

Erosion and mixing of the lunar surface from cosmogenic and primordial radionuclide measurements in Apollo 12 lunar samples

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Abstract—Apollo 12 lunar samples have been analyzed for their cosmogenic and primordial radionuclide contents by nondestructive gamma-ray spectrometry. The radionuclides ^{22}Na , ^{26}Al , ^{40}K , ^{46}Sc , ^{48}V , ^{54}Mn , ^{56}Co , ^{60}Co , ^{232}Th , and ^{238}U were measured on lunar rock specimens 12002,93 through 97, 12005,0, 12016,0, 12034,9, 12051,1, 12051,3, 12053,38, 12053,41 through 44, 12062,0, 12063,0, and 12065,0; on lunar soil sample 12070,3; and on lunar core tube samples 12025,4 through 14 and 12028. Compared with Apollo 11 samples the Apollo 12 samples show a significantly wider range in cosmogenic radionuclide concentrations and a much wider range in the primordial radionuclides. The recent solar flare produced radionuclides ^{48}V (16.1d) and ^{56}Co (77.3d) were near the concentrations observed in Apollo 11 samples, while the ^{46}Sc concentrations were about one half, in agreement with the lower concentration of Ti. Concentration gradient measurements of ^{22}Na and ^{26}Al in the double core tube sample 12025, 12028, in vertical sections from rocks 12002 and 12053, and in whole rocks, indicated mixing of the top 3 cm of lunar soil in 10^5 years and erosion rates of lunar rocks of 1 to 5 mm per million years. Aluminum-26 to ^{22}Na ratios are consistent with constant solar activity during the past million years. The U and Th concentration in the 9 to 16 cm deep region of the double tube 12024, 12028 was two-fold lower than sections above or below this level. This indicates the deposition of a unique type of material during this period of the regolith formation and places a limit on the depth of lunar soil mixing.

INTRODUCTION

THE APOLLO 11 lunar studies established the fact that the radionuclide production in the first centimeter of the lunar surface was the result of an intense solar proton bombardment with a small contribution from higher energy galactic cosmic rays. This was in marked contrast with the results of meteorite studies which, over the years, have provided us with a history of the galactic cosmic ray spectrum but because of their surface ablation during atmospheric entry have yielded little information on the solar irradiation. Since radionuclide production in the top centimeter of the lunar surface results primarily from solar proton bombardment, spallation products can serve as unique indicators of the recent and past history of the sun. Moreover, their measurement also provides a basis for determining dynamic lunar processes such as the erosion of rocks, the mixing of soil, and changes in rock orientations on the lunar surface. While these latter possibilities were touched upon, the major emphasis in the Apollo 11 studies was directed toward establishing the solar contribution to the radionuclide production on the lunar surface (SHEDLOVSKY *et al.*, 1970a; PERKINS *et al.*, 1970a, b). Physical processes such as erosion and lunar rock orientation have since received more detailed attention in several independent studies based on track measurements (CROZAZ *et al.*, 1971; BARBER *et al.*, 1971; FLEISCHER

et al., 1971) and cosmogenic radionuclide measurements (FINKEL *et al.*, 1971). The information gained through Apollo 11 studies served as a basis for a much more detailed study of lunar surface radioactivity as observed in the Apollo 12 samples and for the interpretation of the radionuclide measurements in terms of a variety of dynamic lunar surface and solar processes. The measurement of cosmogenic and primordial radionuclides in Apollo 12 lunar samples has now added an important segment to our knowledge of the lunar surface.

A high degree of accuracy was maintained in radionuclide measurements which permitted the observation of subtle differences in radionuclide content which may be related to differences in specimen size, shape, degree of burial, cosmic irradiation history, erosion rate, and chemical composition. Particular emphasis was placed on determining near surface concentrations of cosmogenic radionuclides in the rocks, and the concentration gradients in both rocks and core tube samples. The concentration gradients in the rock samples provided a basis for a model which describes both radionuclide production and lunar rock erosion, while the gradients in the fines provide a basis for defining mixing rates.

PROCEDURE

Extreme care was taken to ensure the highest possible accuracy in all of the Apollo 12 radionuclide measurements. The general methods employed for sample mockup preparations which were described earlier (PERKINS *et al.*, 1970a, 1970b) were employed with only minor modifications. The mockups were prepared from a mixture of casting resin (Titan Casting Resin, Titan Corp., Seattle, Washington), iron powder and aluminum oxide which contain precisely known radionuclide additions. A mockup produced by this procedure could be made to precisely duplicate the lunar rock geometry, physical density, and electron density and did not degrade or change in any observable manner with time. For the ^{22}Na and ^{26}Al measurements on whole rocks, errors associated with counting statistics were usually on the order of 1–2%. The absolute errors for ^{22}Na and ^{26}Al measurements based on all analytical uncertainties including the error in the radioisotope standards ranged from 2 to 5%.

Multiple-gamma coincidence counting techniques (PERKINS *et al.*, 1970b) permitted the estimation of radionuclide concentration gradients of lunar rocks from which lunar surface orientation and any recent changes in this orientation could be recognized. In addition, newly developed beta-multiple gamma coincidence counting techniques were employed which permitted the surface concentrations of ^{26}Al in the rock samples to be determined.

