abundances of the Luna 16 fines (*2*), but more closely resembles the Apollo 12 and Apollo 14 soils in relative abundances, particularly in the rare-earth element concentrations, and K/Rb ratios. Soil 15531 is enriched in all the trace elements listed in Table 2 as compared to the igneous rock 15555. These enrichments, although smaller, are reminiscent of the differences between Apollo 12 rocks and soils, as shown in Fig. 1. In the case of Apollo 12 soils, the enrichment was ascribed to a component rich in trace elements called KREEP (so called as it is especially rich in potassium, rare-earth elements, and phosphorus) (*4*), with a composition similar to that of the dark-colored portion of the rock 12013 (*10*). The amounts of this material in the Apollo 12 soils varied from about 15 to 50 percent. Likewise, the compositions of Apollo 14 soils (also shown 15555 and soil 15531 are representative of material in this area, preliminary calculations on the amount of KREEP in Fig. 1) suggest they could be very rich in KREEP. If we assume that rock in the soil can be made. Using the portion of dark sample 12013 that is most enriched with trace elements as an end member representing KREEP (the analyses of which are quite variable), somewhere between 5 and 7 percent of KREEP in the soil can account for most of the observed concentration differences between samples 15555 and 15531. Exceptions are Eu and Sr, whose concentrations would be low in such a mixture. The addition of approximately 6 percent 15555 feldspar (or anorthosite?) would account for the Sr, but not quite all of the Eu. This mixture of 88 percent 15555 basalt, 6 percent KREEP, and 6 percent plagioclase would also produce a close match for most of the major elements. If the Apollo 14 soils, which are quite uniform in composition, are taken as the high trace element end member, the amount of Apollo 14 soils necessary to produce the soil enrichment rises to between 11 and 14 percent; here again, an addition of about 5 percent plagioclase is necessary to account for the Sr and Eu concentrations.

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Age of a Lunar Anorthosite

Abstract. *The crystallization age of an Apollo 15 anorthosite rock, 15415,9, returned from the lunar highlands has been measured to be* $(4.09 \pm 0.19) \times 10^9$ *years. The primitive lunar crust must have been formed in the first 300 to 400* $\times 10^6$ *years. The results give some credence to the hypothesis that the primitive lunar surface was molten and large-scale fractional crystallization occurred in the early history of the moon.*

Anorthosite rock fragments and glasses were unexpectedly found in the lunar material brought back by the Apollo 11 mission. The light color, low density, and chemical resemblance to the Surveyor 7 analyses (*1*) of material in the lunar highlands led Wood *et al.* (*2*) to believe that the anorthosite fragments were derived from the older lunar highlands. Wood *et al.* (*2*) proposed a lunar model which suggests that anorthosite formed the primitive outer crust of the moon because of fractional crystallization in magma chambers near the lunar surface and that its rise to the moon's surface was due to its low density (2.7 to 2.8 g/cm^3) compared to that of lunar basalt (3.2 to 3.3 g/cm^3). The lunar surface was later extensively modified by bombardment with large meteoritic or planetary bodies, thus limiting the abundance of large crystalline complexes of anorthosite to the lunar highlands. If this model is correct, radiometric ages for anorthosite should greatly help us to understand the evolution of the lunar crust by placing limits on the time of formation of the anorthosite complexes.

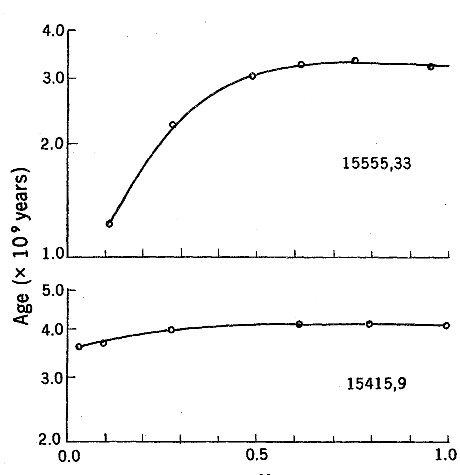

Fig. 1. The ^{40}Ar-^{39}Ar release pattern of lunar rocks 15555,33 and 15415,9-1.

The first large specimen of lunar anorthosite to be collected was found in the Apennine Mountains by astronauts David Scott and James Irwin. This rock presents a delicate challenge to lunar chronologists because it is extremely poor in radioactive elements; and its potassium concentration is only about 100 parts per million. We now report on the measurements of the age of this rock, as well as on the age of a lunar basalt from Hadley Rille.

