Reports

Lunar Volcanism: Age of the Glass in the Apollo 17 Orange Soil

Abstract. *The formation age of the glass in the orange soil brought back by the Apollo 17 astronauts from the Taurus-Littrow valley has been measured by the* ^{40}Ar-^{39}Ar *stepwise heating technique to be* $3710 \pm 60 \times 10^6$ *years. The orange glass is thus much older than expected. Four fragments, presumably from the subfloor basalt, were also analyzed and have crystallization ages of* 3710 ± 70, 3720 ± 50, 3770 ± 50, *and* $3790 \pm 70 \times 10^6$ *years. These ages do not provide evidence for recent extensive lunar volcanism. The magmatic activity in the Sea of Serenity and the Sea of Tranquillity occurred very close in time, if not contemporaneously. The volcanic activity in the Sea of Tranquillity and the Sea of Serenity may have been triggered by the impact event forming the Sea of Rains basin.*

One of the major objectives of the Apollo 17 lunar mission was to investigate and sample the dark mantle in the Taurus-Littrow valley adjacent to the Sea of Serenity. The dark mantle, considered to be of volcanic origin, probably erupted from numerous vents. A remarkable discovery, made on the lunar surface by the Apollo 17 astronauts, of bright orange material circumferential to Shorty Crater suggests a possible volcanic fumarole (*1*). From the fresh appearance and the low crater counts, it was suggested (*1*) that the dark mantle and the orange soil could represent recent lunar volcanism. Positive evidence for extensive recent lunar volcanism would be unexpected on the basis of current models of lunar evolution.

We determined radiometric ages by the ^{40}Ar-^{39}Ar stepwise heating technique. Details of this technique as used in our laboratory have been reported earlier (*2, 3*). We sieved a 0.9-g portion of the orange soil (sample 74220,39) and obtained a 0.12-g sample of fragments larger than 150 μm. The nonglassy material was picked out by hand. A 85-mg sample of orange glass so obtained and several basalt fragments from the soil (sample 75083,2) collected at station 5 of the Apollo 17 landing site were irradiated, along with the hornblende standard NL-25,2 in the core of the Brookhaven high flux beam reactor. The hornblende standard has a ^{40}Ar content of $7.25 \pm 0.14 \times 10^{-5}$ cm^3/g (STP) and a K content of 0.302 ± 0.006 percent as determined by G. N. Hanson by isotope dilution mass spectrometry measurements.

In the ^{40}Ar-^{39}Ar dating technique, it is essential to measure accurately the ^{40}Ar produced from the in situ decay of ^{40}K (denoted in this report as ^{40}Ar*) and the ^{39}Ar produced by an (n,p) reaction of ^{39}K (denoted as ^{39}Ar*). Contributions to Ar isotopes by neutron irradiation of different elements were accounted for on the basis of measured production rates. These corrections are discussed elsewhere (*3*) and noted in the footnote of Table 1, where the Ar isotopic data for the glass and basalts are given.

In lunar samples, ^{36}Ar and ^{38}Ar are formed by the interaction of cosmic-ray protons, largely with Ca. In addition, ^{36}Ar and ^{38}Ar are present from the ion implantation of solar-wind Ar. We

Table 1. Argon isotopic data for orange glass 74220,39 and basalt fragment 75083,2,5.