The beta-multiple gamma detection system employed two 30 cm diameter by 20 cm thick NaI (TI) crystals with their associated 30 cm by 10 cm thick NaI light pipes as the principal gamma ray detectors. A 12.7 cm diameter by 1 cm thick P-10 gas proportional beta detector with a 500 microgram per square centimeter gold-plated mylar window was located against the front face of each detector. The lunar specimen in its double teflon bags plus one polyethylene bag was positioned in a reproducible mode between the two beta detectors for counting. The entire beta-gamma-gamma spectrometer system as shown in Fig. 1 was shielded from natural and cosmic radiation by a 4 inch thick lead cave. Each beta detector acted as a gate for a 4096 channel memory which operated as a 64×64 channel array to record both the single and coincidence gamma-ray events observed by the two NaI (TI) crystals. Beta-particles leaving the upper surface of the lunar sample could trigger the upper beta detector, while the lower beta-detector was triggered by beta particles from the lower surface of the sample. This beta-multiple gamma coincidence counting mode provided an extremely low background and allowed the surface concentrations of ^{26}Al to be estimated by comparison with known standard mockups. The range of the beta particles, about 0.2 and 0.05 mm (for twofold attenuation) for ^{26}Al and ^{22}Na , respectively, defines the maximum depth from which these radionuclides are detected by the coincidence system. Since the Apollo 12

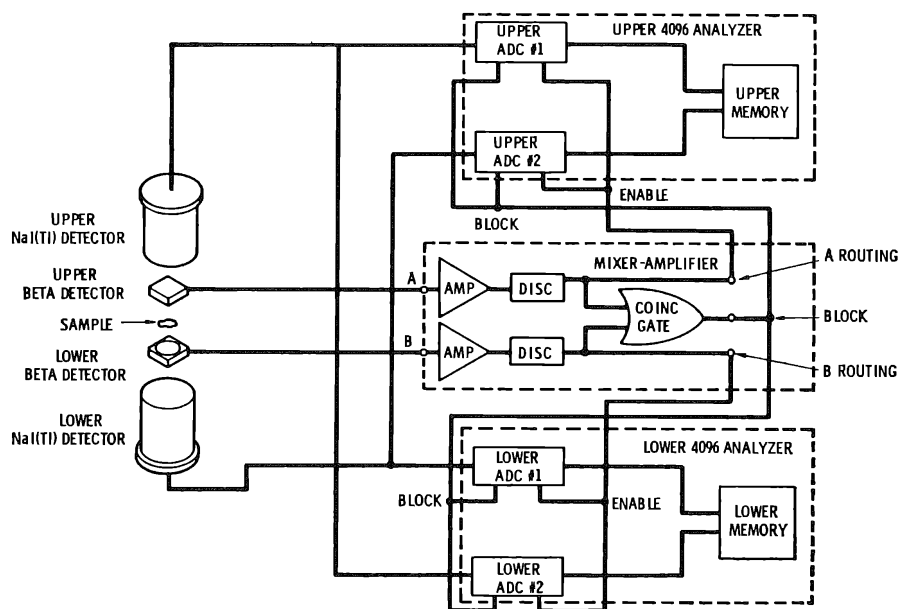


Fig. 1. Beta-multiple gamma-ray spectrometer.

rocks were counted in two Teflon bags plus a thin polyethylene bag, additional attenuation of beta particles occurred, which essentially stopped all of the beta particles associated with the decay of ^{22}Na .

RESULTS AND DISCUSSION

Radionuclide concentration and production rates

A summary of radionuclide concentrations in the rock samples and bulk fines is presented in Table 1. The ^{26}Al and ^{22}Na in sections through two vertical rock slices are included in Table 2. The ^{26}Al , ^{22}Na , Th, and U in the double core tube soil and in a soil sample from the Surveyor III scoop are presented in Table 3. The cosmogenic radionuclide concentrations show general similarities to those in Apollo 11 samples, but there are some very striking differences. For example, the $^{26}\text{Al} : ^{22}\text{Na}$ ratio of 2.56 for the 2360 gram crystalline rock 12063,0 is far higher than previously observed ratios. Conversely, the $^{26}\text{Al} : ^{22}\text{Na}$ ratio is 1.13 in the 482 gram rock 12005,0 the lowest yet observed. This ratio is of particular interest because of the unusually high ^{22}Na concentration of 72 dpm/kg which is about twice that in the other rocks. To explain this high ^{22}Na content on the basis of chemical composition would not be reasonable unless the Mg or Na content was far higher in rock 12005,0 than seems likely based on the observed ranges reported by the preliminary examination team (LSPET, 1970) and at the Second Lunar Science Conference. As discussed later in this article, it appears more likely that the low ratio in rock 12005,0 and the high ratio in rock 12065,0 are due to their shape, their lunar surface orientation, and their erosion rates.

The concentrations of both ^{26}Al and ^{22}Na are about 20% higher in the bulk fines of Apollo 12 versus Apollo 11 samples. As is indicated later, this is easily accounted for by a slightly shallower sampling depth for Apollo 12 fines.

Table 1. Cosmogenic and primordial

Radionuclides	12005,0	12063,0	12016,0	12051,1
	(A)*	(A)	(AB)	(AB)
²² Na (dpm/kg)	72 ± 2	38 ± 2	44 ± 2	40 ± 2
²⁶ Al	81 ± 2	78 ± 2	75 ± 2	93 ± 2
⁴⁶ Sc	5.5 ± 0.8	6.0 ± 0.8	5.6 ± 1.3	7.0 ± 1.2
⁴⁸ V	—	19 ± 12	—	—
⁵⁴ Mn	37 ± 4	37 ± 4	36 ± 4	29 ± 4
⁵⁶ Co	46 ± 6	30 ± 3	14 ± 4	—
⁶⁰ Co	0.50 ± 0.29	0.81 ± 0.42	0.56 ± 0.34	0.36 ± 0.31
K (%)	0.026 ± 0.001	0.055 ± 0.002	0.044 ± 0.002	0.058 ± 0.002
Th (ppm)	0.403 ± 0.017	0.653 ± 0.030	0.570 ± 0.025	0.940 ± 0.050
U (ppm)	0.106 ± 0.010	0.178 ± 0.015	0.157 ± 0.015	0.234 ± 0.020
Sample weight (grams)	482	2360	2028	545
Rock weight (grams)	482	2426	2028	1660

Values prefaced with < represent 2σ of the gross counting rate in the photopeak area.
* Rock type.

