effect of Milrow on the major fault zone may have gone undetected. Monitoring of microearthquake strain release directly beneath the island, as shown in the lower portion of Fig. 3, will be one attempt to investigate that possibility after any future test. The basic concept is to establish a uniform detection capability within a volume large enough to define precisely the rate of low-level strain release along the thrust zone and any changes therein. Six additional seismographs installed May 1971 within 10 km of Cannikin (a proposed high-yield nuclear test) have already significantly improved the detection capability of the Amchitka seismograph network, both for natural earthquake activity and aftershocks related to explosions.

The conclusions based on the facts as we now have them are: (i) most of the natural earthquake activity occurs along a major thrust fault zone some tens of kilometers beneath Amchitka Island; (ii) because of the low-level of ambient stress in the rocks of Amchitka Island, explosion-induced aftershocks have been small, of short duration, and confined to the immediate vicinity of the explosion: and (iii) the scale of tectonic processes in the Aleutians is on the order of hundreds of kilometers of the arc and is tied to global movements in general. On the basis of this evidence and past nuclear tests, it appears unlikely that there will be any interaction between an underground nuclear explosion on Amchitka Island and an imminent major earthquake.

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Ages of Crystalline Rocks from Fra Mauro

Abstract. *Crystallization ages for six rocks from Fra Mauro have been measured by the argon-40–argon-39 method. All six rocks give an age of* $3.77 \pm 0.15 \times 10^9$ *years, which is the same as for fragmental rocks from this site. It is concluded that the Imbrium event and the crystallization of a significant portion of the pre-Imbrian basalts were essentially contemporaneous.*

Crystallization ages based on several independent methods for Apollo 11 and Apollo 12 rocks have grouped at 3.7 and 3.3×10^9 years (*1*). The relatively young ages for these rocks indicate fairly intense activity on the moon during its first billion years. The lunar highlands are expected to contain the records prior to 3.7×10^9 years ago. Fra Mauro, the Apollo 14 landing site, is near a lunar highland area and contains an extensive blanket of material that was ejected from the Mare Imbrium basin by the Imbrium impact (*2, 3*), one of the last major events in the evolution of the premare lunar surface. It

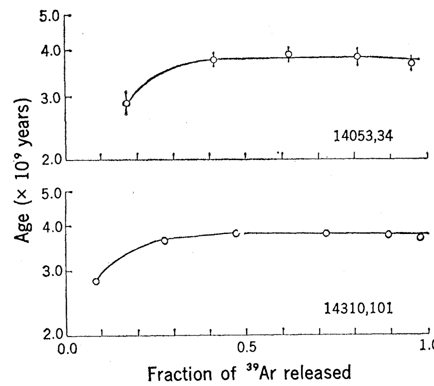

Fig. 1. The $^{40}Ar/^{39}Ar$ release pattern of lunar rocks 14053,34 and 14310,101.

could, then, be expected that some "exotic" rocks (pre-Imbrian basalts) with crystallization ages approaching the age of the solar system would be found in the Fra Mauro region. We have earlier reported (*4*) ages of some fragmental rocks from this region. Here we report on the crystallization ages of the only two igneous rocks larger than 50 g brought back by Apollo 14 astronauts, and we also report the ages of four basalt fragments from various samples of coarse fines.

The lunar rocks were dated by the ^{40}Ar-^{39}Ar method, which has been described in detail by Merrihue and Turner (*5*), Turner (*6*), and Mitchell (*7*). In brief, this technique consists of converting a fraction of ^{39}K in the rock to ^{39}Ar by neutron, proton (n,p) reaction with fast neutrons. By heating in stages, ^{39}Ar is released, along with radiogenic ^{40}Ar. The $^{40}Ar/^{39}Ar$ ratio is then measured in a mass spectrometer. From temperature release data one can calculate the crystallization age and deduce information about its postcrystallization thermal history.

The six lunar samples dated in this work are pieces of two large igneous rocks (14053 and 14310) and four basalt fragments (14152,1-1, 14152,1-2, 14167,6-1, and 14193,2-1. Igneous rock 14310 is a fine-grained plagioclase-rich basalt; igneous rock 14053 is coarser-grained than is rock 14310, and it has an ophitic texture (*2*). Lunar samples weighing 50 to 125 mg each, hornblende monitors of known age, and a nickel wire of high purity were irradiated together in the core of the High Flux Beam Reactor of Brookhaven National Laboratory. The integrated fast neutron flux, as measured by the hornblende monitor and by the ^{58}Ni (n,p) ^{58}Co reaction, was 1.2 to 3.4×10^{18} total neutrons from different

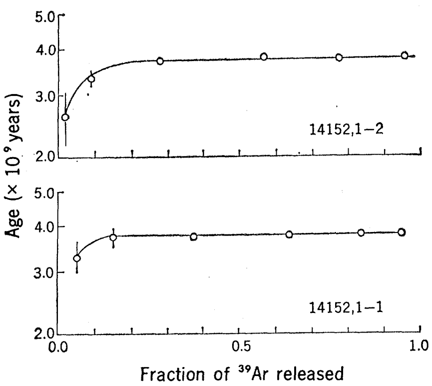

Fig. 2. The $^{40}Ar/^{39}Ar$ release pattern of lunar rocks 14152,1-1 and 14152,1-2.

