fascination in "seeing" for the first time an infrared rainbow which has hung in the sky undetected since before the presence of man on this planet.

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References

1. D. M. Gates, *Science* **151**, 523 (1966).
2. J. Strong. *Procedures in Experimental Physics* (Prentice-Hall, Englewood Cliffs, N.J., 1938), p. 369.
3. W. J. Humphreys, *Physics of the Air* (Dover, New York, 1964), chap. 3.
4. G. Wald, *Science* **101**, 653 (1945).

3 May 1971

Explosion Effects and Earthquakes in the Amchitka Island Region

Abstract. *Microearthquakes were monitored by a network of seismographs located on Amchitka and nearby islands; the nature of earthquake activity in this region was found to be consistent with the hypothesis of underthrusting of the Aleutian arc by a rigid lithospheric plate. Seismic effects of the nuclear explosion Milrow were small, of short duration, confined to the region immediate to the explosion, and were apparently independent of this geotectonic mechanism.*

An important consequence of the hypothesis of sea-floor spreading is that the earth's major tectonic features are the result of the relative movement and interaction of rigid lithospheric plates over its surface (*1*). Plate boundaries are marked by relative motion along transform faults and by zones of convergence or divergence of lithospheric material. Because the locus of most of the world's seismic activity also lies along these boundaries it is little wonder that the concept of plate tectonics receives its widest support from the observations of seismology (*2*). Island arcs, like the Aleutians, are typically zones of convergence, that is, they are underthrust by oceanic plates. Hence, the nature of earthquake activity in the Amchitka Island region is deeply rooted in the tectonics of the entire Aleutian arc and to global movements in general. In view of present interest in the effects of nuclear testing on Amchitka Island, it is imperative that we report important new seismological data relevant to understanding the tectonics of the region and observable seismic effects from the nuclear explosion Milrow (October 1969, about 1 megaton) have been obtained.

In 1969, at the request of the Atomic Energy Commission (AEC), the National Ocean Survey undertook an Aleutian seismic program which included the interpretation and reduction of data from a network of seismographs that continuously monitored activity in the Aleutian Islands and Alaska. This seismic network had three purposes: (i) to monitor the seismicity of the entire Aleutian arc; (ii) to monitor extremely low-level seismic activity in the Amchitka Island region to describe accurately the natural patterns which would be observable on a larger scale over a longer period of time; and (iii) to document the effects from underground nuclear explosions on Amchitka Island.

A regional seismic network was established by supplementing seismographs, already operating in Alaska and on Adak Island as part of the Alaska regional tsunami warning system, with new installations at Granite Mountain in northwest Alaska, and at Shemya and Nikolski in the western and eastern Aleutians, respectively (*3*). To monitor low-level seismic activity in the Amchitka Island region, seismographs with high-gain and high-frequency response characteristics were installed on Amchitka and nearby islands (*4*).

Epicenters for selected seismic events detected by the Amchitka network during 1969 and 1970, together with larger events located independently using teleseismic data, are plotted in Fig. 1. Epicenters at focal depths of 0 to 50 km demonstrate a strong correlation with structural features expressed in the bathymetry of the sea floor; this suggests that these features are the direct result of oblique underthrusting by the oceanic plate. Deeper earthquakes appear more evenly distributed along a steep dip that extends northward from the ridge crest to depths in excess of 200 km, just beyond the volcanic arc. Epicenters of the very deepest events lie primarily in a northeast-trending zone coincident to the intersection (and possible superposition) of the Aleutian arc with the Bowers Ridge, a large arcuate aseismic structure extending into the Bering Sea. This distribution in focal depth becomes more evident by projecting hypocenters within the Rat block into the section A–A′, illustrated in Fig. 2. The geometry of the seismic activity is similar to that obtained in other zones of convergence (*2*) and supports the model of an underthrusting lithospheric plate. The seismicity demarcates the plate, confirms the extent of the seismic zone to within 50 km or less, and lends convincing support to the hypothesis that, below the zone of underthrusting, earthquake-generating stresses are contained within lithospheric material that has descended into the mantle (*2, 5*). These are all significant evidence for the plate tectonics concept. Local flexures, volcanism, and possible lateral movements in the overthrusting lithospheric plate give rise to scattered shallow-focus activity above the inclined seismic zone.

