with frequency would probably limit the accurate measurement of ocean-wave spectra if ionospheric propagation were used.

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1 June 1970; revised 29 July 1970

Potassium-Argon Ages of Lunar Rocks from Mare Tranquillitatis and Oceanus Procellarum

Abstract. *Crystalline rocks from Mare Tranquillitatis have yielded potassium-argon dates as old as 3.8×10^9 years. Crystalline rocks from Oceanus Procellarum give potassium-argon ages as old as 2.8×10^9 years. Evidently the maria are ancient features of the moon and were not formed contemporaneously, a conclusion that also has been verified by other methods. The potassium-argon ages of rocks from Oceanus Procellarum show much more loss of argon than the rocks from Mare Tranquillitatis, an indication that the rocks at Oceanus Procellarum have experienced more severe shock effects or longer cooling rates.*

Analyses of argon in the Apollo 11 crystalline rocks returned from Mare Tranquillitatis were performed in the National Aeronautics and Space Administration Lunar Receiving Laboratory. When these determinations are combined with the best available potassium values, in many cases from adjacent samples (*1, 2*), these rocks give K-Ar ages in the range of 2.2 to 3.8×10^9 years.

We have recently determined K-Ar ages of 21 whole rock samples returned by Apollo 12 from Oceanus Procellarum. These ages are the first of this type to be obtained on Apollo 12 material. We measured the argon content by mass spectrometry, using the basic techniques described previously (*1, 3*). The potassium content, in most cases in adjacent samples, was determined by optical emission and atomic adsorption spectroscopy (*3, 4*). The potassium content for rock 12054 was obtained by gamma-ray analysis and that for rock 12055 was obtained from the average of Apollo 12 crystalline rocks (*3*).

A histogram of K-Ar ages for 20 Apollo 12 rocks is shown in Fig. 1. The precision of the analytical results is such that the error of the K-Ar ages is less than 0.1×10^9 years. For comparison, the histogram of Apollo 11 rocks is also given (*5, 6*). The Apollo 12 samples show a range in K-Ar ages of 1.4 to 2.8×10^9 years.

An exceptional Apollo 12 rock not shown on the histogram of Fig. 1 is sample 12013. This rock is very different from other lunar rocks of both Apollo 11 and Apollo 12 in both its chemistry and noble gas content (*3*). It appears to be an igneous or volcanic breccia containing about 70 percent anorthitic plagioclase. It is enriched in

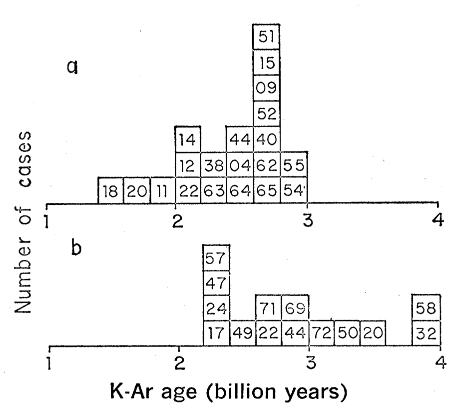

Fig. 1. Histogram of K-Ar ages of lunar rocks. (a) Apollo 12; (b) Apollo 11. The numbers in each block refer to the last two digits of the generic sample number.

K and U and is similar to the residual melt of a fractional crystallization (*3*). Table 1 presents a summary of the crystallization ages of K, U, He, and Ar determined in rock 12013. Three measurements were made for one single chip. The sample for measurement 1 was a single piece, for measurement 2 a crushed piece, and for measurement 3 a finely ground portion. The concentrations of radiogenic argon and helium are very large, as would be expected from the high potassium and uranium contents. It is apparent from the data in Table 1 that the concentrations of radiogenic ^4He and spallogenic ^3He and ^{36}Ar (also ^{21}Ne and ^{38}Ar) are essentially the same for the three measurements of rock 12013. However, the concentration of radiogenic ^{40}Ar in measurement 1, the uncrushed piece, is an order of magnitude greater than that in the crushed samples (measurements 2 and 3). The K-Ar age drops from the high value of 7.9×10^9 years for the uncrushed piece to between 3.6 and 3.8×10^9 years for the crushed sample. This sample apparently contained excess radiogenic argon in voids so that simple crushing released it. The loss of this excess ^{40}Ar must have been essentially complete for after continued grinding of the rock (measurement 3) there was no further reduction in the ^{40}Ar content. That no ^{40}Ar produced in situ was released during crushing can be inferred from the constant concentration of ^4He for all three measurements. The U-He age is only 1.4×10^9 years, far lower than the K-Ar age. This indicates that a portion of the ^{40}Ar produced in situ may have been lost with the ^4He sometime during the rock's history. Thus, the K-Ar ages of measurements 2 and 3 (which are in agreement within the limits of our experimental and sampling errors) may represent a lower limit to the age of crystallization of rock 12013. This age is much greater than any K-Ar age listed in Fig. 1 for other Apollo 12 rocks.

Rock 12013 seems to represent very old material and was ejected to the Apollo 12 landing site a relatively short time ago. The surface exposure age is about 35 million years (*7*). The Xe content consists mainly of a trapped component with about 10 percent spallogenic Xe. There is, however, less than 10^{-11} cm^3/g of excess ^{129}Xe from the decay of extinct ^{129}I (as well as fissiogenic xenon from plutonium), as compared with the xenon component trapped in the solar wind (*8*) and with

Table 1. Crystallization ages of rock 12013.