The lunar rocks 15415,9-1 and 15555,33 were dated by the ^{40}Ar-^{39}Ar method, which has been described by Merrihue and Turner (*3*), Turner (*4*), and Mitchell (*5*). In brief, this technique consists of converting a fraction of ^{39}K in the rock to ^{39}Ar by a ^{39}K (neutron, proton) ^{39}Ar 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 retention ages and deduce information about its postcrystallization thermal history.

The lunar anorthosite, 15415, was collected from the north-northwest rim of Spur crater. From an examination of a thin section, this rock consisted of 99 to 98 percent polysynthetically twinned

Table 1. Argon isotope and age data for the anorthosite rock 15415,9 and basalt 15555,33.

Temperature (°C)	cm³/g × 10^{-8} STP					Cumulative fraction ^{39}Ar	$^{40}Ar/^{39}Ar$	Age‡ (10^9 yr)
	^{40}Ar*	^{39}Ar†	^{38}Ar	^{37}Ar	^{36}Ar			
			Anorthosite rock 15415,9					
800	12.21 ± 0.30	0.21 ± 0.01	0.27 ± 0.00	144 ± 0.6	0.49 ± 0.01	0.03	58.14 ± 4.12	3.59 ± 0.12
900	34.35 ± 0.40	0.56 ± 0.02	1.66 ± 0.01	423 ± 1.4	1.65 ± 0.01	0.10	61.34 ± 2.82	3.68 ± 0.08
1000	104.06 ± 0.50	1.43 ± 0.03	3.70 ± 0.04	932 ± 1.9	2.82 ± 0.01	0.27	72.77 ± 1.74	3.96 ± 0.06
1200	201.98 ± 1.21	2.52 ± 0.05	7.26 ± 0.03	1452 ± 1.1	4.94 ± 0.01	0.61	80.15 ± 1.92	4.12 ± 0.06
1500	113.31 ± 4.03	1.36 ± 0.04	4.52 ± 0.06	962 ± 7.8	3.05 ± 0.05	0.79	83.32 ± 5.33	4.18 ± 0.11
1650	106.14 ± 4.03	1.33 ± 0.03	3.86 ± 0.02	830 ± 7.7	2.76 ± 0.06	1.00	79.80 ± 4.70	4.11 ± 0.10
(800–1650)	572.0 ± 5.8	7.41 ± 0.09	21.27 ± 0.07	4743 ± 0.11	15.71 ± 0.08	1.00	77.2 ± 9.7	3.95 ± 0.15
(1000–1650)	525.5 ± 5.8	6.64 ± 0.08	19.34 ± 0.07	4176 ± 0.11	13.57 ± 0.08	0.90	79.0 ± 7.6	4.09 ± 0.19
			Apollo 15 basalt 15555,33					
600	23.64 ± 0.58	2.19 ± 0.09	0.01 ± 0.00	3 ± 0.0	0.01 ± 0.00	0.11	8.12 ± 0.41	1.23 ± 0.57
700	108.95 ± 2.67	4.77 ± 0.19	0.13 ± 0.00	9 ± 0.0	0.05 ± 0.00	0.28	22.84 ± 1.48	2.22 ± 0.09
800	218.86 ± 5.37	5.47 ± 0.23	0.31 ± 0.00	59 ± 0.2	0.24 ± 0.00	0.48	40.01 ± 2.68	3.01 ± 0.11
900	163.09 ± 1.89	3.42 ± 0.10	0.62 ± 0.00	150 ± 0.2	0.41 ± 0.00	0.61	47.69 ± 1.91	3.28 ± 0.06
1000	161.95 ± 0.77	3.27 ± 0.06	1.03 ± 0.01	273 ± 0.6	0.69 ± 0.00	0.75	49.53 ± 1.14	3.34 ± 0.04
1200	234.64 ± 1.40	5.07 ± 0.09	4.62 ± 0.02	894 ± 0.7	2.93 ± 0.01	0.95	46.28 ± 1.11	3.23 ± 0.04
(600–1200)	911.13 ± 1.40	24.91 ± 0.23	6.71 ± 0.02	1388 ± 0.1	4.27 ± 0.01	0.95	36.4 ± 0.4	2.87 ± 0.07
(900–1200)	559.68 ± 2.67	11.76 ± 0.34	6.27 ± 0.02	1317 ± 1.	4.03 ± 0.01	0.47	47.6 ± 1.5	3.28 ± 0.06

* $^{40}Ar = {}^{40}Ar_{total} - {}^{36}Ar$; assuming solar wind $^{40}Ar/^{36}Ar = 1$. † $^{39}Ar = {}^{39}Ar_{total} - {}^{37}Ar$ (0.0008); Ca-derived $^{37}Ar/^{39}Ar = 1250$. ‡ $J = 0.0983 \pm 0.0040$.

crystals of plagioclase up to ½ cm in diameter and about 1 percent interstitial granular clinopyroxene. No glass was observed. That anorthosite has been moderately shocked is indicated by local development in the plagioclase of faults, probable mechanical twins, and a mosaic structure. The basalt 15555,33 contains euhedral olivine and clinopyroxene crystals enclosed within large anhedral plagioclase crystals.