Further evidence that island arcs are zones of convergence comes from focal mechanism studies (*5, 6*). In Fig. 1, continued underthrusting of the Aleutian arc is indicated by long-period body-wave focal mechanism solutions for four large events in 1969. These solutions are not only consistent with earlier patterns (*6*), but also mark the western margin of the Delarof block as a region of current large-scale tectonic activity.

Major Aleutian earthquakes often precipitate aftershocks that, in some instances, continue for a year or more over zones which include large portions of the arc (*7*). The generally sharp boundaries of these zones suggest that isolated segments of the Aleutian arc are activated independently. Aftershock sequences of major earthquakes occurring in 1957 and 1965 are evidence for the existence of such a boundary between the Rat Islands and the Delarof Islands, approximated by the dashed line in Fig. 1 (the western margin of the Rat block and eastern margin of the Delarof block are near 177°E and 177°W, respectively, along deep canyons which indent the ridge). This view is further supported by structural features inferred from the bathymetry and by an apparent offset in the volcanic arc.

More recent data also suggest a significant difference in the distribution and amount of seismic activity between the blocks. This is demonstrated in the upper portion of Fig. 3 by the cumulative daily strain release, which was computed independently for each block using only events detected at teleseismic distances to insure uniformity. Although the blocks are approximately the same dimensions, strain release in

