a]/37	39*/37	40*/39*	39*[b]	Apparent age (aeons)	(c)
75055 (Subfloor basalt, 76 mg) J = 0.05014 K = 0.052%								
650	1.55±0.17	0.080±4	(0.064±4)	0.425±15	17.5±1.2	0.8	1.19±0.06	(1.18)
750	3.97±0.16	0.0298±12	0.0083±12	0.174±1	67.0±0.9	3.7	2.78±0.02	(2.76)
880	2.26±0.03	0.00982±10	0.00635±10	0.0372±2	122.4±0.8	7.4	3.70±0.01	(3.70)
980	1.12±0.03	0.00699±14	0.00624±14	0.0238±1	127.2±0.8	4.5	3.77±0.01	(3.76)
1120	0.72±0.012	0.00709±6	0.00695±6	0.00604±7	125.5±1.7	3.9	3.73±0.02	(3.73)
1300	0.64±0.011	0.00688±10	0.00686±10	0.00184±5	133.8±4.3	2.1	3.85±0.05	(3.82)
1480	0.626±0.046	0.00702±20	0.00702±20	0.00255±20	131.8±21.9	0.4	3.83±0.28	(3.8)
Total	1.09	0.0076	0.0068	0.0115	110.6	22.8	3.55	
75055 (Subfloor basalt, 49 mg) J = 0.05014 K = 0.052%								
650	3.06±0.27	0.106±9	(0.050±9)	0.355±21	26.1±0.9	1.6	1.58±0.04	(1.54)
750	4.61±0.18	0.0537±21	0.0074±21	0.102±27	93.0±2.4	3.3	3.27±0.04	(3.23)
880	3.64±0.10	0.0134±4	0.0047±4	0.0275±5	128.5±2.0	5.6	3.78±0.03	(3.76)
780	1.82±0.12	0.0107±6	0.0079±6	9.0224±8	127.5±3.2	4.2	3.77±0.04	(3.76)
1120	0.792±0.017	0.0071±1	0.0069±1	0.00304±8.	132.7±3.7	4.8	3.84±0.05	(3.81)
Total	1.87	0.0094	0.0069	0.0107	114.0	19.5	3.59	
76055 (Anorthositic gabbro, 70 mg) J = 0.05014 K = 0.19%								
650	2.68±0.22	0.0229±18	0.0127±18	0.0688±9	143.5±1.9	1.0	3.96±0.02	
750	2.35±0.03	0.0141±2	0.0089±2	0.0700±3	149.6±0.5	8.9	4.03±0.01	
880	2.61±0.03	0.0156±2	0.0089±2	0.0544±7	144.8±0.8	22.4	3.98±0.01	
980	1.35±0.02	0.0107±1	0.0090±1	0.0584±2	145.4±0.4	18.0	3.99±0.01	
1120	0.936±0.01	0.108±1	0.0101±1	0.0395±2	137.0±0.6	13.0	3.89±0.01	
1300	0.682±0.010	0.0104±1	0.0103±1	0.0306±3	139.6±0.6	10.6	3.92±0.01	
1500	0.88±0.17	0.0121±5	0.0114±5	0.0365±8	105.2±15.2	0.7	3.46±0.23	
Total	1.70	0.0124	0.0095	0.0481	143.4	74.6	3.96	
76055 (Anorthositic gabbro, clast, 19.3 mg) J = 0.05014								
650	1.07±0.84	0.032±4	0.029±4	0.059±13	185.1±40.0	0.5	4.39±0.37	
750	1.45±0.24	0.0091±13	0.0075±13	0.0685±21	151.8±4.4	5.5	4.06±0.05	
880	1.27±0.09	0.0106±5	0.0091±5	0.0525±7	144.7±1.7	11.8	3.98±0.02	
980	0.78±0.04	0.0090±4	0.0087±4	0.0591±3	143.1±0.6	18.1	3.96±0.01	
1120	0.80±0.11	0.0093±5	0.0090±5	0.0250±11	148.9±6.7	4.5	4.03±0.08	
1300	0.61±0.07	0.0122±9	0.0122±9	0.0207±4	136.7±3.2	1.8	3.89±0.04	
Total	0.96	0.0100	0.0093	0.0477	145.6	42.2	3.99	

[a](Ar_c^{38}/Ar^{37}) was calculated assuming that Ar^{38} originates solely from cosmogenic argon, $(Ar^{36}/Ar^{38})_c = 0.63$, and trapped argon, $(Ar^{36}/Ar^{38})_t = 5.25$. Where no figure is given, or where the ratio is in parentheses, other sources for Ar^{38} are suspected.

[b]Amounts in units of 10^{-8} ccSTP/g.

[c]The figure in parentheses shows the effect of applying a correction for trapped and cosmogenic argon on the basis of $(Ar^{40}/Ar^{36}) = 1.0$ for both components.

The J-values used are indicated in Tables 2 and 3 and take account of flux variations inferred from Ni flux wires positioned around the samples during irradiation. The error assignments on the tabulated apparent ages take no account of uncertainties in the monitoring and are relevant only to considerations of variations in $(Ar^{40}*/Ar^{39}*)$ from a given sample. The monitoring introduces an additional relative uncertainty between samples of ±0.02 aeons and an absolute uncertainty of ±0.04 aeons, based on the absolute uncertainty of (Ar^{40}/K) in the monitor. The apparent ages are plotted in Figs. 1–6 as a function of the cumulative fraction of Ar^{39*} released.

Also plotted in Figs. 1–6 are the Ar^{39*}/Ar^{37} ratios and the corresponding K/Ca ratios calculated using the expression

$$(K/Ca) = (0.55 \pm 0.02)(Ar^{39*}/Ar^{37}) \quad (2)$$

(*see* Table 1).

The proportion of cosmogenic Ar_c^{38} has been calculated from the Ar^{36}/Ar^{38} ratio, where possible, by assuming a two component mixture of cosmogenic and trapped argon with respective compositions $(Ar^{36}/Ar^{38})_c = 0.63$ and $(Ar^{36}/Ar^{38})_t = 5.25$. The corresponding (Ar_c^{38}/Ar^{37}) ratios are tabulated and have been used to calculate exposure ages. Where significant contributions to Ar^{38} from other sources are suspected the (Ar_c^{38}/Ar^{37}) ratio is omitted or given in parentheses.

15382

KREEP basalt from Stations 6 and 7 (Apennine Front) of the Apollo 15 landing site have been analyzed by Church *et al.* (1972) and Nyquist *et al.* (1972) and found to have chemical and isotopic (Rb–Sr) characteristics similar to those of Apollo 14 Fra Mauro basalts 14073 and 14001,7,3 (Papanastassiou and Wasserburg, 1971). 15382 is a small (total returned weight 3.2 g) but relatively unmetamorphosed sample of KREEP basalt from Station 7 (Spur Crater). We received a 25 mg chip which was cleaned ultrasonically in acetone and analyzed without further separation.

The argon release pattern of 15382, set out in detail in Table 1, is compared in Fig. 1 with the release patterns of three Apollo 14 Fra Mauro basalts 14073, 14001,7,3, and 14310. The variation in the (K/Ca) ratios, inferred from (Ar^{39*}/Ar^{37}), are strikingly similar for all four samples and reflect the chemical similarities referred to above. Our sample of 15382 has slightly higher (K/Ca) ratios in the low temperature release and a correspondingly higher overall (K/Ca) ratio. This probably reflects a higher proportion of interstitial glass for 15382. The (Ar^{40*}/Ar^{39*}) release pattern of 15382 reflects a much higher degree of radiogenic argon loss (~26%) than the Apollo 14 samples but the maximum of the release pattern (900°C fraction, 3.91 ± 0.04 aeons) corresponds closely with the plateau age of (3.89 ± 0.04) aeons determined for the Apollo samples. (Turner *et al.*, 1971, 1972). The high temperature decrease in (Ar^{40*}/Ar^{39*}) ratio characteristic of the Apollo 14 samples is also seen to occur to a similar extent in 15382.

By itself the release pattern for 15382 is insufficient to indicate well-defined defined K–Ar age. It will be necessary to carry out measurements on a plagioclase separate before assigning a precise age to this rock. Nevertheless in view of the coincidence between the Apollo 14 ages and the maximum of the age spectrum for 15382 we would expect such an experiment to yield an age 3.9 aeons. The K/Ca ratio of the 850°C release suggests that it may be dominated by argon from plagioclase.

15382 contains appreciable amounts of cosmogenic and trapped argon but

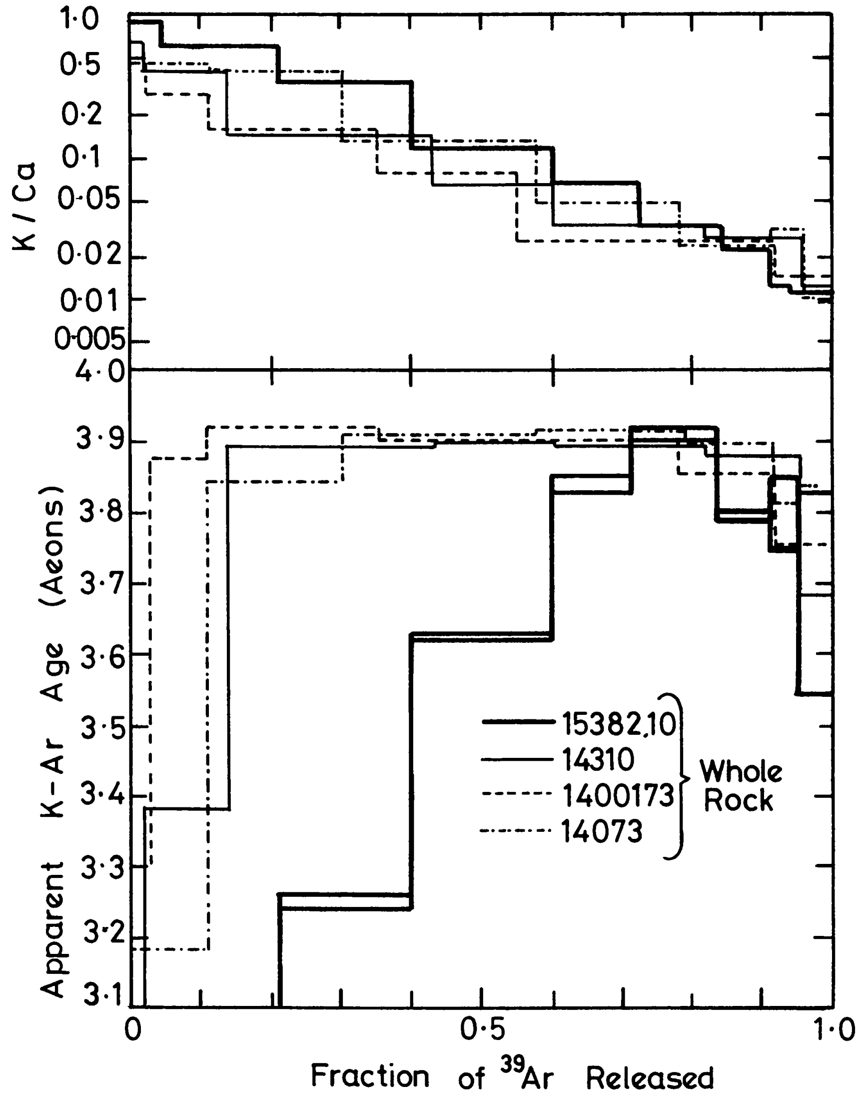

Fig. 1. Apparent age and K/Ca as a function of Ar^{39*} release from a whole rock sample of KREEP basalt, 15382, compared with the corresponding release patterns from Apollo 14 KREEP basalts. The maximum apparent age from 15382 occurs in the 850°C extraction, and at this temperature the apparent ages from the Apollo 14 rocks are not less than the plateau ages. All samples show similar K/Ca patterns and a striking decrease in apparent age in the final release.

because of the high K content the effect on the Ar^{40*}/Ar^{39*} ratio is minimal and no correction has been applied.