Table 2. ²²Na and ²⁶Al concentrations in rock slices 12002,93–97 and 12053,38–44.

Sample	Average Depth† (g/cm²)	²² Na (dpm/kg)	²⁶ Al (dpm/kg)	²⁶ Al/ ²² Na
12002,93	1.5	78 ± 9	95 ± 9	1.22 ± 0.18
12002,94	5.8	49 ± 8	58 ± 6	1.18 ± 0.23
12002,95	9.5	35 ± 4	52 ± 4	1.48 ± 0.20
12002,96	14.6	42 ± 5	44 ± 5	1.05 ± 0.17
12002,97	18.9	39 ± 8	52 ± 8	1.33 ± 0.34
12053,38	1.2	66 ± 10	152 ± 12	2.30 ± 0.39
12053,41	4.9	45 ± 13	75 ± 14	1.67 ± 0.57
12053,44	(8.1)*	(32 ± 4)	(60 ± 5)	(1.88 ± 0.28)
12053,43				
12053,42	14.7	38 ± 8	58 ± 8	1.53 ± 0.38

* Values in parentheses are average values of 12053,41, 44, 43.

Table 3. Summary of radionuclide content of double core tube 12025, 12028 and surveyor dust.

Sample	Average Depth† (g/cm²)	²² Na (dpm/kg)	²⁶ Al (dpm/kg)	Th(ppm)	U(ppm)
12025,14	0.4	197 ± 80	246 ± 69	6.0 ± 2.8	1.4 ± 0.7
12025,13	1.4	109 ± 36	241 ± 31	6.5 ± 1.1	2.2 ± 0.4
12025,13, 12	1.8	70 ± 35	202 ± 29	6.1 ± 1.6	3.1 ± 0.6
12025,12	2.7	62 ± 62	176 ± 51	6.4 ± 2.3	2.4 ± 0.6
12025,11	3.8	53 ± 29	169 ± 33	6.0 ± 1.1	1.9 ± 0.4
12025,10	5.2	56 ± 25	86 ± 21	7.0 ± 1.1	1.9 ± 0.4
12025,9, 8, 7	8.5	35 ± 8	54 ± 7	6.8 ± 0.4	2.1 ± 0.2
12025,6, 5, 4	13.5	34 ± 7	62 ± 8	6.3 ± 0.4	2.1 ± 0.2
12028,11, 13, 14, 16, 17, 18	23.8	44 ± 6	49 ± 4	3.2 ± 0.2	0.90 ± 0.09
12028,20, 21, 22, 23, 25, 26	35.5	37 ± 6	45 ± 5	7.5 ± 0.3	2.0 ± 0.2
12028,27, 28, 30, 31, 32, 36	49.2	36 ± 6	49 ± 5	8.4 ± 0.3	2.3 ± 0.2
12028,37, 38, 40, 41, 43, 44	64.3	41 ± 6	38 ± 5	6.6 ± 0.3	1.9 ± 0.2
Surveyor Soil	5*	44 ± 14	85 ± 14	5.9 ± 0.7	

* Estimated from ²²Na and ²⁶Al concentrations in 12025,10.
† In core tube.

radionuclides in lunar materials.

12051,3	12062,0	12065,0	12034,9	12070,13
(AB)	(AB)	(AB)	(C)	(D)
37 ± 2	33 ± 2	32 ± 2	34 ± 2	80 ± 2
81 ± 2	76 ± 2	82 ± 2	60 ± 3	165 ± 4
5.8 ± 1.1	4.4 ± 4.5	5.4 ± 1.1	—	5.9 ± 1.6
—	—	7 ± 11	—	—
32 ± 4	33 ± 4	31 ± 4	< 40	21 ± 8
16 ± 4	—	22 ± 8	< 56	57 ± 7
0.26 ± 0.26	0.42 ± 0.27	< 1.2	1.5 ± 1.3	1.7
0.058 ± 0.002	0.059 ± 0.002	0.054 ± 0.002	0.432 ± 0.15	0.199 ± 0.006
0.864 ± 0.043	0.871 ± 0.044	0.991 ± 0.049	13.9 ± 0.5	6.73 ± 0.20
0.234 ± 0.020	0.241 ± 0.020	0.282 ± 0.025	3.53 ± 0.17	1.70 ± 0.09
765	727	2088	124	276
1660	739	1209	155	1102

The ⁴⁶Sc concentrations in the Apollo 12 samples are about half those observed in Apollo 11. This is in accord with the substantially lower concentrations of the major target element Ti (LSPET, 1970) in the Apollo 12 samples. The ⁵⁶Co (77.3d) and ⁴⁸V (16.1d), which are both produced by low energy (*p*, *n*) reactions on Fe and Ti, respectively, are at similar concentrations to those observed in Apollo 11 lunar samples. Their production is almost entirely due to solar flare proton bombardment and their concentrations provide an indication of recent integrated solar flux at the Apollo 12 site. The ratio of ⁴⁸V to ⁴⁶Sc, which are both produced from Ti, was three times higher in Apollo 12 samples than the Apollo 11 rocks. This is due to the fact that the time interval between the major solar flares which produced most of the ⁴⁸V and sample collection was much shorter for the Apollo 12 mission. This also explains the comparable amounts of ⁴⁸V in Apollo 11 and Apollo 12 samples even though the target element abundance for its production was much lower in Apollo 12 material. The cosmogenic radionuclide ⁵⁴Mn is produced by a (*p*, 2*pn*) reaction on ⁵⁶Fe. The substantially higher ⁵⁴Mn concentration in the rock samples than in the fines is partially due to the higher stable iron content of the rocks, but is also apparently due to an increase in secondary production with depth in the rocks where significant secondary flux buildup may occur.