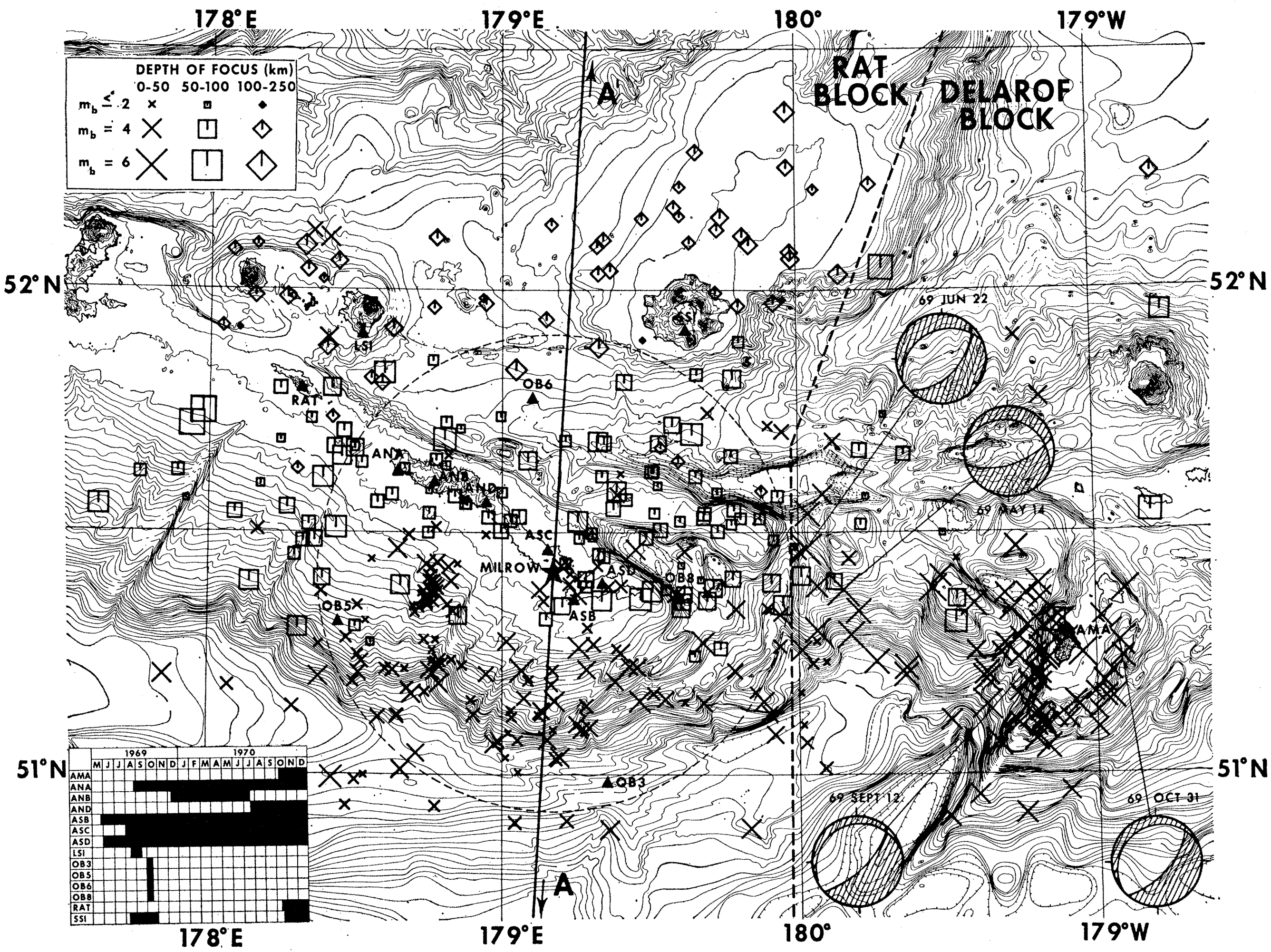
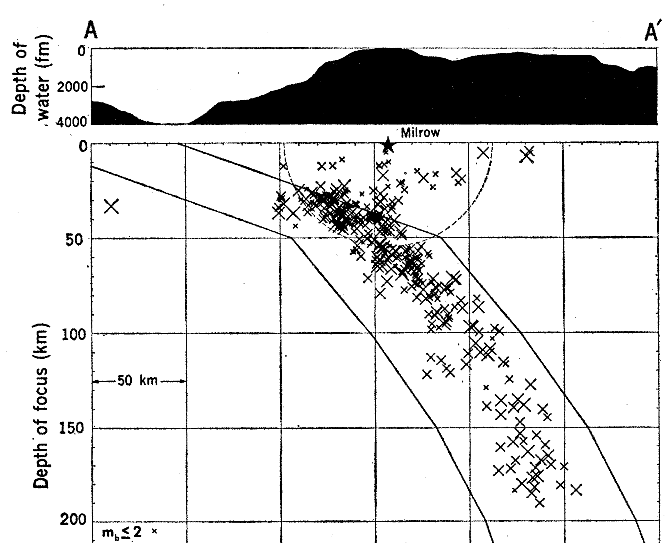


Fig. 1. Seismic events in the Amchitka Island region, 1969–1970, which were clearly recorded by five or more seismographs or teleseismically. Epicenters are plotted according to depth-of-focus class and magnitude (*13*). Seismograph locations are plotted as solid triangles. Periods of operation correspond to solid areas in the operational log (*14*). The balloons are focal mechanism solutions which are illustrated as stereographic projections of the radiation field on the lower hemisphere onto a horizontal plane. Rarefaction quadrants are shaded. Bathymetric contours are at 50-fathom intervals (1 fathom = 1.83 meters).