Temperature (°C)	^{39}Ar* ($\times 10^{-8}$ cm^3/g at STP)	^{40}Ar/^{39}Ar*	^{40}Ar/^{36}Ar	^{36}Ar/^{38}Ar	^{39}Ar*/^{37}Ar	Exposure age ($\times 10^6$ years)	^{40}Ar*/^{39}Ar*	Apparent K-Ar age† ($\times 10^9$ years)
Sample 74220,39 (85 mg)								
650	0.17 ± 0.01	297 ± 17	10.58 ± 0.14	5.22 ± 0.09	0.182 ± 0.006	230 ± 230	205 ± 13	4.18 ± 0.2
800	0.77 ± 0.01	244 ± 3	8.17 ± 0.03	5.14 ± 0.02	0.0360 ± 0.0003	87 ± 40	146 ± 13	3.62 ± 0.15
900	1.20 ± 0.02	200 ± 4	16.19 ± 0.08	4.99 ± 0.11	0.0271 ± 0.0005	45 ± 19	160 ± 6	3.76 ± 0.08
1000	1.63 ± 0.02	167 ± 2	47.0 ± 0.7	4.60 ± 0.11	0.0252 ± 0.0003	26 ± 16	156 ± 3	3.72 ± 0.05
1050	1.34 ± 0.02	155 ± 2	56.4 ± 0.4	4.18 ± 0.07	0.0228 ± 0.0003	33 ± 5	147 ± 2	3.62 ± 0.05
1100	1.03 ± 0.02	159 ± 3	39.5 ± 0.4	4.48 ± 0.14	0.0208 ± 0.0005	31 ± 9	147 ± 5	3.62 ± 0.06
1150	1.76 ± 0.02	164 ± 2	46.6 ± 0.3	4.41 ± 0.14	0.0197 ± 0.0004	27 ± 7	153 ± 3	3.69 ± 0.05
1200	3.14 ± 0.04	161 ± 2	82.4 ± 1.1	3.64 ± 0.07	0.0195 ± 0.0003	34 ± 6	155 ± 2	3.72 ± 0.05
1250	3.88 ± 0.02	160 ± 1	84.7 ± 1.0	3.57 ± 0.04	0.0192 ± 0.0001	34 ± 5	154 ± 1	3.70 ± 0.05
1300	1.89 ± 0.03	165 ± 3	67.6 ± 0.7	3.45 ± 0.04	0.0178 ± 0.0002	47 ± 5	158 ± 3	3.75 ± 0.05
1350	0.43 ± 0.01	160 ± 6	155 ± 6	2.45 ± 0.18	0.0176 ± 0.0006	42 ± 8	158 ± 7	3.74 ± 0.09
1600	0.54 ± 0.01	165 ± 8	216 ± 9	1.58 ± 0.07	0.0178 ± 0.0004	64 ± 6	164 ± 8	3.80 ± 0.09
Sample 75083,2,5 (55.8 mg)								
650	2.56 ± 0.04	60 ± 1	600 ± 35	1.44 ± 0.16	0.035 ± 0.008	340 ± 80	60 ± 1	2.30 ± 0.05
800	4.90 ± 0.06	145 ± 2	507 ± 7	1.54 ± 0.04	0.283 ± 0.0012	274 ± 21	145 ± 2	3.60 ± 0.05
900	3.62 ± 0.05	162 ± 2	304 ± 9	0.97 ± 0.03	0.0268 ± 0.0010	260 ± 19	162 ± 3	3.78 ± 0.05
1050	3.36 ± 0.05	159 ± 3	169 ± 2	0.79 ± 0.01	0.0260 ± 0.0004	252 ± 16	160 ± 3	3.76 ± 0.05
1150	1.21 ± 0.04	163 ± 4	130 ± 2	0.67 ± 0.01	0.0294 ± 0.0005	285 ± 19	164 ± 5	3.78 ± 0.07
1300	1.29 ± 0.04	145 ± 7	28 ± 1	0.63 ± 0.01	0.0339 ± 0.0006	329 ± 25	144 ± 6	3.60 ± 0.08
1600	0.73 ± 0.04	201 ± 40	31 ± 5	0.62 ± 0.01	0.0402 ± 0.0006	389 ± 25	201 ± 30	4.14 ± 0.29

† Neutron production rates for various isotopes from Ca were measured to be: ^{39}Ar/^{37}Ar = $(6.3 \pm 0.3) \times 10^{-4}$, ^{37}Ar/^{38}Ar = $(6.2 \pm 0.8) \times 10^{-5}$, and ^{36}Ar/^{37}Ar = $(22.8 \pm 0.6) \times 10^{-5}$. The Ar isotopic neutron production ratios from K are: ^{38}Ar/^{39}Ar = $(1.00 \pm 0.01) \times 10^{-2}$ and ^{40}Ar/^{39}Ar $< 2 \times 10^{-3}$ (see text).

resolved the cosmogenic and solar-wind components by using cosmogenic (^{36}Ar/^{38}Ar) = 0.62 and solar-wind (^{36}Ar/^{38}Ar) = 5.3. The solar-wind ^{36}Ar is generally accompanied by excess ^{40}Ar, as indicated by the low ^{40}Ar/^{36}Ar ratios listed in column 4 of Table 1. The excess ^{40}Ar has been interpreted to be due to the ion implantation (*4*). The solar-wind ^{36}Ar and excess ^{40}Ar will be referred to here as $^{36}Ar_{tr}$ and $^{40}Ar_{tr}$, respectively. It is necessary to correct for $^{40}Ar_{tr}$ to obtain $^{40}Ar^*$. The $^{40}Ar_{tr}/^{36}Ar_{tr}$ ratios in lunar soils and breccias commonly vary from 0.5 to 2. The variations in the $^{40}Ar_{tr}/^{36}Ar_{tr}$ ratios make it necessary to determine this ratio for each individual sample. For the glass in the orange soil we achieved this in the following manner.