The very low ⁶⁰Co concentrations (see Table 1) in the lunar materials are to be expected from the low nickel and cobalt concentrations of the lunar surface. Based on integral neutron flux estimates of 10¹⁵–10¹⁶ (ALBEE *et al.*, 1970), neutron capture by stable cobalt could have produced the observed ⁶⁰Co concentrations. Only upper limits were obtained for ⁷Be (53d) and ⁵¹Cr (28d), and these were similar to those observed in the Apollo 11 samples.

It has been shown that rather steeply declining concentration gradients for some cosmogenic radionuclides do exist in lunar rocks (SHEDLOVSKY *et al.*, 1970a, 1970b; O'KELLY *et al.*, 1970a, b; PERKINS *et al.*, 1970a, b), and of course similar gradients would exist in the lunar soil. Of the cosmogenic radionuclides, ²²Na and ²⁶Al concentrations are most easily measured with good accuracy by nondestructive techniques. In addition, they are by virtue of the differences in their half-lives, a convenient pair for studies of lunar surface orientation of lunar rocks, any recent changes in

orientation, erosion rates of the lunar rocks, mixing rates and the mixing depth of lunar soil, and of major temporal changes in the cosmic-ray flux or energy spectrum. The fraction of the total ^{26}Al and ^{22}Na produced in Apollo 12 rocks by solar protons as estimated from galactic cosmic ray production in meteorites is comparable with the estimated production in Apollo 11 rocks (PERKINS *et al.*, 1970b). This supports our earlier conclusion that the solar activity has remained relatively constant for the past million years.

Radionuclide production rate calculations

To interpret ^{22}Na and ^{26}Al concentrations in terms of lunar surface processes, it is essential to know their expected production rates as a function of depth in the lunar surface. Since radionuclide production in the first centimeter of the lunar surface is mainly due to solar flare protons, a very rapidly descending production rate exists. The major target elements in lunar material for ^{22}Na production are Mg and Na below 20 MeV, and Mg, Si, and Al at higher energies. The major target elements for ^{26}Al production are Al, Si, and Mg below about 25 MeV and Si and Al at higher energies.

A calculation of the production rate depth gradients for ^{22}Na and ^{26}Al requires a knowledge of both the excitation functions for their production from the elemental composition of lunar materials and the energy spectrum of the incident solar protons.

Known excitation functions for ^{22}Na production were used. Direct measurements of excitation functions for ^{26}Al production were used where available (RANCITELLI and WOGMAN, 1971); otherwise they were estimated from analogous reactions.

For the calculations a representative shape factor for the solar cosmic ray energy spectrum was determined from satellite data collected during the November 1968, December 1968, and April 1969 flares (HSIEH and SIMPSON, 1970). Expressed in the kinetic power law form, the solar proton energy distribution can be stated as

$$\frac{dJ}{dE} = ke^{-\alpha}$$

where J is the proton flux (P/cm²-sec-steradian-MeV), E is the particle energy (MeV), and k is a constant determined from the flare intensity. The shape function, α , was 3.1. for two of the flares and 3.5 for the third flare. For production rate calculation an α value of 3.1 was used.

The calculations assumed the lunar surface to consist of an infinite plane. The laminae thicknesses within the plane were set at 0.5 mm and given a cross section compatible with thin target calculations. Activation within the laminae due to second particles was assumed negligible. For a unit incident flux within a specific angular distribution, energy attenuation was calculated as a function of the depth of the laminae within the plane for 2 MeV increments from 10 to 400 MeV. Activation within each laminae was calculated by integrating the product of the flux and the excitation function over the depth corrected energy distribution.

Production rates based on both sun angle irradiation, which assumes that all of the bombarding particles arrive at the lunar surface along the lines of sunlight, and

2π isotropic irradiation were calculated. The actual exposure on the lunar surface is probably a combination of both sun angle and isotropic irradiation. However, an isotropic irradiation flux which produces a slightly steeper production rate gradient than a sun angle irradiation was assumed in the analysis of observed concentrations. A concentration gradient for zero erosion was calculated for the lunar fines composition and this curve was then normalized to the observed ^{22}Na and ^{26}Al in the first 5.4 g/cm^2 of depth (Fig. 2). A correction for the galactic contribution was made prior to this normalization. The normalization constant derived in this manner was subsequently employed to adjust the calculated production rates in rocks 12002 and 12053.

The ^{22}Na concentration in lunar material reflects only the solar flare activity during the past decade, and of course is very dependent on the most recent large solar flares. The calculated concentration gradients for ^{22}Na and ^{26}Al based on isotropic irradiation and the chemical composition (BRUNFELT *et al.*, 1971; GOLES *et al.*, 1971; WILLIS *et al.*, 1971) of rock 12002 are presented in Figs. 3a and 3b. The four gradients for ^{26}Al are those which would exist if the lunar surface were of density 3 and were eroding at rates of zero, 0.1, 1.0, and 10 mm per million years. The observed concentrations of ^{22}Na and ^{26}Al at depths of several cm are about 35 and 55 dpm per kg respectively, while the calculated surface concentrations indicate ^{22}Na and ^{26}Al