Measurement No.	Total ^{40}Ar ($\times 10^{-4}$ cm^3/g)	$^{40}Ar/^{36}Ar$	K-Ar age* ($\times 10^9$ years)	Total ^4He ($\times 10^{-4}$ cm^3/g)	$^4He/^3He$	U,Th-He age† ($\times 10^9$ years)
1	81.9	52,700	7.9	36.3	10,300	1.4
2	7.17	4,150	3.6	38.7	8,490	1.5
3	8.27	3,390	3.8	36.0	8,880	1.4

* Calculated from 1.66 percent potassium (*3*). † Calculated from 10.7 percent uranium (*3*).

Table 2. Relative xenon isotopic composition of rock 12013.

^{132}Xe ($\times 10^{-12}$ cm^3/g)	^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
1490	3.92 $\pm$0.04	7.04 $\pm$0.04	17.4 $\pm$0.1	102.9 $\pm$0.5	22.2 $\pm$0.2	107.3 $\pm$0.5	100	37.1 $\pm$0.4	31.1 $\pm$0.2

Table 3. Crystallization ages for lunar rocks ($\times 10^9$ years).

Site	K-Ar*	Rb-Sr	Pb-Pb
Mare Tranquillitatis, Apollo 11	3.8	3.7 (*11*)	3.4–4.2 (*12*)
Oceanus Procellarum, Apollo 12	2.8	3.3 (*10*)	

* Maximum K-Ar ages from histogram (Fig. 1) for rock No. 58,32.

spallation xenon as seen in the spectra of other crystalline rocks from Oceanus Procellarum (*7*). The xenon isotopic composition of rock 12013, normalized to ^{132}Xe, is presented in Table 2.

In Table 3 the K-Ar ages are compared to Rb-Sr and Pb-Pb ages for the lunar rocks. Subsequent analyses by other investigators for rocks at Mare Tranquillitatis also yielded whole rock and separated mineral K-Ar ages in the range 2.2 to 3.9 $\times 10^9$ years (*2*). It appears that the Rb-Sr age and the Pb-Pb ages of Apollo 11 rocks fall at the upper end of the spread in K-Ar ages, an indication that many of these rocks have experienced a partial diffusive loss of their radiogenic argon. This has been corroborated by Turner who determined losses of ^{40}Ar from 13 to 48 percent in seven Apollo 11 rocks (*9*). Thus it appears doubtful that the K-Ar age of a single lunar rock selected at random would represent the time of crystallization; the time of crystallization would tend to be somewhat lower because of gas loss. The difference between rare gas retention ages and Rb-Sr or U-Pb ages can furnish valuable information about the thermal history of the rocks.

We determined the U,Th-He ages for most of the Apollo 11 and Apollo 12 crystalline rocks analyzed by making corrections for ^4He trapped in the solar wind and by estimating the uranium and thorium content, when not directly measured by gamma-ray spectometry, from the measured potassium concentration, utilizing average K/U and Th/U ratios measured by the Lunar Sample Preliminary Examination Team (*1, 3*). Within the large limits of error imposed by the method of determining the parent and daughter concentrations, most of the ages fall within 50 percent of the K-Ar ages for both Apollo 11 and Apollo 12 samples. One might expect that helium would be lost to a much greater extent than argon. The similarity of the helium and argon ages indicates that, to a large degree, helium and argon are lost together from some sites and are quantitatively retained by other sites rather than being lost as a gas by a homogeneous diffusion process. For two rocks, 12002 and 12051 from Oceanus Procellarum, the Rb-Sr age (*10*) is 0.6 $\times 10^9$ years older than the maximum K-Ar age, an indication of an argon loss for each of the 20 rocks dated of over 25 percent. If the Rb-Sr age of rocks is characteristic of all Apollo 12 rocks, then the fractional radiogenic Ar loss of all Apollo 12 rocks reported here is greater than that for rocks at Maria Tranquillitatis. For the Apollo 11 rocks the gas loss is most likely due to shock effects (*9*). Possibly the rocks from Oceanus Procellarum have experienced more severe Ar loss during impact.

The unusual chemical composition and higher K-Ar age of rock 12013 suggests that this rock is not part of the same type of lava flow as that sampled by Apollo 12. This rock may represent a late-stage crystallization in an area of older igneous rocks which was ejected at the Apollo 12 site by a large meteorite impact. Thus its primary origin may have been in a nearby feature such as basement rock from the crater Copernicus or highland material from Fra Mauro. If rock 12013 is a constituent highland-like material, its greater age is consistent with the commonly held belief that the lunar highlands are older and richer in anorthosite.

Isotopic ages indicate that the lunar maria have crystallization ages approaching 4 $\times 10^9$ years (*12*). A comparison of K-Ar ages for rocks at Mare Tranquillitatis and Oceanus Procellarum indicates a difference in K-Ar age of almost 10^9 years, and, considering the uncertainties in argon loss, a difference in age of at least several hundreds of millions of years is indicated. Clearly the maria are ancient features on the moon that originated at times approaching the time of formation of the moon itself. However, the maria are not contemporaneous in a geological sense. Evidently the subsurface of the moon required at least several hundred million years to cool below the crystallization temperature.

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