The (Ar_c^{38}/Ar^{37}) ratios are high in the low temperature release due to the presence of Ar^{38} produced by cosmic ray bombardment of potassium. Following a minimum in the 850°C release the ratio increases due to the release of argon produced by cosmic ray bombardment of Fe (Turner *et al.*, 1972). Based on a (Ar_c^{38}/Ar^{37})–(Ar^{39*}/Ar^{37}) correlation we deduce a value of $(Ar_c^{38}/Ar^{37}) = 0.027 \pm 0.001$ for the Ca-derived argon. This corresponds to an (Ar_c^{38}/Ca) ratio of $(3.3 \pm 0.1) \times 10^{-6}$ ccSTP/g. The exposure age of 15382 based on a nominal production rate of Ar^{38} from Ca of 1.4×10^{-8} ccSTP/g/10^6yr (Turner *et al.*, 1971) is 240 m.y. The slope of the correlation plot is 0.039 ± 0.010 and corresponds to a relative production ratio for cosmogenic Ar^{38} of $P_{38}(K)/P_{38}(Ca) = 2.6 \pm 0.7$.

67075

Rock 67075 from the rim of North Ray Crater is a very weakly consolidated anorthosite consisting of greater than 95% feldspar. The sample we received was gently crushed in a stainless steel mortar and feldspar grains (−100+150 mesh) were separated by sieving. This fraction was washed ultrasonically in acetone prior to analysis.

The release pattern of 67075 (Table 1 and Fig. 2) indicates rather simple systematics; the 800°C release shows the effects of a small amount of Ar^{40*} loss while the four high temperature fractions give identical Ar^{40*}/Ar^{39*} ratios within the limits of error. The major argon release occurs in the 1250°C and 1500°C fractions, an indication of the extremely good argon retention characteristics of lunar

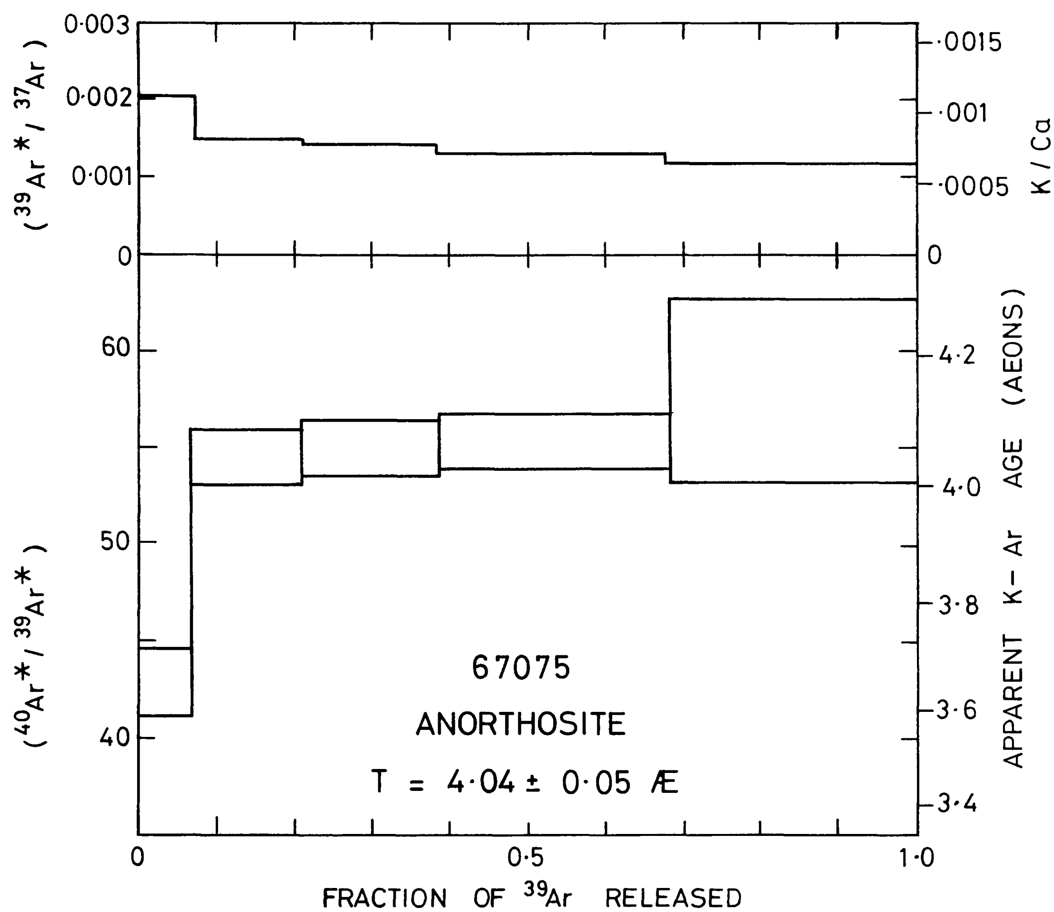

Fig. 2. Apparent age and K/Ca as a function of Ar^{39*} release from cataclastic anorthosite, 67075 (coarse plagioclase). Unlike most rocks analyzed, less than 10% Ar^{39} is released below 900°C. The very small variation in (Ar^{39*}/Ar^{37}) ratio over the release reflects the chemical homogeneity of the sample. The ages have been corrected assuming no cosmogenic Ar^{40} and a trapped (Ar^{40}/Ar^{36}) ratio of 1 ± 1.

anorthosites (Turner, 1971). The (K/Ca) ratio for 67075 is extremely low (0.00076 ± 0.00003) and the correction for calcium derived Ar^{39} correspondingly large (33%). 67075 also contains appreciable amounts of trapped and cosmogenic argon (the overall Ar^{40*}/Ar^{36} ratio is 38.2). We would expect the contribution of cosmogenic Ar^{40} to be negligible since the major target element in 67075 is calcium. However we would expect significant contributions from trapped Ar^{40}. We have therefore calculated the proportion of trapped Ar^{36} in each temperature fraction from the (Ar^{36}/Ar^{38}) ratio and from this calculated the proportion of trapped Ar^{40}, assuming $(Ar^{40}/Ar^{36})_t = 1.0$. The effect of applying this correction is to reduce the apparent K–Ar ages by 10 to 50 million years and is indicated in the table by the figure in parentheses. Based on this correction and taking account of the uncertainty in the actual trapped (Ar^{40}/Ar^{36}) ratio we infer an age for 67075 of (4.04 ± 0.05) aeons, from the 900°C–1250°C release.

The cosmogenic (Ar_c^{38}/Ar^{37}) ratio in 67075 is essentially constant with a mean value of 0.00111 ± 0.0005. The corresponding (Ar_c^{38}/Ca) ratio is $(6.4 \pm 0.3) \times 10^{-7}$ ccSTP/g and exposure age 46 m.y.

62295

62295 has been classified as a type C2 metaclastic rock (Wilshire *et al.*, 1973). Consisting principally of plagioclase it also contains olivine, spinel, and a fine grained mesostasis and may represent an impact melt (Agrell *et al.*, 1973). The sample was collected from the rim of Buster Crater at Station 2 on the Cayley Plains and has been described with a high degree of confidence as Buster Crater ejecta (LSPET, 1972). We have analyzed a 91 mg whole rock fragment of 62295.

The Ar^{40*}/Ar^{39*} release pattern (Table 1 and Fig. 3) is compromised by an incorrect setting of the furnace heater for the first extraction which accounts for 43% of the argon release. The Ar^{40*}/Ar^{39*} ratio for the first three extractions is high although the 800°C ratio does show the effects of a small amount, $\leqslant 4\%$, of Ar^{40*} loss. The high temperature release $(T \geqslant 1100°C)$ shows the drop in apparent age characteristic of many Apollo 14 and 15 basalts (e.g., 15382). It is possible that a common factor affects the release patterns from all of these rocks. The Ar^{39*}/Ar^{37} release pattern from 62295, however, is markedly different from the corresponding ratios from KREEP basalts, indicating a much more homogeneous distribution of potassium and calcium in this rock.

The reason for the high temperature decrease in apparent age in this rock is not understood. On the assumption that it represents post crystallization Ar^{40*} loss due to a phase change (e.g., devitrification) in an otherwise retentive phase we would expect the maximum of the release pattern to indicate the time of the last *major* mobilization of argon in this rock. Based on the 900°C and 1000°C release we infer a cooling age for 62295 of 3.89 ± 0.05 aeons. We are guided in this interpretation by experiments with mineral separates from Apollo 14 basalts (Turner *et al.*, 1972) but realize that the situations may not be strictly analogous. The age of 62295 based on total argon release is 3.81 aeons.