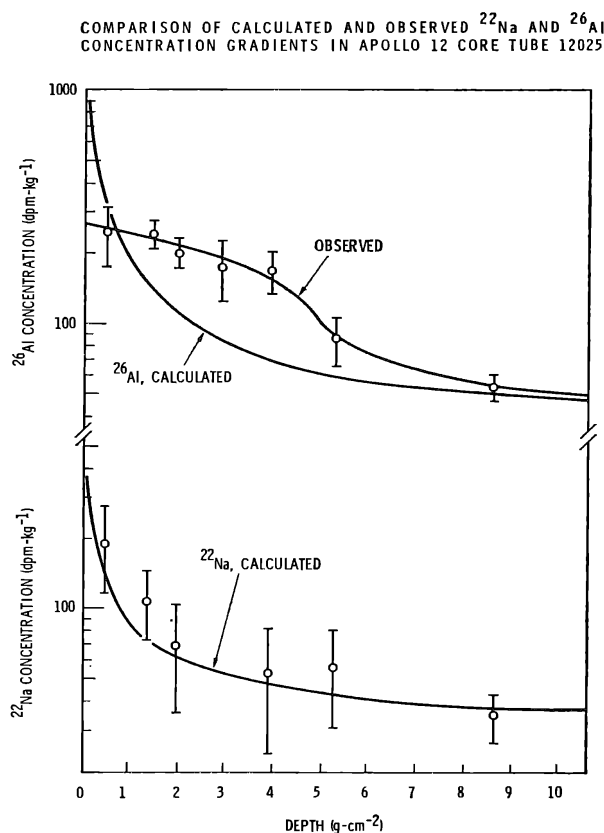


Fig. 2. Comparison of calculated and observed ^{22}Na and ^{26}Al concentration gradients in Apollo 12 double core tube 12025.

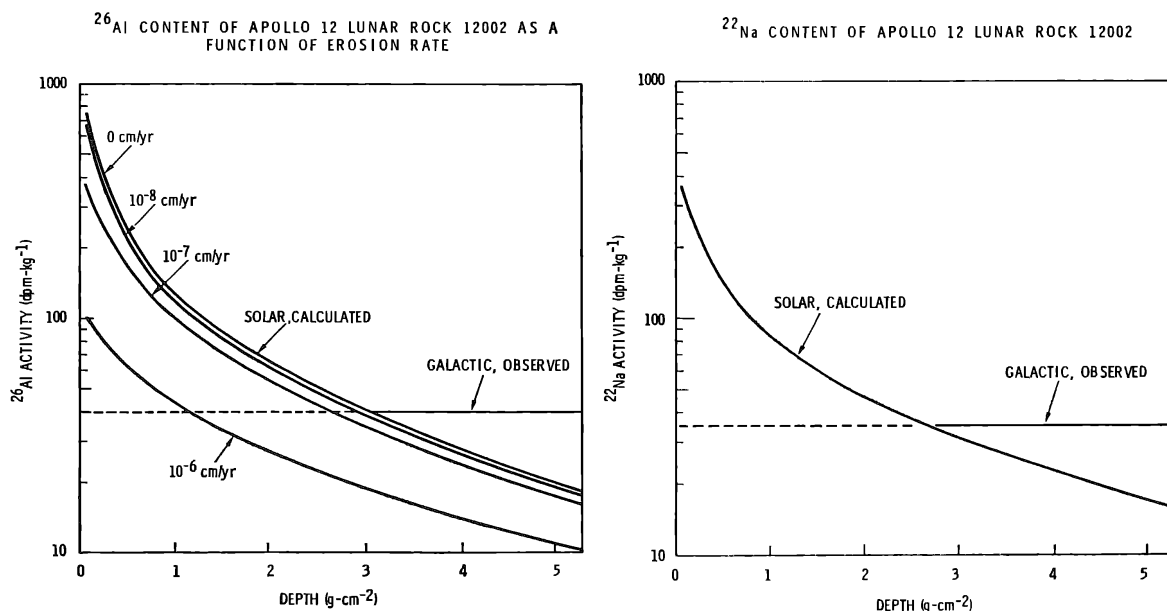


Fig. 3 (a) Calculated ^{26}Al Content of Lunar rock 12002 as a function of erosion rate (left); (b) calculated ^{22}Na content of Apollo 12 lunar rock 12002 (right).

values of about 400 and 800 dpm per kg respectively, in the first 0.5 mm. Thus, concentration changes of some fifteen-fold for ^{26}Al between the top and bottom of a few cm thick rock could exist if no erosion occurred. Erosion rates of 10 mm per million years and 1 mm per million years respectively, would lower the concentration in the first 0.5 mm by about eightfold and twofold, respectively. Since erosion would not affect the ^{22}Na concentration gradient, a tenfold change in concentration between the top and bottom surface could exist.

Orientations and surface radionuclide concentrations

Two methods were employed for lunar surface orientation studies of the lunar rocks. The first involves the analysis of gamma-ray spectrometric data accumulated in the normal coincidence counting of the samples. Coincidence counting rates in the two large NaI (Ti) crystals which view the samples are particularly sensitive to radionuclide location within the sample, especially where three gamma-rays are emitted per disintegration, as is the case for ^{22}Na and ^{26}Al . Thus the surface(s) with the highest ^{22}Na and ^{26}Al can be identified. A second and more sophisticated technique involved the beta-multiple gamma detection system described above. Table 4 summarizes the results on lunar rock orientation and ^{26}Al surface concentrations as determined by normal gamma coincidence counting and the beta-multiple gamma coincidence techniques.

From normal gamma coincidence of lunar rocks 12005,0, 12016, 12051,1, 12051,3 and 12063,0, the highest ^{22}Na concentrations were found to be at the top for the designated orientations as designated in Table 4 and Fig. 4. The highest ^{26}Al concentrations were also on the top for all except 12063,0. These observations indicate that the designated orientations in Table 4 were similar to the most recent lunar

Table 4. Lunar rock orientations and surface concentrations of ²⁶Al.