Assuming constant ($^{40}Ar^*/^{39}Ar^*$) and ($^{40}Ar_{tr}/^{36}Ar_{tr}$) ratios, we may write

$$(^{40}Ar/^{36}Ar_{tr}) = (^{40}Ar_{tr}/^{36}Ar_{tr}) + (^{40}Ar^*/^{39}Ar^*)\,(^{39}Ar^*/^{36}Ar_{tr}) \quad (1)$$

Thus a plot of ($^{40}Ar/^{36}Ar_{tr}$) versus ($^{39}Ar^*/^{36}Ar_{tr}$) should yield a straight line. Figure 1a is such a plot for the orange glass (sample 74220,39). Only minor deviations from linearity are observed. A least-squares fit gives an intercept value of 3.3 ± 0.2 and a slope of 154 ± 3. We made the $^{40}Ar_{tr}$ correction, using a ($^{40}Ar_{tr}/^{36}Ar_{tr}$) ratio of 3.3 ± 0.2. The $^{40}Ar^*/^{39}Ar^*$ ratios can be converted to an age, t, by means of the relation

$$t = 4.34 \log \left[1 + \frac{\lambda}{\lambda_e} \cdot \frac{(^{40}Ar^*/^{40}K)_{std}}{(^{40}Ar^*/^{39}Ar^*)_{std}} \cdot (^{40}Ar^*/^{39}Ar^*)_s\right] \quad (2)$$

where the subscript std refers to the hornblende standard and the subscript s refers to the lunar sample, $\lambda = 5.305 \times 10^{-10}$ per year and $\lambda_e = 0.585 \times 10^{-10}$ per year (the subscript e refers to electron capture). The ^{40}Ar-^{39}Ar ages are determined from the high-temperature constant $^{40}Ar^*/^{39}Ar^*$ ratios, where $^{40}Ar^*$ and $^{39}Ar^*$ are released from the most retentive K-sites. The ages calculated for individual temperature fractions from $^{40}Ar^*/^{39}Ar^*$ ratios (column 8, Table 1) are plotted in Fig. 1b. The ages decrease with temperature to a minimum of 3.62×10^9 years at 1050°C. The high ages at lower temperatures reflect a slight inadequacy in the $^{40}Ar_{tr}$ correction. A constant age, within experimental uncertainties, is observed for fractions from 1150° to 1350°C. Between these temperatures, 62 percent of the total $^{39}Ar^*$ is released.