The Ar^{36}/Ar^{38} ratios in all gas release fractions are very close to that expected

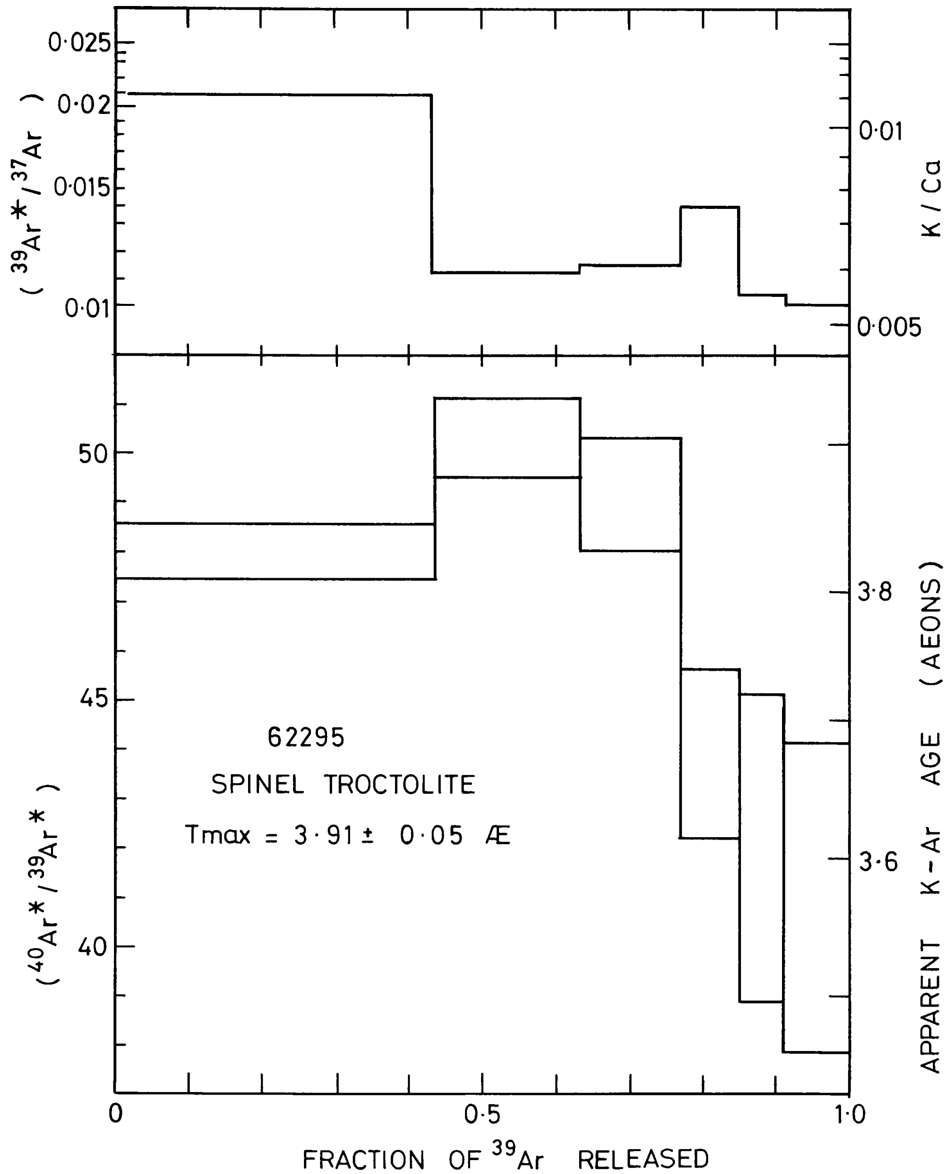

Fig. 3. Apparent age and K/Ca as a function of Ar^{39*} release from the metaclastic rock, 62295. The release pattern is compromised by the incorrect setting of the furnace heater for the first extraction but an age of 3.89 ± 0.05 AE is obtained for the major part of the release. A striking decrease in apparent age is observed in the final extractions.

for cosmogenic argon (0.63) and the (Ar^{38}/Ar^{37}) ratios show little variation. The average (Ar^{38}_c/Ar^{37}) ratio is (0.0076 ± 0.0002), corresponding to $(Ar^{38}_c/Ca) = (4.4 \pm 0.2) \times 10^{-6}$ ccSTP/g. The exposure age of 62295 is 310 m.y.

66095

Rock 66095 was collected from the Cayley Plains at the base of Stone Mountain on the South Ray ejecta blanket. Originally described as a crystalline rock (LSPET, 1972) it has been reclassified as a type B4 dark matrix breccia (Wilshire *et al.*, 1973) containing relict clasts in a feldspar rich matrix. The (Ar^{40*}/Ar^{39*}) and (Ar_c^{38}/Ar^{37}) release patterns of a whole rock fragment of 66095 are shown in Fig. 4. Both release patterns are complex and do not yield well-defined Ar^{40}–Ar^{39} *or* Ar^{38}–Ar^{37} ages. The release patterns may be complicated by the presence of older relict clasts in the rock.

The Ar^{39}/Ar^{37} ratio in the initial gas release is very high (0.36) indicating the presence of potassium rich sites of low argon retentivity. This initial extraction also shows the presence of "excess" Ar^{38} which was probably formed by neutron capture on Cl^{37}. Although chlorine is normally concentrated in residual phases

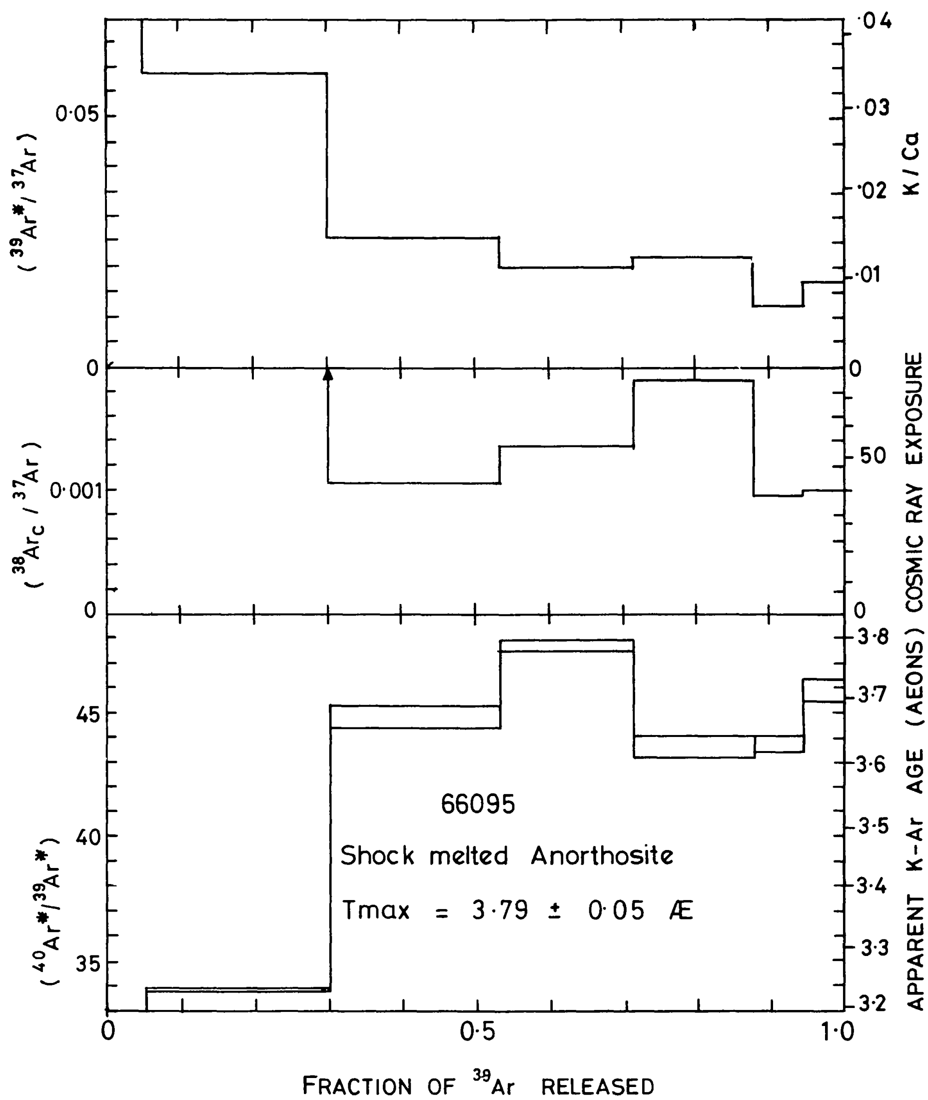

Fig. 4. Apparent K–Ar age, cosmic ray exposure age and K/Ca from shock melted anorthosite 66095. The (Ar^{40*}/Ar^{39*}) release pattern does not show a well-defined plateau, possibly due to the presence of older relict clasts. Relict clasts with prior irradiation histories may also be partly responsible for the complex (Ar_c^{38}/Ar^{37}) release pattern. (Ar_c^{38}/Ar^{37}) ratios have been corrected for potassium derived Ar^{38}, but the presence chlorine-derived Ar^{38} is suspected in the low temperature release.

(Reed *et al.*, 1972) in this rock it is present in concentrations of 1.5–2% possibly as lawrencite ($FeCl_2$) associated with goethite (Taylor *et al.*, 1973) and the correlated release of Ar^{38} with Ar^{39*} is fortuitous.

The high initial Ar^{39}/Ar^{37} ratio is similar, although smaller than, the corresponding initial ratios from 15382 and the Apollo 14 KREEP basalts. This is consistent with the observation (LSPET, 1972) that anorthositic rocks at the Apollo 16 site have been intruded by low melting point material having KREEP composition.

Taken at face value, the variations in the (Ar_c^{38}/Ar^{37}) ratio, which correspond to exposure ages in the range 40–80 m.y., and in particular the high ratio at 1100°C, imply a complex history of near surface irradiation for the components of 66095 prior to their incorporation in 66095. This in turn suggests that 66095 may have been produced as a result of a relatively minor impact possibly around 3.6 aeons or later and that the heating associated with this impact lead to minor amounts of radiogenic and cosmogenic argon loss.

L2015

The Luna 20 sample analyzed was part of the 0.51 g allocation to the Royal Society of London. This allocation, designated L2015, was selected from the 27–32 cm zone of the Luna 20 core. The fragment we have analyzed was part of an 11.3 mg crystalline fragment of glassy and friable feldspar L2015,3,1. Prior to receipt by us its magnetic properties were investigated non-destructively at the University of Newcastle. Because of its friable nature the sample broke easily into several smaller pieces and a number of these, totaling 8.7 mg, were irradiated in SH23. The remainder has been retained for mineralogical analysis and the results of this will be reported later.