The two lunar samples weighing 105 to 179 mg along with two hornblende standards weighing about 90 mg each were encapsulated in quartz tubing under reduced pressure. The quartz tube along with a high-purity nickel wire 380 μm thick was packed in a watertight aluminum can. The package was then irradiated in the core of the high flux beam reactor at Brookhaven National Laboratory. The fast neutron flux was monitored by the hornblende standard and by the nickel wire. The integrated fast neutron flux was 1×10^{19} n/cm². The neutron flux variation along sample length of 3 cm was less than 1 percent. Irradiated samples were removed from the quartz tubes and loaded in a gas extraction system connected to a 152-cm, 60° sector, magnetic deflection mass spectrometer. Gases were extracted from a sample by radio-frequency induction heating in a series of successively higher temperatures ranging from 600° to 1650°C. The argon was purified by means of hot titanium getters and a charcoal trap that was cooled with a mixture of Dry Ice and acetone. Samples and standards were held at each temperature for 1 hour, and each gas fraction was measured under static conditions. Procedural blanks were measured between each series of temperature runs and were generally less than 1 percent of the sample for every Ar isotope, except ^{39}Ar, for which it was generally less than 2 percent. Instrument sensitivity was measured by means of an argon standard and was 1.8×10^{-11} cm³/mv STP. The correction for mass discrimination was 0.8 percent per mass for argon isotopes.

The argon isotopic data for the rocks 15415,9 and 15555,33 are given in Table 1. The data have been corrected for procedural blanks. In lunar samples ^{39}Ar is produced both from potassium and calcium. The contribution of ^{39}Ar produced from calcium in the rock was corrected by subtracting 1/1250 of ^{37}Ar from total ^{39}Ar measured in the sample. This was based on a measurement of the $^{37}Ar/^{39}Ar$ ratio in a calcium fluoride target irradiated in the high flux beam reactor. An error in the measurement of this ratio affects significantly only the age measurement of the anorthosite because of its high calcium content. Both the samples yield a constant $^{40}Ar/^{39}Ar$ ratio for high-temperature fractions. The $^{40}Ar/^{39}Ar$ ratio can be converted to an age, t, by the following expression

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

where

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

and T is the mean life of ^{40}K, 1.885 $\times 10^9$ years, subscript s refers to hornblende standard, and t_s is the known age of the standard $(2.61 \pm 0.06) \times 10^9$ years (*6*).

The ages are plotted in Fig. 1 and are also listed in Table 1. The uncertainties are based on the errors in measurements of ($^{40}Ar/^{39}Ar$) ratios, calcium derived ^{39}Ar, and in the age of the standard. The total argon ages correspond to the conventional K-Ar ages, while the high temperature ^{40}Ar-^{39}Ar age would be older if the sample has suffered partial loss of argon.

Our data on temperature release show that the basalt has lost about 24 percent of its radiogenic argon, while the anorthosite has lost very little (about 4 percent) of its radiogenic argon. Since ^{39}Ar (produced from ^{39}K) and ^{37}Ar (produced from ^{40}Ca) are released in an approximately constant ratio over the entire temperature range (Table 1) we conclude that K (thus ^{40}Ar) is residing in calcium sites of the plagioclase crystals. From the foregoing arguments we conclude that the $(4.09 \pm 0.19) \times 10^9$ years age represents the time when the anorthosite complex was formed near the lunar surface and that it has been virtually unaffected by postcrystallization thermal events. The lunar anorthosite is probably a fragment from a primitive lunar crust which was formed about 4.1×10^9 years ago.

The Hadley Rille basalt 15555,33 is a mare basalt. We have measured its age as $(3.28 \pm 0.06) \times 10^9$ years. This is in excellent agreement with (3.33 ±

0.05) $\times 10^9$ years age measured for another piece of this rock using the same method (7). The 3.28×10^9 years age indicates that the mare from which it came was filled with molten basalt and crystallized about 3.3×10^9 years ago. This basalt could, however, be a rather late stage flow in the Imbrium basin.

