plagioclase (gabbroic anorthosite and anorthosite) may be found on the moon in future Apollo missions.

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Age Determinations and Isotopic Abundance Measurements on Lunar Samples

Abstract. *A K-Ar age of 2300 × 10^6 years has been determined for a sample of type A crystalline rock (57,34). The presence of an anomalously large quantity of ^{40}Ar, in a sample of type C breccia (65,35) precluded the calculation of its K-Ar age. Both of the rock types are characterized by low Rb/Sr ratios and consequently low $^{87}Sr/^{86}Sr$ values. The U-Th-Pb results for a sample of type D fines (84,33) yield a $^{207}Pb/^{206}Pb$ age of 4760 × 10^6 years, but ages based on U-Pb and Th-Pb ratios are anomalously high. Isotopic compositions of Li, K, Rb, Sr, U, and Th are very close to the accepted values for terrestrial materials.*

Isotopic determinations were undertaken for several geochronologically important elements found in three types (A, C, and D) of lunar material acquired during the flight of Apollo 11. Two additional samples are currently being studied, and the results will be reported elsewhere. The object of the study was (i) to precisely determine the concentrations of certain parent-daughter elemental pairs; (ii) to measure isotopic abundances for comparison with values for terrestrial elements; and (iii) to determine the geological age of the specimens.

Our routine experimental procedures were slightly modified to facilitate the measurement of isotopic abundances in addition to the determination of elemental concentrations. Isotope dilution techniques were exclusively used in determining the latter. Analyses of Li, K, Rb, Sr, Pb, U, and Th were carried out on two (one 15-cm radius and one 25-cm radius) 90-degree deflection, solid-source mass spectrometers, both of which are equipped with triple-filament source assemblies and electron multiplier ion detection systems. A modified M.S.-10 mass spectrometer (Associated Electrical Industries), operated in the static mode, was used for all argon analyses. All chemical procedures and vacuum fusions were monitored for contamination through the analysis of "blanks." Contamination corrections applied for Rb, Sr, and Ar were <0.5 percent; corrections for U and Th amounted to about 1 percent, as did those for K, with the exception of one extraction of the latter which required a 2 percent correction; a 10 percent correction was required for terrestrial Pb contamination. Our determinations of the concentrations of Rb and Sr in the Cal. Tech. standard solutions supplied with the lunar samples agree with the stated values to within 0.25 percent.

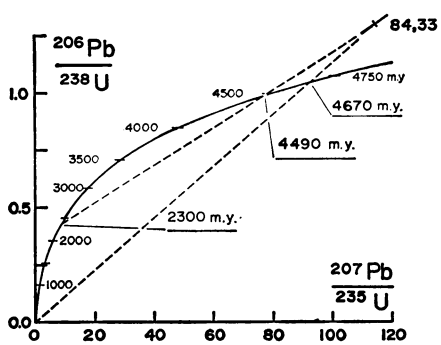

Fig. 1. Concordia diagram; U-Pb data for type D fines.

Argon was extracted from two samples of type A crystalline rock (57,34) under slightly differing experimental conditions. In the first instance (extraction No. 2, Table 1) the purified gas was collected in two calibrated volumes having ratios of about 1:2. The smaller volume of gas was equilibrated with ^{38}Ar tracer on the mass spectrometer inlet line just before isotopic analysis, while the larger portion was used unspiked to determine the relative isotopic abundances. The $^{36}Ar/^{38}Ar$ ratio determined for the latter was used to correct the results of the spiked analysis. In calculating the age it was assumed that there was no primordial ^{40}Ar component. In the second instance (extraction No. 3, Table 1) the gas was equilibrated with the ^{38}Ar tracer in the usual manner during sample fusion. The $^{36}Ar/^{38}Ar$ ratio measured for the unspiked portion of extraction No. 2 was again used to correct the observed abundances for this sample.

The K measurements were made on chips of material broken from the larger samples fused for Ar extraction and should therefore provide a realistic estimate of the K content of the latter. An examination of the ^{40}Ar and K values (Table 1) reveals that the concentrations of both are slightly different in the two portions of this sample.

The greatest variation however was noted for the ^{36}Ar content. While both samples yielded essentially the same quantity of ^{40}Ar, extraction No. 2 contained nearly twice as much ^{36}Ar as extraction No. 3. In spite of this variation the calculated ages for the two samples are very close at 2300 × 10^6 and 2270 × 10^6 years, respectively.

Two extractions were carried out for a sample (65,35) of type C breccia; the first was equilibrated with the ^{38}Ar tracer in the routine fashion during fusion, and the second was not mixed with tracer. The $^{36}Ar/^{38}Ar$ ratio determined for the latter was to be used to correct the results obtained for extraction No. 1. However, this material contained very large quantities of both ^{36}Ar and ^{40}Ar, and consequently it has not been possible to calculate a realistic age for the sample. This is in agreement with preliminary data reported for breccia samples (*1*). The K concentration was again determined on numerous chips from the larger sample used for the Ar extraction in an attempt to ensure the

Table 1. Isotopic and elemental abundance data. For ^{40}K, $\lambda\beta$ (decay constant for β decay) = 4.72×10^{-10} year^{-1}, $\lambda\varepsilon$ (decay constant for electron capture) = 0.585×10^{-10} year^{-1}, and atomic abundance = 1.19×10^{-4}.