The results of our argon analysis are summarized in Table 2. L2015,3,1 is the least favorable sample we have so far analyzed. The potassium concentration inferred from our data is 50 ppm which compares with 120 ppm for anorthosite 15415 and 100 ppm for anorthosite 67075. In consequence the *total* Ar^{40*} content was 3.9×10^{-8} ccSTP and despite an increase in the neutron fluence by a factor of 4 above our normal dose the total Ar^{39*} content was only 5.9×10^{-10} ccSTP. Because of the very low (K/Ca) ratio, 0.00038, the correction for Ca derived Ar^{39} was also extremely large (53% for the 1300°C major release). An additional problem arose with the presence of significant amounts of trapped and cosmogenic argon. The Ar^{40*}/Ar^{39*} ratios in the table are uncorrected for this contribution. We have estimated the effect of such a correction assuming zero cosmogenic Ar^{40} and $(Ar^{40}/Ar^{36})_t = 1.0$ for the trapped component. The corrected age is indicated in parentheses in Table 2. Based on the 1300°C major release and the correction for trapped Ar^{40} we deduce a K–Ar age of (4.0 ± 0.3) aeons for L2015,3,1. The result from L2015 is consistent with the Ar^{40}/Ar^{39} ages obtained by Huneke *et al.* (1973) on two Luna 20 metamorphosed rocks (22006 and 22007) of 3.9 ± 0.04 AE.

The cosmic ray induced isotopes from L2013,3,1 present a more well defined picture and the (Ar_c^{38}/Ar^{37}) ratio is essentially constant in the 1300°C–1550°C release with a mean value of 0.0086±0.0001. This corresponds to an (Ar^{38}_c/Ca) ratio of (4.8±0.2)×10^{-6} ccSTP/g and an exposure age of 340 m.y.

75055

This sample was part of a rock fragment removed by astronaut Schmitt from a meter sized boulder on the rim of Camelot Crater (Station 5). It has been described (LSPET, 1973) as a coarse grained basalt consisting of approximately 35% plagioclase, 45% yellowish brown pyroxene and 20% opaque minerals (ilmenite). The dominant grain size was around 1 mm and in the hand specimen the sample resembled the Apollo 11 low-K basalts. Preliminary examination of the samples from the vicinity of Camelot Crater indicate that subfloor basalts covered this part of the valley floor to a depth of at least 100 m before formation of the crater. We have analyzed two chips from 75055. A preliminary report of the results from one of them is reported in Turner *et al.* (1973).

The argon release patterns from the two chips are shown in Table 3 and Fig. 5 and are essentially identical. Both samples yielded low (Ar^{40*}/Ar^{39*}) ratios in the initial release, indicating small losses of Ar^{40} (11% and 12%) probably as a result of solar heating. The corresponding (Ar^{39*}/Ar^{37}) ratios indicate that the losses are associated with potassium rich sites, probably an interstitial K-rich glass phase (Lunatic Asylum, 1970; Turner *et al.*, 1972).

The (Ar^{36}/Ar^{38}) ratios from these two samples indicate the presence of both trapped and cosmogenic argon. 75055 is a mare basalt rich in both Fe and Ti and we therefore expect significant production of Ar^{40} from cosmic rays. The figures in parentheses in Table 3 indicate an attempt to correct for trapped and cosmogenic Ar^{40} assuming (Ar^{40}/Ar^{36}) = 1.0 for *both* components. This uncertain correction is most significant for the very high temperature release and the rise in apparent age for the 1300°C fraction may represent the effect of under correction. We have taken a weighted mean of the 980°C–1300°C release to indicate an age of (3.76±0.05) aeons for 75055.

Based on a (Ar^{38}_c/Ar^{37})–(Ar^{39*}/Ar^{37}) correlation passing through the 980°C and 880°C points we deduce a value of (Ar^{38}_c/Ar^{37}) = 0.0061±0.0003 for the Ca derived cosmogenic Ar^{38}. The corresponding (Ar^{38}_c/Ca) ratio is (1.26±0.06)×10^{-6} ccSTP/g and the exposure age 90 m.y.†

76055

76055, described in the preliminary examination as a vesicular anorthositic gabbro, was collected by the astronauts 3 km north of the landing site, at Station 6, near the base of the North Massif. The anorthositic gabbro appears to be a major rock type at Station 6 forming a matrix to other types of brecciated samples. Pre-

†The exposure ages for 75055 and 76055 are 10% lower than the ages quoted in Turner *et al.* (1973). The latter were based on the 980°C release without the correction for K derived Ar^{38}_c implicit in the correlation diagram approach.

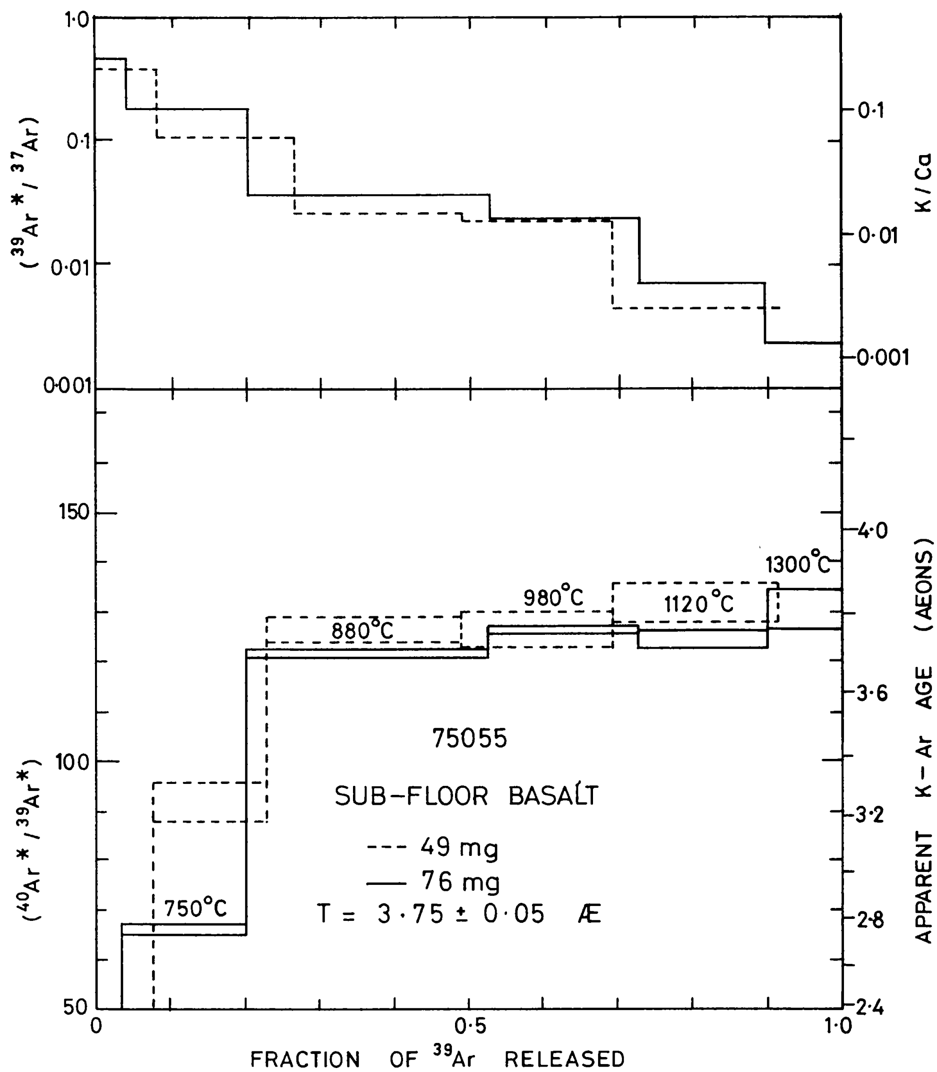

Fig. 5. Apparent age and K/Ca from two whole rock samples of subfloor basalt 75055. The release patterns are essentially identical yielding plateau ages of 3.76±0.05 AE. ($Ar^{40}*/Ar^{39}*$) ratios have not been corrected for cosmogenic and trapped argon assuming (Ar^{40}/Ar^{36}) = 1±1 for both components. Both samples show similar ($Ar^{39}*/Ar^{37}$) release patterns.

liminary examination indicates that the material is thoroughly recrystallized. Our sample of 76055 consisted largely of a greenish gray fine grained matrix of plagioclase and smaller amounts of pyroxene with irregular lenses of pyroxene and plagioclase which appear in binocular microscope examination of the hand specimen to be a coarser grained version of the matrix. We have analyzed a 70 mg chip of the matrix and a 19 mg chip of one of the lens like clasts. A preliminary report of the results from 76055 is given in Turner *et al.* (1973).

The argon release pattern of 76055 (Table 3 and Fig. 6) does not show effects of appreciable argon loss but does have some structure. The initial release of both matrix and clast shows a high ($Ar^{40}*/Ar^{39}*$) ratio while in the high temperature release from the matrix the ratio decreases. The coarse grained clast does not