The data are still very limited, particularly from lunar highlands, but from evidence gathered so far we propose the following lunar chronology: (i) formation of at least a portion of the anorthositic crust occurred about 4.1 billion years ago; (ii) the Imbrium basin was formed about 3.8 billion years ago, as indicated by the Fra Mauro rocks (8); (iii) the filling of Mare Tranquillitatis occurred about 3.7×10^9 years ago (9); and (iv) that of Oceanus Procellarum, and possibly Mare Serenitatis, about 3.2 to 3.4×10^9 years ago (10). It would thus appear that the major mare surfaces on the moon were formed during the period 3.2 to 3.8×10^9 years ago and since then very little change has taken place in the major mare picture. The anorthosite age suggests that if the Wood *et al.* (2) model of evolution of lunar crust is correct, as much as 400 to 500 $\times 10^6$ years were required for sufficient cooling to completely form the anorthosite layer which was subsequently penetrated by planetesimals to form the lunar maria. However, there is no evidence that there was a uniform layer of anorthosite over the entire moon.

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Mineralogic and Petrologic Study of Lunar Anorthosite Slide 15415,18

Abstract. *The anorthosite slide 15415,18 contains > 98 percent subhedral plagioclase (97 mole percent anorthite), two pyroxenes: diopsidic augite (46 percent wollastonite, 39 percent enstatite, 16 percent ferrosilite) with subsidiary (100) lamellae and grains of hypersthene (2.5 percent wollastonite, 58 percent enstatite, 39.5 percent ferrosilite), and traces of ilmenite. The pyroxene occurs interstitial to, and as small grains enclosed within, plagioclase. The textures and compositions of the phases appear compatible with an origin by concentration and adcumulus growth of plagioclase from a gabbroic anorthosite (or hyperaluminous) magma in a "plutonic" environment.*

The thin section of rock 15415 examined, approximately 26 mm^2 in area, is sketched in Fig. 1A. It is composed essentially of five or six subhedral plagioclase grains, the largest (incomplete) individual crystal being 3 by 2 mm. The edges of several other possibly large grains are present, together with smaller (~ 1 mm) fragments. Boundaries between the larger, roughly equant plagioclase grains are smooth and gently curved, with rounded corners. The effects of shock deformation are conspicuous, consisting of fracturing of the grains, offsetting and bending of some boundaries and twin lamellae, undulose extinction, and secondary twinning.

Diopsidic augite with exsolved hypersthene (~ 1 percent) is present as small anhedral triangular crystals (up to 250 μm), interstitial to the larger plagioclase grains. Small ilmenite grains are associated with some of these interstitial areas. Minute pyroxene crystals (< 50 μm) are also present as inclusions in two of the large plagioclase grains: they are quite numerous in one, and are apparently randomly oriented; they are fewer and partly oriented in the other.

Electron microprobe data on the composition of phases present are given in Table 1. The measured plagioclase compositions vary between about An_{96} (96 mole percent anorthite) and An_{98}; step-scanning across a grain with relatively symmetrical undulose extinction revealed slight compositional variation; the extinction irregularities are presumed to be due to strain. All twinning observed appeared to be polysynthetic; orientation on a universal stage revealed both normal (presumably albite) twinning in five of the 12 grains measured, and parallel (presumably periclase) twinning in 11 grains; $2V_x$ on four grains averaged 74°.

Systematic study of the feldspar grains was undertaken to test for any evidence of preferred orientation. Optical directions were readily obtained, and the orientations of the optic normal (Y) for at least one twin element in each of 12 grains is shown in Fig. 1B.

The bulk of the pyroxene present is diopsidic augite ($Wo_{46}En_{39}Fs_{16}$) (46 percent wollastonite, 39 percent enstatite, 16 percent ferrosilite); but all four of the larger interstitial grains could be seen to be composite, with small patches and thin lamellae (see Fig. 1D) of a second phase. Microprobe study revealed these to be hypersthene ($Wo_{2.5}En_{58}Fs_{39.5}$) and that even some of the very small pyroxene grains isolated in the plagioclase were in fact composite intergrowths of monoclinic and orthorhombic(?) pyroxene (see Table 1 and Fig. 1C). Universal stage measurements on the larger augitic pyroxenes gave $2V_z = 50°$. The hypersthene lamellae are perpendicular to the optic plane of the monoclinic host and inferred to be parallel to