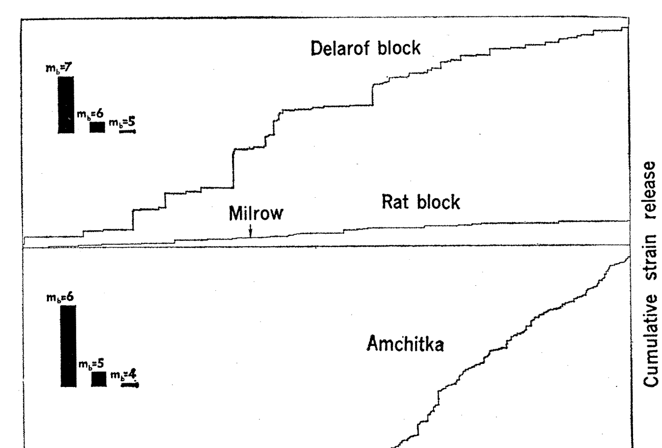


Fig. 2 (left). Focal depth distribution of seismic events within the Rat block section along the segment A–A′ of Fig. 1, 1969–1970. The hypothetical model of a plunging oceanic plate was independently derived from travel-time residuals from the nuclear explosion Long Shot (*15*).

Fig. 3 (right). Cumulative daily strain release (the sum of the square roots of the energies of individual earthquakes). Upper portion: Rat and Delarof blocks for teleseismic events (1969–1970). Lower portion: Amchitka Island region for all events detected (11-month period). Steps correlate with large events. The Delarof block has released strain equivalent to nearly four magnitude 7.0 earthquakes over this 2-year period.

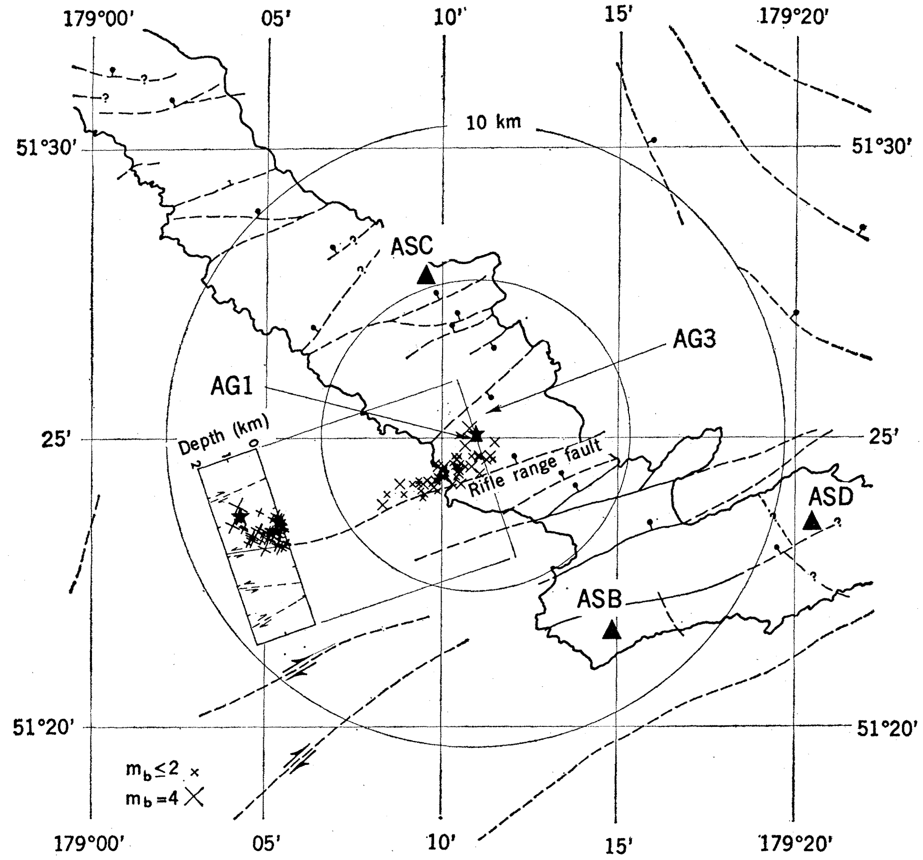


Fig. 4. Aftershocks induced by Milrow; AG1 and AG3 were temporary low-gain geophones which operated during the aftershock period. Milrow is indicated by the star. [Geology from *U.S. Geological Survey Technical Letter Amchitka 5* (1967).]

the Delarof block was about nine times that in the Rat block over this period of 2 years.