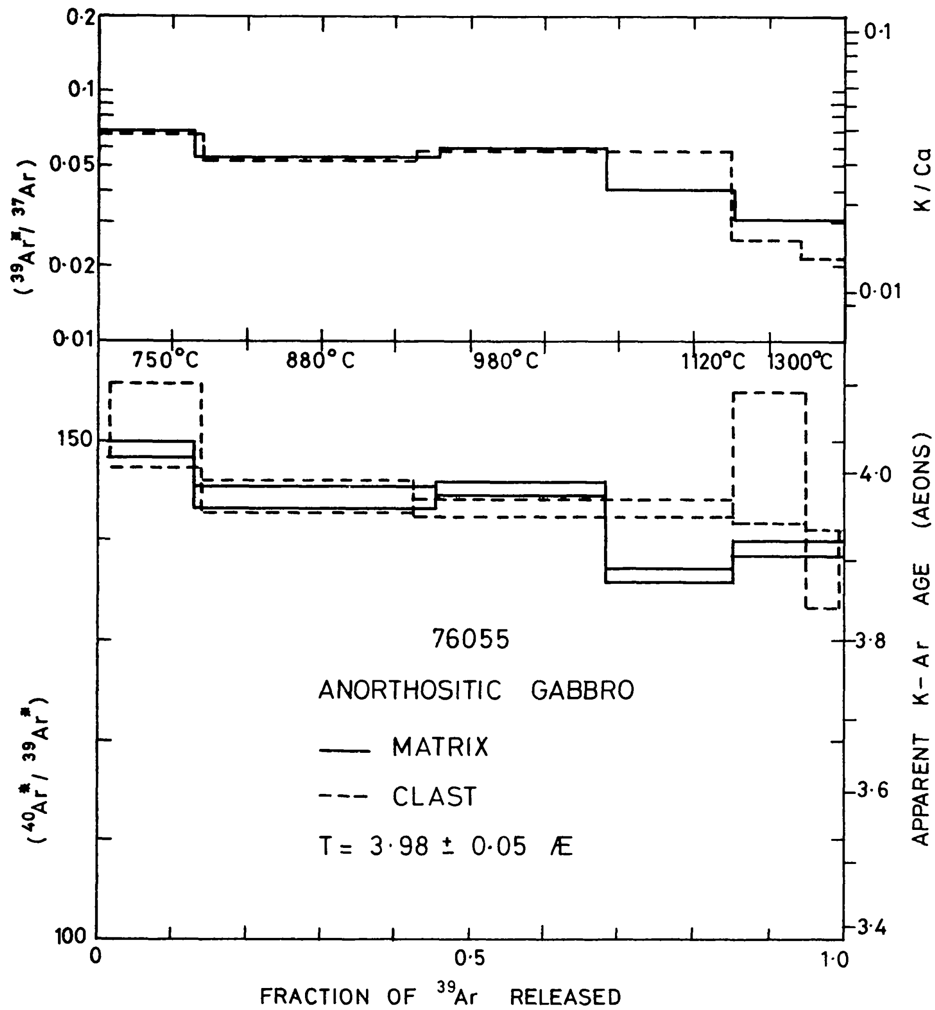

Fig. 6. Apparent age and K/Ca from samples of matrix and darker-colored clast from metamorphosed anorthositic gabbro, 76055. Both samples yielded high apparent ages from the 750°C extraction and well-defined plateau ages of 3.98 ± 0.05 AE. The matrix showed a striking decrease in apparent age in the final release which was not observed from the coarser grained clast. The K and Ca distribution of matrix and clast are essentially identical on the basis of the (Ar^{39*}/Ar^{37}) release patterns.

appear to exhibit the high temperature decrease despite apparently identical chemistry (based on K/Ca ratio) and suggests that this feature of the release pattern may be a function of grain size. Once more on the *ad hoc* assumption that the high temperature part of the release pattern of the matrix is representative of post cooling Ar^{40*} loss we calculate an age of 3.98 ± 0.05 aeons for both matrix and clast based on the 880°C and 980°C release. The ages based on the overall release are respectively 3.96 and 3.99 aeons.

The (Ar_c^{38}/Ar^{37}) ratio is approximately constant over most of the release but does show the characteristic rise at high temperatures due to the presence of Fe induced Ar_c^{38}. The minimum ratio, 0.0089 ± 0.0003, in the 880°C and 980°C release is reduced to 0.0084 ± 0.0006 by a correction for Ar_c^{38} produced from cosmic ray bombardment of potassium (*see* 15382). The corresponding (Ar_c^{38}/Ca) ratio is $(1.74 \pm 0.12) \times 10^{-6}$ ccSTP/g and exposure age 125 m.y.

Cosmic Ray Exposure Ages

The determination of cosmic ray exposure ages from rock samples identified as ejecta from particular craters provides a method for establishing a time scale for lunar cratering in recent times. Table 4 summarizes the cosmic ray exposure ages determined in the present work together with the cratering event with which the age may be associated. Also included in the table are additional published ages which relate to other cratering events. The ages determined in the present work as well as the age for Cone Crater (Turner *et al.*, 1971) are based on (Ar_c^{38}/Ca) ratios for Ar^{38} produced directly from Ca and a nominal production rate of 1.4×10^{-8} ccSTP/g^{-1}m.y.$^{-1}$. The distinction between Ar^{38} produced from Ca and Ar^{38} produced from K, Ti, and Fe has been made on the basis of (Ar_c^{38}/Ar^{37})–(Ar^{39*}/Ar^{37}) correlations referred to previously and comparisons of our data with Ar^{38}–Ca exposure ages calculated using different production rates should take this into account.

The exposure ages we have determined do not take account of shielding but, since the rocks associated with specific recent cratering events have not been subjected to burial and re-excavation, the assumption of identical production rates probably reflects relative ages fairly accurately.

Several recent cratering events have now been dated with some degree of confidence by the Ar^{38}–Ar^{37} technique; Apollo 14 Cone Crater, 26 m.y. (Turner *et al.*, 1971); Apollo 16 North Ray, 46 m.y.; Apollo 17 Camelot, 90 m.y. Together with the exposure age of 68815 (1.7–2.3 m.y., Behrmann *et al.*, 1973), which is probably indicative of the age of Apollo 16 South Ray Crater, these ages provide a fairly well defined absolute time scale with which to compare relative ages based on crater morphology.

Table 4. Cosmic ray exposure ages and crater ages.

Sample	Exposure Age[a] (m.y.)	Associated Crater
15382	240	—
67075	46	North Ray
62295	310	(Buster)[b]
66095	40–80	—
L2015	340	—
75055	90	Camelot
76055	125	—
14053	26[c]	Cone
68815	1.7[d], 2.3[e]	South Ray

[a] Ar_c^{38}–Ar^{37} ages based on a nominal production rate of 1.4×10^{-8} ccSTP/g^{-1}m.y.$^{-1}$.

[b] The exposure age is not the age of Buster (*see* text).

[c] Turner *et al.*, 1971.

[d] Kr^{81}–Kr exposure age, Behrmann *et al.*, 1973.

[e] Ne^{21} exposure age, Behrmann *et al.*, 1973.

The ages of 15382, L2015, and 76055 cannot at this stage be associated with specific cratering events. The 20–30% enhancement of the high temperature (Ar_c^{38}/Ar^{37}) ratio in 76055 due to production from Fe suggests a hard irradiation spectrum for this rock and therefore a surface exposure, however we cannot quantify this suggestion at present. Although 66095 may be South Ray ejecta its complex Ar_c^{38}/Ar^{37} release pattern precludes the estimation of a meaningful age.

Buster Crater (Station 2 at the Apollo 16 site) is on geomorphological grounds a relatively recent crater. Behrmann *et al.* (1973) estimate an age for Buster of about 56 m.y. on the basis of track measurements. Our analysis of 62295 indicates an exposure age of 310 m.y. which is inconsistent with the identification of 62295 as Buster ejecta (LSPET, 1972) and the apparent youthfulness of the crater *unless* 62295 has a history of preirradiation. Buster is a relatively small crater, 90 m in diameter and a history of preirradiation is quite possible. We note in this context the absence of a high temperature enhancement of the (Ar_c^{38}/Ar^{37}) ratio ($\leq$ 5%) which may imply irradiation at depth.

ARGON DIFFUSION

In attempting to interpret Ar^{40}–Ar^{39} ages from complex brecciated highland samples it is necessary to make certain assumptions about the thermal history of the sample during and after the brecciation process. For example, attempts to relate Ar^{40}–Ar^{39} ages to the times of major impacts (Turner *et al.*, 1971; Turner, 1971a) assume that temperatures reached during the impact or within the ejecta blanket following the impact were sufficient to expel most, if not all, of the pre-existing argon.

We have attempted to estimate the temperatures required to expel argon from lunar minerals, in particular plagioclase, by estimating diffusion coefficients and activation energies from the Ar^{39*} release patterns. We have also considered the effect of the neutron irradiation on our calculations, following the observation, (Davis *et al.*, 1971) that argon is released more readily from neutron irradiated samples than from unirradiated samples.

In Fig. 7 we plot $\log(D/a^2)$† against 1000/T for three anorthosites 67075, 100–150 mesh; L2015 mm sized fragments; 15415 mm sized fragments (data from Turner, 1971a); and a plagioclase separate from 14310 (data from Turner *et al.*, 1972). Also indicated schematically is the region of the plot occupied by the Apollo 11 basalt whole rock data (Turner, 1971c) which are dominated by argon in the K-rich glass phase and correspond to a comparatively low activation energy of ~ 30 kcal mole^{-1}K^{-1}.

The figure clearly reflects features already noted namely the good argon retention characteristics of lunar anorthosites (Turner, 1971b) and plagioclase feldspar (Turner *et al.*, 1971). The activation energies inferred for 67075, 15415, and 14310

†D is the diffusion coefficient, a grain diameter and T the absolute temperature. D/a^2 has been calculated assuming volume diffusion from spherical grain geometry (*see* for example Carslaw and Jaeger 1959, p. 286).