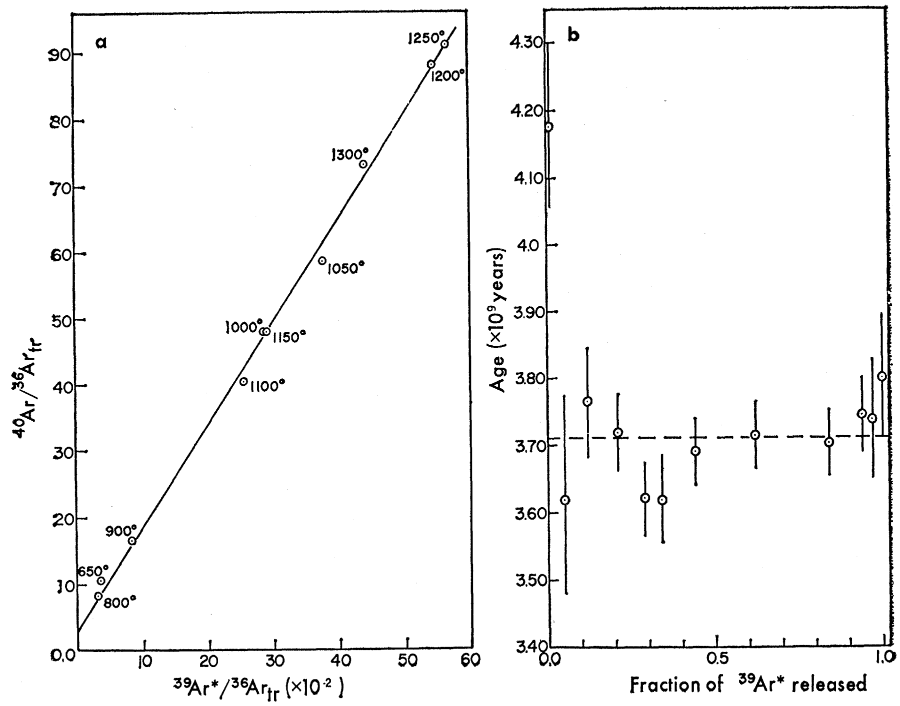

Fig. 1. (a) A plot of $^{40}Ar/^{36}Ar_{tr}$ versus $^{39}Ar^*/^{36}Ar_{tr}$ for the lunar orange glass 74220,39. (b) A plot of the ^{40}Ar-^{39}Ar age versus the cumulative fraction of $^{39}Ar^*$ released. The $^{40}Ar_{tr}$ correction has been made on the basis of an intercept $^{40}Ar/^{36}Ar_{tr}$ ratio of 3.3 ± 0.2 obtained from (a).

A mean ^{40}Ar-^{39}Ar age of 3.71 ± 0.06 × 10^9 years is obtained from this plateau. The uncertainty reported is calculated for a 95 percent confidence level and includes the uncertainties in the ^{40}Ar/K ratio of the hornblende standard, in the precision of measurements of the $^{40}Ar^*/^{39}Ar^*$ ratios for the sample and the standard, and in the $^{40}Ar_{tr}$ correction as described earlier. If the $^{40}Ar_{tr}$ correction were made using an $^{40}Ar_{tr}/^{36}Ar_{tr}$ ratio of 0.5, the ^{40}Ar-^{39}Ar age would increase by 50 × 10^6 years. On the other hand, if a $^{40}Ar_{tr}/^{36}Ar_{tr}$ ratio of 5 were used, the age would decrease by 30 × 10^6 years.

We have also analyzed four basalt fragments from the soil at station 5 of the Apollo 17 landing site. The ages (in 10^9 years) are as follows: 3.71 ± 0.07, 3.72 ± 0.05, 3.77 ± 0.05, and 3.79 ± 0.07 for soil fragments 75083,2,8; 75083,2,9; 75083,2,5; and 75083,2,1, respectively. Detailed temperature release data for a typical sample are given in Table 1. The $^{40}Ar^*/^{39}Ar^*$ release pattern is typical of lunar mare basalts. The 650° and 800°C fractions indicate $^{40}Ar^*$ diffusion loss followed by a $^{40}Ar^*/^{39}Ar^*$ plateau. We have calculated an accurate age of 3.77 ± 0.05 × 10^9 years.

The cosmic-ray exposure ages were determined from the ^{38}Ar produced by galactic cosmic-ray interactions with Ca and from the ^{37}Ar produced by an (n,α) reaction on Ca during neutron irradiation. Details of the method have been given elsewhere (*3*). The exposure age of the glass of the orange soil is 32 ± 4 × 10^6 years. The exposure ages of the basalt fragments (in 10^6 years) are as follows: 180 ± 20, 100 ± 10, 260 ± 30, and 400 ± 40 for lunar soil fragments 75083,2,8; 75083,2,9; 75083,2,5; and 75083,2,1, respectively.

The ^{40}Ar-^{39}Ar ages of the orange glass and the subfloor basalt fragments range between 3.71 and 3.79 × 10^9 years. The subfloor unit at Taurus-Littrow valley is possibly an extension of the mare flooding of the Sea of Serenity (*1*). If so, the basalt would date the filling of the Sea of Serenity at 3.75 ± 0.05 × 10^9 years. Most of the basalts from the Sea of Tranquillity have similar ages, in the range from 3.6 to 3.7 × 10^9 years (*5*). As the event forming the Sea of Rains basin has been dated at 3.8 ± 0.1 × 10^9 years (*2, 6*), the basalt flooding of the Tranquillity and Serenity basins must have occurred shortly after the excavation of the Sea of Rains. Indeed, the impact forming the Sea of Rains may have triggered the basalt filling of the Sea of Tranquillity and the Sea of Serenity. On the other hand, the much younger ages, 3.2 to 3.4 ×10^9 years, for the Marsh of Decay (*7*) and the Ocean of Storms (*5*) indicate that these basalt flows cannot be associated with the impact forming the Sea of

Rains basin. The ages observed here and those from previous missions do not provide evidence for extensive volcanism in the last 3×10^9 years of lunar history.

Glasses on the moon can form either by impact or by volcanic processes. The age indicates that the glass of the orange soil formed close in time to the volcanic activity in the Sea of Serenity, $3.75 \pm 0.05 \times 10^9$ years ago. The orange soil certainly was not formed by a recent fumarole. The young exposure age, $32 \pm 4 \times 10^6$ years, found for the glass of the orange soil is in agreement with its fresh appearance on the lunar surface. Since the orange soil was found around Shorty Crater, it may have been exposed by the formation of Shorty Crater.