Extraction No.	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr$ Spiked	$^{87}Sr/^{86}Sr$ Unspiked	$^{87}Sr/^{86}Sr$ Avg.	$^{87}Rb/^{86}Sr$	K (ppm)	K/Rb	^{40}Ar ($\times 10^{-8}$ cm^3/g)	$^{40}Ar/^{36}Ar$	$^{36}Ar/^{38}Ar$	K-Ar age ($\times 10^6$ years)	Remarks
						Type A – crystalline, No. 57,34							
1	5.853	171.0	0.7052	0.7043 0.7055	0.7050	0.0991	2520	430.5					
2							2588		4543	83.988 83.671	2.768	2300	Spiked Unspiked
3							2647		4646	160.418		2270	Spiked
						Type C – breccia, No. 65,35							
1	3.741	165.5	0.7033	0.7036	0.7034	0.0654	1470	392.9	140,800	2.361			Spiked
2										2.087	5.383		Unspiked

Table 2. The U-Th-Pb analyses, type D fines No. 84,33. For ^{238}U, λ (total decay constant) = 1.537×10^{-10} year^{-1}; for ^{235}U, $\lambda = 9.722 \times 10^{-10}$ year^{-1}; for ^{232}Th, $\lambda = 4.881 \times 10^{-11}$ year^{-1}. Ratio $^{238}U/^{235}U = 137.7$.

U (ppm)	Th (ppm)	Pb Total (ppm)	Pb Radiogenic (ppm)	Pb Atomic ratios 206/204	207/204	208/204	Age ($\times 10^6$ years) $^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{208}Pb/^{232}Th$
0.530	1.31	2.26	1.55	45.8* 51.9†	33.6* 37.6†	64.8* 70.6†	4670	5410	4885	8200

*Measured ratios. †Corrected for Pb blank.

determination of a K content representative of the total sample. The K concentration for this material is considerably lower than that determined for the type A crystalline rock (Table 1).

Rubidium and Sr results for one extraction from each of the two samples (57,34 and 65,35; types A and C) are given in Table 1. The Rb concentrations are very low, and consequently the ^{87}Sr enrichment is very small. However the experimental data points do fall reasonably close to a 3200×10^6 years reference isochron on a Rb-Sr evolution diagram, thus providing some evidence for higher ages than the K-Ar ages calculated for sample 57,34. Rubidium and Sr analyses for the remaining lunar samples may serve to confirm the greater age indicated.

A major portion of the sample of fines (84,33; type D) was used for U, Th, and Pb determinations. Considerable difficulty was experienced in working with the larger sample, but reasonable results were obtained. As mentioned above, about 10 percent of the Pb was attributed to contamination arising in the laboratory and the isotopic ratios were corrected by use of the relative abundances of modern day terrestrial lead. In addition, a correction for primordial lead amounting to about 32 percent of the sample was made, based on the relative abundances of meteoritic lead as determined by Patterson (*2*) (Table 2). The $^{207}Pb/^{206}Pb$ age has been calculated to be 4670×10^6 years which, although a bit high, is much more realistic than the other ages based on the Pb-U and Pb-Th ratios (Table 2). The data were plotted on a concordia diagram (Fig. 1), and dashed lines were drawn from this experimental point to zero age and to the 2300×10^6 years age point (the K-Ar age for our sample of type A crystalline rock). In the latter case the line cuts concordia at 4490×10^6 years. The position of the experimental point above the curve is considered to be indicative of either loss of U from the sample or gain of modern terrestrial Pb. The former is in good agreement with the preliminary results (*1*), and the latter has been corrected for the Pb of the "blank" extraction processed with the sample. While it is possible that the sample was contaminated before processing, exacting precautions were taken to avoid this possibility. In support of the proposed loss of U, it should be noted that the Th result also appears to be low. If indeed both parent elements have been lost, this loss, expressed as a percentage of the U and Th required to produce concordant ages at 4670×10^6 years, amounts to 19 percent for U and 48 percent for Th.

Isotopic abundances of Li, K, Rb, and Sr were measured for samples 57,34 and 65,35 and of U and Th for sample 83,33. Since no major deviations from accepted terrestrial values were found, the experimental data have been omitted but will be presented in our final report.

Evidence has been presented to support two contrasting ages for lunar materials. One based on the $^{207}Pb/^{206}Pb$ ratio determined for a bulk sample of type D fines is in essential agreement with the accepted age of the earth. The lower K-Ar age of 2300×10^6 years assigned to a single sample of type A crystalline rock is considered to be a valid determination and may indicate a stage in the evolutionary history of the moon.

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