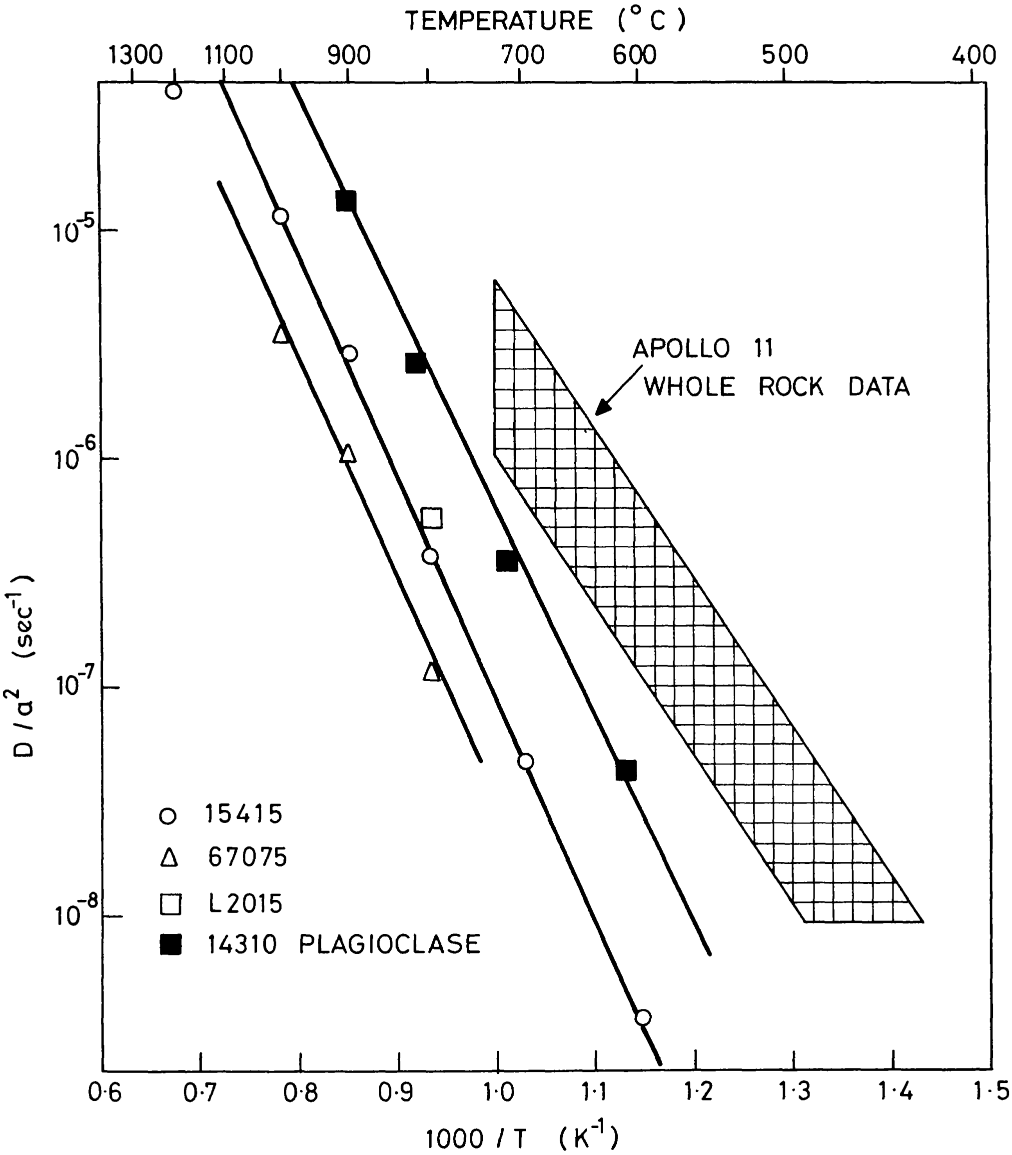

Fig. 7. Log_{10} (D/a^2) vs. 1000/T for laboratory release of Ar^{39} from irradiated anorthosites from Apollo 15 and 16 and Luna 20, and a plagioclase separate from Apollo 14 basalt 14310. Calculated activation energies for all samples were 45 kcal/mole. The region on the plot occupied by Apollo 11 whole rock data corresponds to lower activation energies (30 kcal/mole).

plagioclase are indistinguishable, 45 kcal $\text{mole}^{-1}\text{K}^{-1}$. Fechtig *et al.* (1960) have determined an activation energy of 56 kcal $\text{mole}^{-1}\text{K}^{-1}$ for argon diffusion in terrestrial anorthite.

Davis *et al.* (1971) have noted (*see also* Alexander *et al.*, 1973) that argon is released preferentially from neutron irradiated samples as compared to unirradiated samples. For rock 10044 Davis *et al.* (1971) noted a bodily shift in the whole release pattern by 200°C to lower temperatures as a result of the irradiation. For an Apollo 14 breccia, 14318, Alexander *et al.* (1973) present release patterns which show a broadening by about 200°C as a result of the irradiation. Neither of these results, referring as they do to relatively complex rocks, are directly applicable to diffusion from single minerals but indicate for example that the activation energy for the unirradiated feldspar are almost certainly higher than 45 kcal $mole^{-1}K^{-1}$. We intend to carry out further experiments on an unirradiated feldspar separate from 67075 to quantify the effect.

Based on the above observations we present some calculations which illustrate the conditions necessary for argon loss in retentive minerals such as anorthite. Assuming only that diffusion rates obey an activation relationship of the form $D = D_0 \exp(-\Delta E/RT)$ we have calculated, for activation energies, ΔE, of 45 and 55 kcal $mole^{-1}K^{-1}$, the temperatures, θ, and heating times, τ, required to duplicate the effects of a one hour laboratory heating at 1250°C (one hour at 1250°C is sufficient to remove around 70% of the argon from 67075).

The results of the calculation are presented in Table 5 along with some relevant "lengths." The conduction length, $a = (2\kappa\tau)^{1/2}$ is the depth from which significant heat losses can occur in time, τ, and is relevant to a consideration of the time-temperature history of an ejecta blanket. The thermal diffusivity, $\kappa = 10^{-5}$ $km^2\ yr^{-1}$, was calculated assuming an effective thermal conductivity of a porous rock layer of 1 watt $m^{-1}K^{-1}$ (Mizutani and Newbigging, 1973), a density of 3.3×10^3 kg m^{-3} and a specific heat of 10^3 joules kg^{-1}.

We have also calculated a depth, d, below the surface at which the ambient temperature equals θ simply as a result of the lunar heat flow. The present day heat flow of 3.0 10^{-2} watts m^{-2} coupled with an estimated mean conductivity for the upper 20 km of 2 watts $m^{-1}\ K^{-1}$ (Mizutani and Newbigging, 1973) corresponds to a mean crustal temperature gradient of 15°C/km. The temperature gradient 4.0 aeons ago can only be inferred from thermal history calculations. The calculations of Wood (1972) indicate early temperature gradients of around 13°C km^{-1} but assume an average (lattice) thermal conductivity of 4 watts $m^{-1}sec^{-1}$. The blanketing effect of a reduced thermal conductivity in the outer 20 km or so could increase the temperature gradient considerably. We have calculated d on the basis of an assumed early crustal temperature gradient of 30°C km^{-1}, based on the heat

Table 5. Calculated temperatures and heating times required to produce major argon loss from lunar anorthosites.

Time, τ (yr)	Conduction length,[a] a	$\Delta E = 45$(kcal $mole^{-1}K^{-1}$) θ(°C)	d(km)[b]	$\Delta E = 55$(kcal $mole^{-1}K^{-1}$) θ(°C)	d(km)[b]
1	4 (m)	680	23	750	25
10^2	40	520	17	600	20
10^4	400	410	14	490	16
10^6	4 (km)	330	11	400	13
10^8	40	260	9	340	11
5.10^8	100	240	8	310	10

[a] $a = (2\kappa\tau)^{1/2}$ is depth from which significant conduction losses can occur in time, τ. Calculated using $\kappa = .10^{-5} km^2 yr^{-1}$.

[b] $d = \theta/(d\theta/dz)$ is the depth below the surface at which the ambient temperature equals θ. Calculated assuming $(d\theta/dz) = 30$°C km^{-1} and a surface temperature of 0°C (see text).

flow calculated by Wood (1972) and the thermal conductivities calculated by Mizutani and Newbigging (1973).

It is clear from Table 5, which refers to a highly retentive mineral phase, that material excavated from depths of 10 km is unlikely to retain significant amounts of radiogenic argon from the period of burial. This observation is relevant to a consideration of material from highland regions uplifted during the formation of the giant lunar basins. It is also clear from Table 5 that in order for ejecta blankets, with thicknesses of the order of hundreds of meters, to produce argon loss in entrained feldspathic rocks, initial temperatures in excess of 500°C are required. It is also clear but worth stressing that the cooling of ejecta blankets is virtually instantaneous when compared to the time scale of the uncertainties associated with radiometric dating of lunar rocks (typically 40 m.y.).

Summary and Discussion

In Table 6 we list the Ar^{40}–Ar^{39} ages determined in the present work and, for the purpose of discussion, a summary of representative Ar^{40}–Ar^{39} ages from the literature for the whole series of Apollo and Luna missions. The listing is not intended to be a comprehensive review of Ar^{40}–Ar^{39} ages. To maintain, as far as possible, a degree of self consistency the ages are taken from the work of only two

Table 6. Representative Ar^{40}–Ar^{39} ages of lunar samples[a].

Sample(s)	Age (aeon)	Reference
Mare type basalts		
A11, high K	3.56±0.09	Turner (1970, 1971c)
A11, low K	3.83±0.09	Turner (1970, 1971c)
12002, 12015, 12065 (A12)	3.26±0.06	Turner (1971c)
15555 (A15)	3.31±0.03	Podosek *et al.* (1972)
Luna 16 B-1	3.45±0.04	Huneke *et al.* (1972)
75055 (A17)	3.76±0.05	This work
Highland samples		
12013 (A12 "granitic" breccia)[b]	4.03±0.07	Turner (1971c)
14310, 14093 (A14, basalt)	3.88±0.05	Turner *et al.* (1971, 1972)
14053 (A14, basalt)	3.95±0.05	Turner *et al.* (1971)
15382 (A15, KREEP basalt)[c]	3.91±0.05	This work
15415 (A15, anorthosite)	4.05±0.15	Turner (1971a)
67075 (A16, anorthosite)	4.04±0.05	This work
62295 (A16, troglodite)	3.89±0.05	This work
66095 (A16, polymict breccia)	3.6–3.8	This work
L2015 (Luna 20, anorthosite)	4.0±0.3	This work
22006 (Luna 20)	3.9±0.04	Huneke *et al.* (1973)
76055 (A17, anorthositic gabbro)	3.98±0.05	This work

[a]*See also* Alexander *et al.* (1972), Eberhardt *et al.* (1973), Husain *et al.* (1972), Kirsten *et al.* (1972), York *et al.* (1972).

[b]12013 is listed with the highland samples solely on the basis of its age.

[c]Based on maximum of release pattern (*see* text).

laboratories, using, since Apollo 14, the same neutron flux monitor. Where available the results of other laboratories on these and related samples are in basic agreement with the ages presented in Table 6 and references to the work of other authors are given in a footnote.

K–Ar and Ar^{40}–Ar^{39} ages may refer to a number of possible types of event and it is worth listing what we believe to be the major types responsible for the data in the table.

(a) Crystallization and cooling ages of extrusive rocks. On geological and petrological grounds the ages of the mare basalts are usually interpreted in this way (Turner, 1970; Albee *et al.*, 1970).

(b) Uplift and cooling of plutonic rocks such as anorthosites as a result of major impact events. As was demonstrated in the previous section it is likely that material excavated from depths of 10 km or greater will not have commenced significant argon retention until the time of uplift.

(c) Resetting of K–Ar ages by residence in a hot ejecta blanket. The temperatures required for resetting are dependent on the time for which the heat is retained which in turn is dependent on the thickness of the ejecta blanket. We estimate that most lunar rock types buried at a depth of a 100 m would be thoroughly outgassed by starting temperatures of the order of 500°C. Under this heading we would also include melting or solid state recrystallization of material as a result of heating by major impacts.

(d) Resetting or partial resetting of K–Ar ages by heating in minor impact events. Ejecta from minor craters cool very rapidly requiring correspondingly higher temperatures to produce significant argon loss. Evidence in the form of high ages from material from the rims of recent km sized craters (Cone, Camelot, North Ray) indicates that for most of the ejecta heating effects are minimal and insufficient to produce significant argon loss,

In view of the broad geological interpretation of the lunar highlands as material uplifted or deposited by major impacts in the lunar crust we would tend to interpret the highland ages in terms of (b) and (c).