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Late Cretaceous (Maestrichtian?) Silicoflagellates from the Alpha Cordillera of the Arctic Ocean

Abstract. *A Late Cretaceous (probably Maestrichtian) silicoflagellate assemblage has been recovered for the first time from the middle section of a core taken from the Alpha Cordillera in the central Arctic Ocean. The finding of* Globigerina pachyderma *in the top and very rarely in the bottom part of the core suggests a faulting or slumping process in the area.*

Significant progress has been made recently concerning the history of the Arctic Basin. Discussions of the paleoclimatology and the magnetic polarity of late Cenozoic deep-sea sediments have been based on sediment cores collected from Fletcher's Ice Island (T-3) (*1*). Furthermore, Karasik (*2*) estimated the age of the Eurasia Basin to be approximately 60 to 70 million years from geomagnetic polarity history; and the magnetic profile records and comparison with the North Atlantic led Vogt and Ostenso (*3*) to suggest that sea-floor spreading ceased along the Alpha Cordillera 40 million years ago. Spreading along this axis was active at least 60 million years ago, and initiation of spreading may have been as early as 220 million years ago. According to Pitman and Talwani (*4*), the Nansen Ridge has been the locus of all the Arctic Ocean spreading for the past 63 million years. All of these studies make it clear that, until now, the occurrence of pre-Pliocene deposits has not been confirmed.

Core 437 was taken at 85°59.87′N and 129°58.76′W at a depth of 1584 m from Fletcher's Ice Island (T-3), on 2 September 1969 (Fig. 1). The core is 282 cm long. Lithologically, the upper 46 cm consists of "normal" Arctic gray-brown [2.5Y 5/4, according to Munsell's *Soil Color Chart* (*5*)] lutite. Below this is 172 cm of bright orange yellow (2.5Y 6/6) tuffaceous lutite. Bedding is very prominent in this sequence and makes an apparent angle of 45° to the horizontal. X-rays of the clay minerals in three samples from this interval showed approximately 40 percent illite, 20 percent chlorite, 10 to 20 percent kaolinite, and 5 to 30 percent montmorillonite. Underlying this unit is 64 cm of dark brown (5Y 3/2) lutite. Contacts may be unconformable.

Core sediments are divided into 15-cm segments and numbered consecutively upward. Paleomagnetic work at 5-cm intervals shows normal polarity throughout the core. Planktonic Foraminifera, *Globigerina pachyderma* (Ehrenberg) and fewer *G. quinqueloba* Natland, both cold-water species, are found in the upper and lower portions of the core. *Globigerina pachyderma* is present in the upper 46 cm (segments 19 through 17) and very rarely in the lower segments (6 and 1). A few specimens of *G. quinqueloba* are also identified in these segments.

Samples from the center of each segment were treated for examination of the silicoflagellate assemblage (*6*). Only the middle part of the core (segments 16 through 2) contained abundant silicoflagellates. The assemblage is rather monotonous, consisting of the following taxa (Fig. 2), discussed in order of decreasing abundance.

Vallacerta siderea, originally described by Schulz (*7*) from West Prussia, is the most dominant species; individuals have four to eight radial

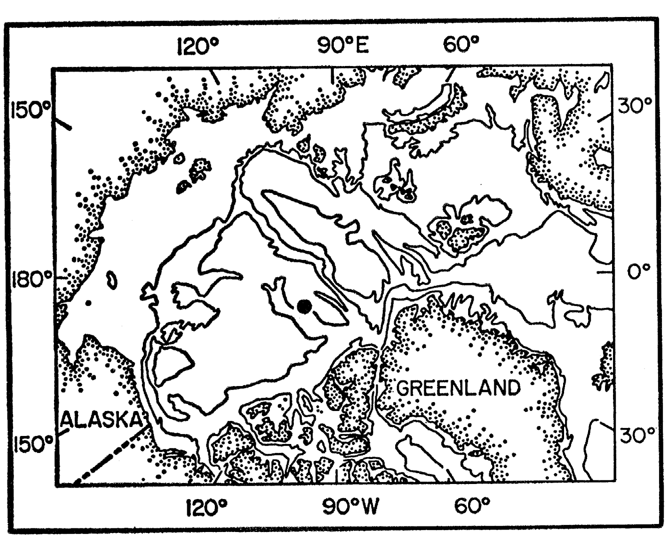

Fig. 1. Index map of the Arctic Ocean and the location of core 437 from Fletcher's Ice Island (T-3) (filled circle).