Rock	²⁶ Al Surface Concentrations		Most Recent Rock Orientation* (γ-Coincidence)
	Top	Bottom	
12005,0	164 ± 17	91 ± 12	A
12016,0	135 ± 16	119 ± 12	B
12051,1	160 ± 20	159 ± 18	C
12051,3	242 ± 18	120 ± 10	D
12063,0	—	—	E

* A Approximately as shown in Fig. 4; B Inverted from orientation shown in Fig. 4; C, D Approximately as shown in Fig. 4 but with small end partially submerged; E Inverted from orientation shown in Fig. 4.

surface orientation. However, since rock 12063 showed the highest ²²Na concentration on the designated top and the highest ²⁶Al on the bottom, then its most recent orientation must have been opposite to the orientation indicated in Fig. 4. Also, to have the highest ²⁶Al on the bottom of the rock's orientation on the lunar surface would require that the rock be turned over in the past few hundred thousand years. This recent change in the orientation of rock 12063,0 has also been suggested from track measurements (CROZOS *et al.*, 1971). The measured ²⁶Al surface concentrations by beta-multiple gamma coincidence counting of the top and bottom halves of lunar rocks 12005,0, 12016,0; 12051,1; and 12051,3 for their designated orientation are also shown in Table 4. These surface concentrations confirm the orientation observed by the normal counting procedures for all except rock 12051,1, where statistical uncertainty precludes this judgment. Of much greater interest, however, are the relative and actual surface concentrations of ²⁶Al. If the designated bottom surfaces were not exposed to solar protons, within the last few million years, their concentrations should be on the order of 55 dpm per kg. There may be some bias in our measured values due to differences in surface roughness of the samples and the mockup standards and plastic bag folding; however, at present it appears that this bias could be no greater than 10 to 20%. However, it is apparent that the designated rock bottoms are significantly higher in ²⁶Al than the expected 55 dpm/kg had they been submerged in the lunar surface. Of particular interest is the fact that the top surfaces show maximum concentrations of less than 250 dpm per kg in the top 0.2 mm as measured by the beta-multiple gamma coincidence counting. If they were completely exposed to the solar proton flux, they would have surface ²⁶Al concentrations on the order of 800 dpm per kg, assuming zero erosion. This estimated value of 800 dpm per kg versus a calculated value of about 1000 dpm per kg for the first 0.2 mm of depth would be expected because of curved surfaces of the lunar rocks. If these lunar rocks were precisely half buried in the lunar soil, then one could safely estimate the ²⁶Al concentration of the exposed surface from our knowledge that the buried surface must have a concentration of about 55 dpm per kg. The difference between our measured bottom surface concentration and the true bottom concentration would then be due to the fact that part of our designated bottom was actually exposed on the lunar surface. From these considerations we estimate that the average surface concentrations (in the top 0.2 mm) could have been as high as 400 dpm per kg, or