Mare basalt ages

The age of 75055, 3.76 ± 0.05 aeons, is comparable to the average age, 3.84 ± 0.09 aeons, determined previously for three Apollo low K basalts and confirms that the period of extrusion of mare basalts began as early as 3.8 aeons ago. The high age of 75055 as compared to most other mare basalts emphasizes the need to reexamine the Apollo 11 low K suite of rocks. K–Ar ages of Apollo 11 low K rocks have now been determined by at least three laboratories (Turner, 1970, 10003, 10044, 10062; Davis *et al.*, 1971, 10044; Eberhardt *et al.*, 1971, 10003) and appear to be systematically older by approximately 200 million years than the high-K rocks. This effect is not apparent in the Rb–Sr ages which have been determined on two low K rocks; 10058 ($T = 3.63 \pm 0.2$ aeons) and 10044 ($T = 3.71 \pm 0.11$ aeons) (Papanastassiou *et al.*, 1970) but is not precluded by that data. The only direct comparison with Ar^{40}–Ar^{39} ages for 10044 ($T = 3.73 \pm 0.09$ aeons, Turner, 1970; T = 4.0 ± 0.07 aeons, Davis *et al.*, 1971) indicates a larger conflict between individual Ar^{40}–Ar^{39} ages than between Ar^{40}–Ar^{39} and Rb–Sr. There is clearly a need for more precise age determinations on a number of Apollo 11 low K rocks.

If the high K–Ar ages are confirmed we would interpret the Apollo 11 data as indicating a sequence of extrusive lava flows commencing with the low K basalts at 3.8 aeons or earlier and ending with the high K basalts at 3.6 aeons. Such a sequence would not conflict with the evidence for the major lunar basins being formed prior to 3.9 aeons (next section). We should note that whether such a sequence exists or not it is clearly the age of 3.6 aeons which is relevant to considerations of surface crater densities.

Highland ages

The picture that has emerged from the measurement of ages from the lunar highlands is both striking and surprising. We find no ages greater than 4.05 aeons and no well-defined ages (i.e., with relatively simple release patterns) younger than 3.88 aeons, although we should point out that Husain and Schaeffer (1973) have recently reported a number of ages around 4.2 aeons for light matrix breccias from Apollo 16. Since, as we shall argue below, the ages obtained probably date at least three of the major impact basins on the moon and bracket the ages of three others it is clear that much of the moon's present appearance was generated in a geologically brief but intense period of bombardment.

We have built up a tentative but self consistent picture on the basis of the following evidence and assumptions.

(a) The age of 3.76 ± 0.05 aeons for the Taurus-Littrow (A17) lava flows places a very firm lower limit to the period of intense bombardment of the lunar surface which produced the large basins such as Imbrium. The Apollo 11 low-K rocks could also be used in this context if they are indeed early basalt flows since to our knowledge there is no evidence for interbedded Imbrium ejecta in the Apollo 11 rock suite.

(b) The time of the Serenitatis impact is probably provided by the age of the highland rocks from Taurus-Littrow (A17), that is to say 3.98 ± 0.05 aeons. Unless the sample we have dated represents a covering of later deposits we would expect, on the basis of the location of the Apollo 17 site in the mountains surrounding the Serenitatis Basin, that it represents material excavated, or uplifted, from great depth and therefore that argon retention began only after the impact. The sequence of basin formation times on geological grounds is, Serenitatis, Nectaris, Humorum, Crisium, Imbrium, and Orientale, and if the age assignment for Serenitatis is correct, 6 of the major impact basins are bracketed in a 200 m.y. period.

(c) We infer an age of 3.88 ± 0.05 aeons for the Imbrium event based on the ages of the Fra Mauro basalts (14073, 14310, and 14001,7,3) and 15382. This assignment is based on the geological interpretation of the Fra Mauro site (A14) as ejecta from the Imbrium impact and on the assumption of a common place of origin for 15382 and the Apollo 14 basalts, based on their chemical similarities. These assumptions would imply that the rock ages are greater than or, if argon outgassing was complete, equal to the age of the Imbrium impact. A corollary of this interpretation would be that the ages of 3.95 ± 0.04 aeons determined for a second class of Fra Mauro basalts, characterized by lower initial strontium (Papanastassiou and Wasserburg, 1971) represent material which crystallized in the pre-Imbrium region prior to the impact and was not outgassed *or* that it represents material deposited in the Fra Mauro region from an earlier impact and underlies the Imbrium ejecta. The arguments in favor of one assignment or the other (i.e., 3.88 or 3.95 aeons) for the Imbrium event are not very strong. Indeed the 0.07 aeon difference in the ages is only marginally significant.

(d) On the assumption that material at the Luna 20 site between Mare Crisium and Mare Fecunditatis is dominated by Crisium ejecta (since the Crisium Basin is on geological grounds more recent than the Fecunditatis Basin) we interpret the age of 4.0 ± 0.3 aeons determined for L2015 as probably representative of the Crisium event. Because of the analytical problems associated with L2015 this age is too inaccurate to be particularly useful. The more precise age of 3.9 ± 0.04 aeons determined by Huneke *et al.* (1973) on 22006 (and 22007) we therefore take to represent the time of the Crisium impact.

(e) The interpretation of the Apollo 16 data presents the most serious difficulties in view of the location of the Apollo 16 site in the densely cratered Southern Highlands. Geological interpretations of this region are most uncertain in their ability to identify the complex brecciated samples with specific cratering events. The Cayley and Descartes formations, both originally considered to be volcanic land forms, appear from analyses of Apollo 16 rocks to be the products of large impact events. Measurements of crater density and morphology (Soderblom and Boyce, 1972) indicate that the Cayley Plains which occur moonwide as "pools" in highland depressions at altitudes varying by over 2 km are older than the oldest mare (Tranquillitatis) and younger than the Fra Mauro Formation and hence the Imbrium event. This is supported by the stratigraphic relationship between the Cayley Formation and the furrowed terrain considered to be Imbrium ejecta.

Although crater densities in the Descartes Formation are somewhat less than the Cayley Plains both units may have been formed contemporaneously, with the craters on the hilly Descartes Formation having been erased more efficiently by more active mass wasting. The fact that crater densities in the Cayley Formation are less than in the Fra Mauro Formation does not rule out the possibility that ejecta from basins older than the Imbrium Basin (e.g., Nectaris) may underlie the surface. On the basis of these considerations and the great complexity of the Descartes region we are unable, at this stage, to relate the ages of 67075 (4.04 ± 0.05) and 62295 (3.89 ± 0.05), even tentatively, to specific events but note that they are consistent with the very short period of major impacts inferred in the preceding discussion.

Husain and Schaeffer (1973) report Ar^{40}–Ar^{39} ages around 4.2 aeons for a number of light matrix breccias from Apollo 16. This observation further reflects the great complexity of the Apollo 16 site and suggests to us the presence of underlying debris from earlier impacts. The conclusions of our discussion are bounded to a high degree by the *presumed* association of the age of 76055 with the Serenitatis impact and to a lesser degree by the association of the ages of 22006 and 29007 (Huneke *et al.*, 1973) with the Crisium impact. Clearly more Apollo 17 age determinations are required in order to substantiate or invalidate our conclusions but at this stage the Apollo 16 data does not appear to us to invalidate them.

(f) The age of rock 12013, 4.04 ± 0.07 aeons is consistent with it having been formed (from pre-existing Rb rich material, Lunatic Asylum, 1970) as a result of one of the major impact events but again we cannot assign a specific lunar event to 12013. We note however the high radioactivity detected by the gamma ray spectrometer experiment (Arnold *et al.*, 1972) in the region of Oceanus Procellarum.

(g) We have not found any evidence, so far, from Ar^{40}–Ar^{39} experiments of events prior to 4.05 aeons and it is clear that the record prior to that has been erased in most of the samples collected, by the major basin forming impacts. This is not surprising in view of the fact that by far the greater proportion of material excavated will have come from depths where significant argon retention is impossible. Evidence for the early record is provided by Rb–Sr and U–Pb measurements and we follow Tera *et al.* (1973, and earlier references) in their interpretation of an early differentiation of the lunar crust around 4.5 aeons ago.

The details of our interpretation of the data may be subject to modification, as sample relationships at various landing sites become clearer, but the major features seem to be established. We have adopted the following sequence of events as a working hypothesis for the time scale of lunar geology (times are in aeons, and the ages for the mare basalts are representative only of the landing sites not necessarily for the whole maria):

Formation of radioactive crust	4.5
Impacts producing the Australe, Nubium, Tranquillitatis Fecunditatis, and Smythii basins	4.5–4.0
Formation of Serenitatis Basin	4.0
Formation of Nectaris and Humorum basins	4.0–3.9
Formation of Crisium and Imbrium basins	3.9
Formation of Orientale Basin	3.9–3.8
Extrusion of low K basalts in Mare Tranquillitatis and Taurus-Littrow	3.8
Extrusion of high K basalts in Mare Tranquillitatis	3.6
Extrusion of basalts in Mare Fecunditatis	3.4
Extrusion of basalts in Mare Imbrium	3.3
Extrusion of basalts in Oceanus Procellarum	3.2

(sequence of basin forming events from Stuart-Alexander and Howard, 1970).

The observation that several major impact features and innumerable smaller ones were formed on the moon within the time period 4.0 to 3.9 aeons poses severe problems in understanding how the moon could have collided with several large objects in such a short time span, 600 million years after the solar system formed. It will undoubtedly raise the possibility that we are witnessing the tail end of disruption brought about by capture of the moon by the earth. It is worth considering briefly some of the implications of this view which might regard the impacting objects as material torn from the moon during capture at distances close to the Roche limit. The calculations of Öpik (1961), based on measurements of the ellipticities of lunar craters, suggest that the craters were formed when the moon was at least 5 earth radii from the earth. This appears to place severe constraints on explanations of the basins and craters as products of infalling debris following capture, since it requires that a significant amount of material be perturbed into orbits extending beyond 5 earth radii and not collide with the moon until the moon has receded sufficiently. The calculations of MacDonald (1964) indicate that the rate of recession to 5 earth radii is extremely rapid but whether the process is a viable one we are unable to say. If the differences in rock ages are taken to imply that basin formation extended for periods of at least 100 million years the constraints become even more severe since in that time the orbit would have expanded to the order of 30 earth radii.