Earthquake strain release local to Amchitka Island was monitored in a representative hemisphere 55 km in radius and centered on Milrow (see dashed circles in Figs. 1 and 2). This volume contains most of the underthrust zone below the south end of Amchitka Island. For a period of 11 months, which included all detected events, we obtained (lower portion of Fig. 3) a fairly uniform rate of strain release equivalent to nearly three magnitude 6.0 earthquakes over the same period of time. Hence, the rate of strain release is indicative of a continuing tectonic process beneath the island.

A source of concern is the possibility that a nuclear explosion may trigger a destructive earthquake. It is now well known that nuclear explosions are always followed by relatively small earthquakes, which originate near the explosion cavity or along faults in its immediate vicinity (*8*); but attempts to show that the earthquakes extend more than a few tens of kilometers from those sites have been unsuccessful (*9*). Observations of seismic effects from the nuclear explosion Milrow confirm these results. Careful monitoring of earthquake patterns before and after Milrow by the local Amchitka seismograph network revealed no evidence for any apparent spatial or temporal changes in the natural seismicity (*10*). However, a swarm of hundreds of very small shallow-focus earthquakes having an asymmetric radiation pattern did occur immediately after detonation in a zone not more than 5 km in radius from ground zero. This activity terminated abruptly 37 hours later at the time of the Milrow cavity collapse. The magnitude of the largest of these aftershocks was about 3.4, and only two were larger than 3.0 (Milrow and its cavity collapse were magnitude 6.5 and 4.3, respectively). None of the aftershocks were detected at teleseismic distances.

With the exception of the period shortly after the explosion and the period immediately before the collapse when individual events could not be distinguished, all the aftershocks could be readily identified and approximately located by their signal character and relative arrival times. Figure 4 shows the epicenter and focal depth distribution for aftershocks located using data from at least four of the five seismograph locations indicated. The correlation of these patterns with conspicuous faults trending east-northeast is not surprising in view of the similar correlation of explosion-induced aftershocks with preexisting geologic features at the Nevada Test Site (*8*). The Milrow aftershocks, however, were considerably smaller in size, number, and duration than aftershocks from similar explosions in Nevada (*8*), and nearby faults were significantly less displaced (*11*). No aftershocks were detected at teleseismic distances from the earlier nuclear explosion Long Shot (80 kilotons, October 1965) on Amchitka. Seismic monitoring reveals very little natural earthquake activity on Amchitka Island proper, and marine terrace studies indicate that the upper crust has been relatively stable during recent geologic time (*11*).

All these observations point to local tectonics as a key factor in determining the extent of aftershocks in time and space. One mechanism that supports this view has been proposed by Kisslinger and Cherry (*12*). They suggest that the interaction of explosion-generated elastic body waves with heterogeneities in the vicinity of the explosion creates a field of small dislocation loops. The continued action of the regional stress field on these dislocations then produces the swarm of aftershocks. Consequently, a low level of ambient stress in an explosion-altered medium would be expected to produce aftershocks which are smaller, less extensive, and of shorter time duration. On Amchitka, in situ studies of stress in shallow drill holes suggest that a relatively low level of ambient tectonic stress exists in the surface rocks, even in areas near faults (*11*); moreover, the scale of the mechanism generating the aftershocks was sufficiently small to be apparently completely relaxed by the Milrow cavity collapse.