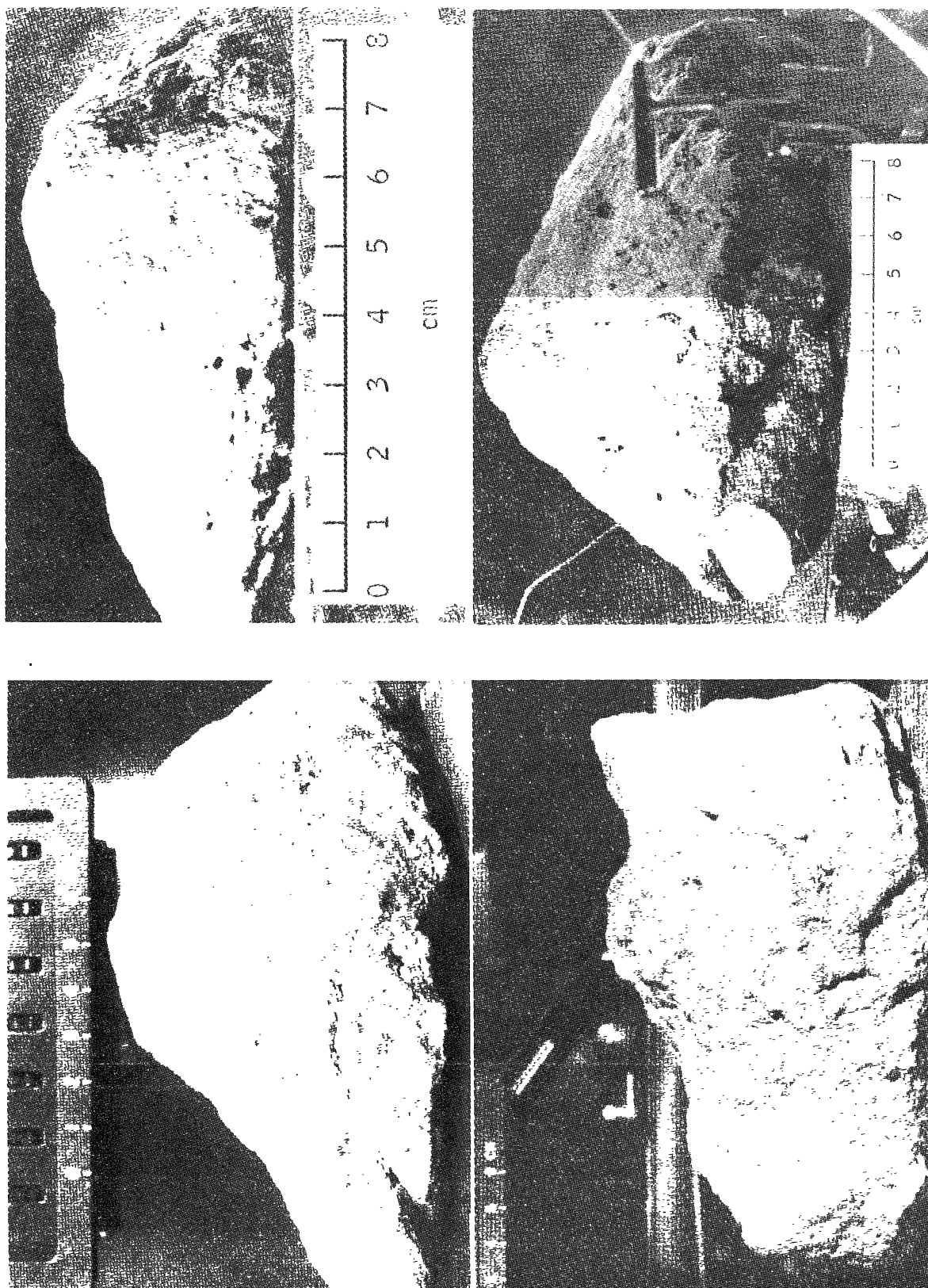


Fig. 4. Apollo 12 samples for which the lunar surface orientation has been determined. Rocks 12005 (upper left); 12016 (upper right); 12051 (lower left); 12063 (lower right).

about one-half of the equilibrium concentration. This rather low concentration requires an erosion rate of about 1 mm per million years, but must be considered with caution since the actual burial depth of these samples is not known.

Erosion and mixing rates

A much more precise estimate of lunar rock erosion rates can be obtained from examination of the ^{26}Al concentrations in "vertical sections" through rocks 12053 and 12002. The concentrations in various depth sections from the top to bottom surfaces of these rocks are included in Table 2. The calculated ^{26}Al contents as a function of erosion rate in the top centimeter of lunar rocks with the chemical compositions of 12002 and 12053 are plotted in Fig. 5. The highest ^{26}Al concentration of 152 dpm per kg in the top 0.8 cm section of rock 12053 is consistent with a surface concentration of about 400 dpm per kg and an erosion rate of about 1 mm per million years. On comparing the ^{26}Al concentration in this top specimen (12053,38) with that in an equivalent weight thickness of lunar fines (Table 3 and Fig. 2), and correcting for chemical composition, it appears that the ^{26}Al is equal to about one-half the saturation value and this would also be achieved with an erosion rate of about 1 mm per million years.

The ^{26}Al concentration in the surface specimen of rock 12002 is about two-thirds that of 12053,38. Based on chemical composition, rock 12002 should have a 5% lower ^{26}Al content and a 50% higher ^{22}Na content than 12053 for equal erosion rates. That rock 12002 is at saturation seems clear from a comparison of the ^{26}Al concentrations in deep sections of this rock with similar depths in rock 12053. The relatively low ^{26}Al concentration in specimen 12002,93 might possibly have resulted if it occupied a position of low vertical angle in the lunar orientation of the rock. Its relatively low ^{22}Na content supports the possibility that it occupied a low vertical angle on the moon. The alternate explanation that the erosion rate was substantially higher, on

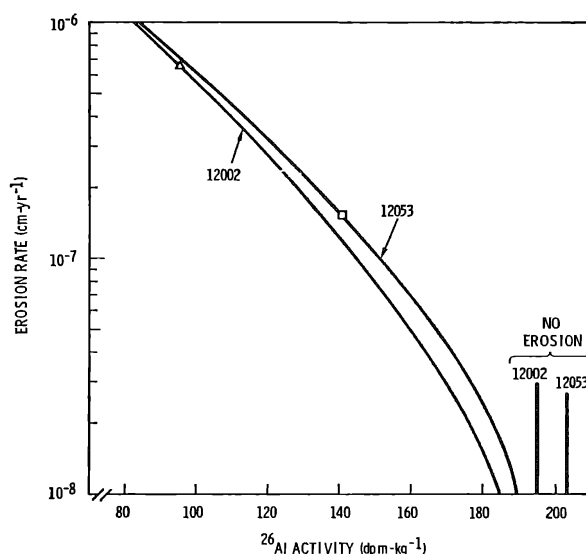


Fig. 5. Calculated ^{26}Al content in the top centimeter of lunar rocks as a function of erosion rate.

the order of 4 or 5 mm per million years cannot be precluded. However, this erosion rate is substantially higher than estimates based on cosmic ray track measurements on other rocks (CROZAZ *et al.*, 1971; BARBER *et al.*, 1971; FLEISHER *et al.*, 1971).