Alternative explanations of the rapid sequence of impacts include the collision with smaller earth satellites as the moon recedes due to tidal friction. We note here the constraint that in 100 million years the moon's orbit typically recedes by only 3000 km (assuming that rapid recession following capture is discounted).

A number of types of explanation in terms of collisions with objects in orbit around the sun are possible. It is possible, for example, that the collisions represent the final sweeping up of debris from the formation of the solar system.

It now seems implausible to explain the collision with a large object at 4.0 aeons as a statistical freak since there appear to be 6 statistical freaks and moreover they appear, on the basis of the densely cratered highlands, to have been accompanied by myriads of smaller freaks. Perhaps instead we are looking at the bombardment of the moon by the collision products of some early asteroidal break up. It is interesting to note in this context the observation of an iron meteorite with an age of 3.8 aeons (Burnett and Wasserburg, 1967), and of an achondrite, Pasamonte, which appears to have suffered episodic Ar^{40} loss at 4.1 aeons (Podosek and Huneke, 1973). It seems likely to us that explanations of the lunar (and implied terrestrial) bombardment might be found by further examination of meteoritic material.

Acknowledgment—This work was supported by Grant No. (GR/3/1715) from the Natural Environment Research Council. Irradiations were provided under a joint agreement between the Science Research Council and the Atomic Energy Authority (Grant No. B/RG/26562).

REFERENCES

Agrell S. O., Agrell J. E., Arnold A. R., and Long J. V. P. (1973) Some observations on rock 62295 (abstract). In *Lunar Science—IV*, pp. 15–17. The Lunar Science Institute, Houston.

Albee A. L., Burnett D. S., Chodos A. A., Eugster O. J., Huneke J. C., Papanastassiou D. A., Podosek F. A., Price Rus G. III, Sanz H. G., Tera F., and Wasserburg G. J. (1970) Ages, irradiation history and chemical composition of lunar rocks from the Sea of Tranquillity. *Science* **167**, 463–466.

Alexander E. C. Jr., Davis P. K., and Reynolds J. A. (1972) Rare gas analyses on neutron irradiated

Apollo 12 samples. *Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta*, Suppl. 3, Vol. 2, pp. 1787–1795. MIT Press.

Alexander E. C. Jr., Davis P. K., Reynolds J. H., and Srinivasan B. (1973) Radiogenic xenon and argon in 14318 and implications (abstract). In *Lunar Science—IV*, pp. 30–32. The Lunar Science Institute, Houston.

Behrmann C., Crozaz G., Drozd R., Hohenberg C., Ralston C., Walker R., and Yuhas D. (1973) Radiation history of the Apollo 16 site (abstract). In *Lunar Science—IV*, pp. 54–58. The Lunar Science Institute, Houston.

Burnett D. S. and Wasserburg G. J. (1967) Evidence for the formation of an iron meteorite at 3.8×10^9 years. *Earth Planet. Sci. Lett.* **2**, 137.

Carslaw H. S. and Jaeger J. C. (1959) *Conduction of heat in solids.* Oxford University Press.

Church S. E., Bansal B. M., and Wiesmann H. (1972) The distribution of K, Ti, Zr, U and Hf in the Apollo 14 and 15 materials. In *The Apollo 15 Lunar Samples*, pp. 210–213. The Lunar Science Institute, Houston.

Davis P. K., Lewis R. S., and Reynolds J. H. (1971) Stepwise heating analysis of rare gases from pile-irradiated rocks 10044 and 10057. *Proc. Second Lunar Sci. Conf., Geochim. Cosmochim. Acta*, Suppl. 2, Vol. 2, pp. 1693–1703. MIT Press.

Eberhardt P., Geiss J., Grögler N., Krähenbühl U., Mörgeli M., and Stettler A. (1971) Potassium-argon age of Apollo 11 rock 10003. *Earth Planet. Sci. Lett.* **11**, 245–247.

Eberhardt P., Geiss J. Grögler N., and Stettler A. (1973) Ar^{39}/Ar^{40} ages and Ar^{37}/Ar^{38} exposure ages of lunar samples (abstract). In *Lunar Science—IV*, pp. 206–208. The Lunar Science Institute, Houston.

Fechtig H., Gentner W., and Zähringer J. (1960) Argon bestimmungen an Kalium-mineralien—VII. Diffusion verluste von Argon Mineralein und ihre Auswirkung auf die Kalium-Argon Alterbestimmung, *Geochim. Cosmochim. Acta* **19**, 70.

Huneke J. C., Podosek F. A., and Wasserburg G. J. (1972) Gas retention and cosmic ray exposure ages of a basalt fragment from Mare Fecunditatis. *Earth Planet. Sci. Lett.* **13**, 375–383.

Huneke J. C., Podosek F. A., and Wasserburg G. J. (1973) An argon bouillabaisse including ages from the Luna 20 site (abstract). In *Lunar Science—IV*, pp. 403–405. The Lunar Science Institute, Houston.

Husain L., Schaeffer O. A., Funkhouser J., and Sutter J. (1972). The ages of lunar material from Fra Mauro, Hadley Rille and Spur Crater. *Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta*, Suppl. 3., Vol. 2, pp. 1557–1567. MIT Press.

Husain L. and Schaeffer O. A. (1973) ^{40}Ar–^{39}Ar Crystallization ages and ^{38}Ar–^{37}Ar ray exposure ages of samples from the vicinity of the Apollo 16 landing site (abstract). In *Lunar Science—IV*, pp. 406–408. The Lunar Science Institute, Houston.

Kirsten T., Deubner J., Horn P., Kaneoka I., Kiko J., Schaeffer O. A., and Thio S. K. (1972) The rare gas record of Apollo 14 and 15 samples. *Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta*, Suppl. 3, Vol. 2, pp. 1865–1889. MIT Press.

LSPET (1972) Preliminary examination of lunar samples. In *Apollo 16 Preliminary Science Report*, NASA SP-315, Sec. 7B.

Lunatic Asylum (1970) Mineralogic and isotopic investigations on lunar rock 12013. *Earth Planet. Sci. Lett.* **9**, 137–163.

MacDonald G. J. F. (1964) Tidal friction. *Rev. Geophys.* **2**, 467–539.

Merrihue C. M. and Turner G. (1966) Potassium-argon dating by activation with fast neutrons. *J. Geophys. Res.* **71**, 2852–2857.

Mizutani H. and Newbigging D. F. (1973) Elastic wave velocities of Apollo 14, 15 and 16 rocks and thermal conductivity profile of the lunar crust (abstract). In *Lunar Science—IV*, pp. 528–530. The Lunar Science Institute, Houston.

Nyquist L. E., Gast P. W., and Church S. E. (1972) Rb–Sr systematics for chemically defined Apollo 15 materials. In *The Apollo 15 Lunar Samples*, pp. 380–384. The Lunar Science Institute, Houston.

Öpik E. J. (1961) Tidal deformations and the origin of the moon. *Astron. J.* **66**, 60.

Papanastassiou D. A., Wasserburg G. J., and Burnett D. S. (1970) Rb–Sr ages of lunar rocks from the Sea of Tranquillity. *Earth Planet. Sci. Lett.* **8**, 1–19.

Papanastassiou D. A. and Wasserburg G. J. (1971) Rb–Sr ages of igneous rocks from the Apollo 14 mission and the age of the Fra Mauro formation. *Earth Planet. Sci. Lett.* **12**, 36–48.

Podosek F. A., Huneke J. C., and Wasserburg G. J., (1972) Gas retention and cosmic ray exposure ages of lunar rock 15555. *Science* **175**, 423–425.

Podosek F. A. and Huneke J. C. (1973) Argon 40–Argon 39 chronology of four calcium-rich achondrites. *Geochim. Cosmochim. Acta* **37**, 667–684.

Reed G. W. Jr., Jovanovic S., and Fuchs L. (1972) Trace element relations between Apollo 14 and 15 and other lunar samples and the implications of a moonwide Cl-KREEP coherence and Pt-metal noncoherence. *Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta,* Suppl. 3, Vol. 2, pp. 1989–2001. MIT Press.

Soderblom L. A. and Boyce J. M. (1972) Relative ages of some near-side and far side terra plains based on Apollo 16 metric photography. In *Apollo 16 Preliminary Science Report,* NASA S.P.-315. Sect. 29A.

Stuart-Alexander D.E. and Howard K. A. (1970) Lunar Maria and Circular Basin—a review. *Icarus* **12**, 440–456.

Taylor L. A., Mao H. K., and Bell P. M. (1973) Apollo 16 "rusty rock" 66095 (abstract). In *Lunar Science—IV,* pp. 715–716. The Lunar Science Institute, Houston.

Tera F., Papanastassiou D. A., and Wasserburg G. J. (1973) A lunar cataclysm at ~ 3.95 AE and the structure of the lunar crust (abstract). In *Lunar Science—IV,* pp. 723–725. The Lunar Science Institute, Houston.

Turner G. (1970) Argon 40–Argon 39 dating of lunar rock samples. *Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta,* Suppl. 1, Vol. 2, pp. 1665–1684. (Pergamon), and *Science* **167**, 466–468.

Turner G. (1971a) ^{40}Ar–^{39}Ar age and cosmic ray irradiation history of the Apollo 15 anorthosite, 15415. *Earth Planet. Sci. Lett.* **14**, 169–175.

Turner G. (1971b) Argon 40–Argon 39 dating; the optimization of irradiation parameters. *Earth Planet. Sci. Lett.* **10**, 227–234.

Turner G. (1971c) ^{40}Ar–^{39}Ar ages from the lunar maria. *Earth Planet. Sci. Lett.* **11**, 169–191.

Turner G., Huneke J. C., Podosek F. A., and Wasserburg G. J. (1971) ^{40}Ar–^{39}Ar ages and cosmic ray exposure ages of Apollo 14 samples. *Earth Planet. Sci. Lett.* **12**, 19–35.

Turner G., Cadogan P. H., and Yonge C. J. (1973) Apollo 17 age determinations. *Nature* **242**, 513–515.

Ulrich G. E. (1973) A geologic model for North Ray Crater (abstract). In *Lunar Science—IV,* pp. 745–747. The Lunar Science Institute, Houston.

Wilshire H. G., Stuart-Alexander D. E., and Jackson E. D. (1973) Petrology and classification of the Apollo 16 samples (abstract). In *Lunar Science—IV,* pp. 784–786. The Lunar Science Institute, Houston.

York D., Kenyon W. J., and Doyle R. J. (1972) ^{40}Ar–^{39}Ar ages of Apollo 14 and 15 samples. *Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta,* Suppl. 3, Vol. 2, pp. 1613–1622. MIT Press.