irradiations. Irradiated samples were analyzed in a 6-inch (15.2-cm), 60° sector, magnetic deflection mass spectrometer (*8*). Gases were extracted from a given sample by induction heating for 1 hour at each temperature in a series of successively higher temperatures ranging from 500° to 1500°C. The rare gases were purified by hot titanium getters and a charcoal trap cooled with dry ice–acetone mixture. Procedural blanks were measured between each series of temperature runs and were less than 1 percent of the sample for every Ar isotope except ^{39}Ar. Instrument sensitivity was measured by means of an air argon standard and was 2.89×10^{-11} cm³/mv (at standard temperature and pressure) for ^{40}Ar. The correction for mass discrimination was 1 percent per mass for argon isotopes. Another correction is explained in the footnotes to Table 1. The error limits in Table 1 are estimated errors based on the errors in the measurements of $^{40}Ar/^{39}Ar$ ratios in the sample and monitor, but they do not include a 5 percent error in the age of the hornblende monitor.

All six samples yield a constant $^{40}Ar/^{39}Ar$ ratio for high-temperature fractions, during which more than 80 percent of the total argon was released, as is shown in Figs. 1–3. The errors are within the circled points unless shown otherwise. The $^{40}Ar/^{39}Ar$ ratio may be converted to an age, t, by the following expression:

$$t = T \ln [1 + J\ (^{40}Ar/^{39}Ar)]$$

where

$$J = [\exp\ (t_m/T) - 1]/(^{40}Ar/^{39}Ar)_m$$

and T is the mean life of ^{40}K, 1.90×10^9 years, subscript m refers to monitor, and t_m is the known age of the monitor, 2.61×10^9 years. Any error in the age of the monitor would be reflected in the age of the sample dated.

The ages are plotted in Figs. 1–3 and are also listed in Table 1 along with total argon ages based on $(^{40}Ar/^{39}Ar)_{total}$. A comparison between the total argon and high-temperature argon ages leads us to conclude that there has been only a small loss of ^{40}Ar from these lunar rocks. All the rocks give the same age within experimental error, $3.77 \pm 0.15 \times 10^9$ years, which is the same as the ages we obtained for Apollo 14 fragmental rocks, $3.75 \pm 0.15 \times 10^9$ years (*4*). We conclude that the 3.75×10^9 years for the fragmental rocks reported earlier (*4*) is the age of the formation of those breccias and hence the age of the Imbrium impact event, since the Fra Mauro formation reportedly consists of material ejected at the time of impact.

The 3.77×10^9 years age of the basaltic rocks, including igneous rocks 14053 and 14310, are interpreted by us as being the crystallization ages. The probability is very high that at least some of the pieces of basalt measured represent pre-Imbrian bedrock. The age data suggest, therefore, that at least some of the pre-Imbrian basalts are no more than 150 million years older than the Imbrium event itself, the 150-million-year figure being derived from the error in age measurement. We cannot, however, rule out the possibility that these basalts were generated by the Imbrium impact event itself.

All the data indicate that extensive activity, both meteoritic bombardment and volcanism, which formed the lunar surface features we see today continued until at least 600 million years after the moon came into being.

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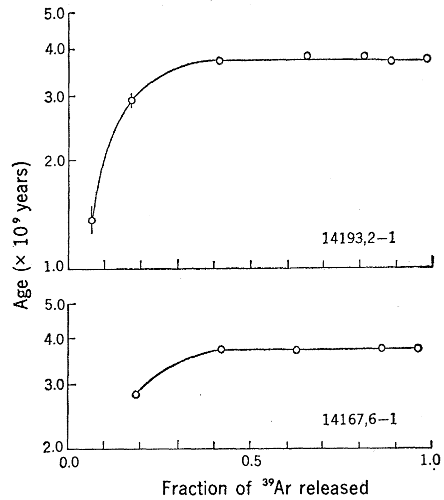

Fig. 3. The $^{40}Ar/^{39}Ar$ release pattern of lunar rocks 14167,6-1 and 14193,2-1.

Table 1. Argon-40–argon-39 ages of Apollo 14 crystalline rocks.

Sample	$(^{40}Ar/^{39}Ar)_m$	Total argon		High-temperature argon		
		$^{40}Ar/^{39}Ar$*	Age × 10^9 years	Temperature range	$^{40}Ar/^{39}Ar$	Age × 10^9 years
14310,101	330 ± 7	660 ± 14	3.68 ± 0.04	700–1500	684 ± 15	3.74 ± 0.04
14053,34	306 ± 8	627 ± 62	3.69 ± 0.17	700–1500	680 ± 60	3.83 ± 0.15
14152,1-1	330 ± 7	686 ± 63	3.75 ± 0.17	600–1500	696 ± 58	3.77 ± 0.15
14152,1-2	330 ± 7	669 ± 32	3.71 ± 0.07	700–1500	688 ± 26	3.75 ± 0.05
14167,6-1	114 ± 1	223 ± 5	3.61 ± 0.04	700–1500	245 ± 6	3.76 ± 0.04
14193,2-1	114 ± 1	217 ± 15	3.60 ± 0.11	700–1500	243 ± 15	3.75 ± 0.10

* Correction for the ^{39}Ar contribution for the ^{42}Ca (n,α) ^{39}Ar reaction (on the assumption that $^{37}Ar/^{39}Ar$ from Ca is 1000): $^{39}Ar = (^{39}Ar)_{total} - 0.001\ (^{37}Ar)$.

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