In Fig. 2 we see that the major thrust fault zone and most of the earthquake activity are some tens of kilometers beneath Amchitka Island. Hence, explosion-induced aftershocks, because they are very small, of short duration, and occur in the immediate vicinity of the explosion, do not seriously constitute a hazard to this zone. A more serious possibility is that an 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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References and Notes

1. D. P. McKenzie and R. L. Parker, *Nature* **216**, 1276 (1967); W. J. Morgan, *J. Geophys. Res.* **73**, 1959 (1968); X. Le Pichon, *ibid.*, p. 3661.
2. B. Isacks, J. Oliver, L. R. Sykes, *J. Geophys. Res.* **73**, 5855 (1968); P. Molnar and J. Oliver, *ibid.* **74**, 2648 (1969); M. Katsumata and L. R. Sykes, *ibid.*, p. 5923.
3. H. M. Butler, *Earthquake Notes* **42**, 15 (1971). The Cape Sarichef seismograph has since been moved to Nikolski.
4. K. W. King, "Aleutian/Amchitka seismic program," *National Ocean Survey Rep. CGS-746-10* (1971). In operational aspects of this program, I am indebted to the NOS Special Projects Party, Las Vegas, Nev., and especially to K. W. King, S. R. Brockman, and D. Overturf.
5. B. Isacks and P. Molnar, *Nature* **223**, 1121 (1969); *Rev. Geophys.* **9**, 103 (1971).
6. W. Stauder, *J. Geophys. Res.* **73**, 3847 (1968); *ibid.*, p. 7693.
7. R. J. Brazee, *Earthquake Notes* **36**, 9 (1965); J. N. Jordan, J. F. Lander, R. A. Black, *Science* **148**, 1323 (1965); J. A. Kelleher, *J. Geophys. Res.* **75**, 5745 (1970).
8. R. M. Hamilton, F. A. McKeown, J. H. Healy, *Science* **166**, 601 (1969).
9. J. H. Healy and P. A. Marshall, *ibid.* **169**, 176 (1970).
10. E. R. Engdahl and A. C. Tarr, "Aleutian seismicity—Milrow seismic effects," *National Ocean Survey Rep. CGS-746-102* (1970); (also see Fig. 3).
11. W. J. Carr, L. M. Gard, G. D. Bath, D. L. Healey, *Geol. Soc. Am. Bull.* **82**, 699 (1971). Although the island has been in the field of strong motion of many major earthquakes in the past few tens of thousands of years, apparently none of them has triggered slip on the surface faults.
12. C. Kisslinger and J. T. Cherry, Jr., *Trans. Am. Geophys. Union* **51**, 353 (1970); and personal communication.
13. Magnitudes for events located by the local seismograph network are estimated using the relationship $m_b = -0.76 + \log (A/T) + 0.91 \log (S)$ where A is the maximum amplitude of the envelope of high-frequency longitudinal (P) waves; T is the period; and S is the slant distance to the seismograph.
14. OB3, OB5, OB6, and OB8 are ocean-bottom seismometers which operated during the Milrow test as part of a joint AEC–Advanced Research Projects Agency seismic program.
15. K. H. Jacob, *Trans. Am. Geophys. Union* **52**, 279 (1971); and personal communication. The lower boundary of the plate from 0 to 50 km is approximate.
16. I thank A. C. Tarr and A. F. Espinosa for critically reviewing the manuscript; A. C. Tarr for the benefit of computer programs and many helpful discussions; W. H. Dillinger for the focal mechanism solutions; C. Rojahn for help in processing the data; and L. M. Murphy for administrative support.

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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 ± 0.15 × 10⁹ 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

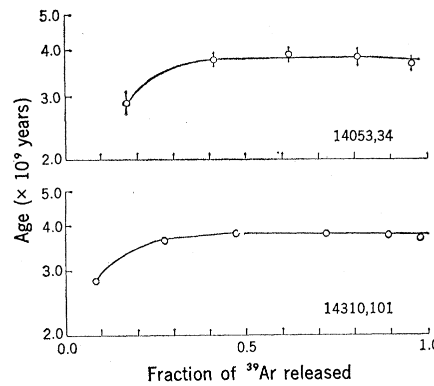

Fig. 1. The $^{40}Ar/^{39}Ar$ release pattern of lunar rocks 14053,34 and 14310,101.

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