Plotted in Fig. 2 are the vertical concentration profiles of ^{22}Na and ^{26}Al in the first 6 cm of depth of the double core tube 12025. The depth profile in units of g/cm^2 for ^{26}Al in the soil (Table 3) is very similar to that in the lunar rocks (Table 2) beyond the first few centimeters. For this comparison a density of $1.8 \text{ g}/\text{cm}^3$ (Apollo 12 Preliminary Science Report, 1970) was assumed. The very striking observation, however, is that the ^{26}Al concentration gradient in the first 2 cm is nearly flat. That this is not due to mixing of this area of the core either during or subsequent to sampling is attested to by the fact that a steeply descending gradient is observed for the 2.6 yr ^{22}Na (See Figs. 3a and 3b). To obtain the observed concentration profile for the ^{26}Al (7.6×10^5 yr) would require rather complete mixing of soil on the lunar surface to a depth of 2 or 3 cm every 10^5 years. The uniform stratigraphy of this section of the core tube supports mixing to this depth, and precludes the possibility that the flat ^{26}Al gradient has resulted from recent deposition of new material. The concentrations of both ^{22}Na and ^{26}Al in the double core tube 12025, 12028 decrease to a relatively constant value at depths greater than 10 cm. The average ^{26}Al content in the 10 cm to 39 cm depth section where galactic cosmic ray production predominates is 45 dpm/kg. This value agrees well with a value of 48 dpm/kg which was calculated by assuming a 2π exposure and using the method of FUSE and ANDERS (1969) which relates ^{26}Al content to chemical composition of meteorites. This rather good agreement would strongly suggest that the average galactic cosmic ray flux in meteorites is very similar to that at 1 A.U. The ratio of ^{26}Al to ^{22}Na in the deep portion of the core tube is about 1.0. This is substantially higher than the ratio of 0.78 in chondrites (RANCITELLI *et al.*, 1969, RANCITELLI *et al.*, 1971), but is properly accounted for by the lower magnesium content of lunar material and hence the lower ^{22}Na production in lunar soil.

The depth gradients for ^{22}Na and ^{26}Al are particularly significant because of the information they provide on soil mixing and radionuclide production rates, but they also provide an important base line for other purposes. From the ^{26}Al and ^{22}Na concentrations in the Apollo 12 bulk fines samples 12070,3, an average sampling depth of 3.5 cm is indicated. The soil from the Surveyor II Scoop (Table 3) indicates a burial depth of 3 cm, and assuming similar mixing rates at Tranquillity Base, an average sampling depth for the bulk fines sample, 10084, of 5 cm is indicated. The ^{22}Na and ^{26}Al concentrations in the trench rock 12034 (see Table 1) are consistent with a burial depth of greater than 5 cm. The ^{26}Al to ^{22}Na ratio of 1.13 with the high ^{22}Na concentration of 72 dpm per kg in rock 12005,0 is consistent with concentrations present in bulk fines sample 12070,3 and possible lunar rock erosion rates. Rock 12005,0 is a thin relatively flat rock of about 4 cm maximum thickness. Its ^{22}Na and ^{56}Co concentrations, although twice that of the other lunar rocks, were the same as those in fines sample 12070,3, while ^{26}Al was one-half that in the fines. Such a thin rock would have a minimum ^{26}Al production from galactic or higher energy solar protons, but would, of course, have a large surface area for production from low energy solar protons. Rapid erosion over the large surface of a rock with this geometry could explain the observed ^{22}Na and ^{26}Al concentrations. It is recognized, of

course, that a very unusual chemical composition could also explain the unusual ^{26}Al : ^{22}Na ratios and that our explanation must be regarded as tentative until chemical analyses are available.

Cosmic ray exposure ages

Estimates of the cosmic ray exposure age for rock 12062 were made by the ^{22}Na - ^{21}Ne method based on reported noble gas measurements (LSPET, 1970). For this calculation it was assumed that the production rates of ^{22}Na and ^{22}Ne were equal and the ^{22}Ne - ^{21}Ne ratio was 1.05. This calculation gives a ^{22}Na - ^{21}Ne exposure age for rock 12062 of 164 million years, suggesting a long surface or near surface life.

Primordial radionuclides

The concentrations of the primordial radionuclides K, U, and Th in lunar materials allow a comparison of the moon's geochronology with other objects in the solar system and help establish the types of processes which have shaped the moon's surface.

The concentrations of potassium, uranium, and thorium in several crystalline rocks, a breccia (12034), and the bulk fines (12070), are included in Table 1. The potassium content of five rocks fall within the narrow range of 0.044 to 0.059% in agreement with the earlier findings of LSPET (1970), while rock 12005 contains 0.026% K, the lowest yet observed in lunar material. The Th and U content of the crystalline rocks varied over a wider range, 0.416 to 0.99 and 0.109 to 0.241 ppm, respectively, with rock 12005,0 containing the lowest concentrations observed in lunar materials, suggesting an origin independent of the other crystalline rocks reported on to date. The K, U, and Th content of the Apollo 12 crystalline rocks is one-third to one-fourth those observed on the Apollo 11 samples with one notable exception. Apollo 11 rock 10003, classified as a group 2 rock by COMPSTON *et al.*, 1970, contained Th, U, and K in concentrations similar to those of the Apollo 12 rocks. In marked contrast to the Apollo 11 samples, the K, U, and Th concentrations in Apollo 12 breccias and fines are very high compared with the crystalline rocks. The K, U, and Th of the breccia 12034 are seven to tenfold higher than in the crystalline rocks. The Apollo 12 bulk fines, 12070, were also enriched in their primordial radionuclide content relative to the crystalline rocks, but to a lesser degree than the breccia. It is therefore evident that the soil is not a simple erosion product of these crystalline rocks and the breccia are not simple impact products of surrounding soil. It is tempting to suggest that the soil is a mixture of material composed primarily of crystalline rocks with a 10 to 15% admixture of material with the high primordial radioisotope composition of the feldspathic differentiate rock 12013, however, this is unsatisfactory since the low K/U ratios indicate the soil and breccia are on the average more highly differentiated than any of the crystalline rocks. As suggested by several groups at the Apollo 12 lunar science conference, the soil contains a highly differentiated component similar to that reported in 12031 which could account for the apparent highly differentiated nature of the soil.

The relative atomic abundances of Th/U in the six Apollo 12 crystalline rocks

were constant at 3.8 ± 0.1 , in excellent agreement with our previous measurement of 3.8 ± 0.2 in three Apollo 11 rocks and the calculated value of 3.8 ± 0.3 for the present day solar system (FOWLER and HOYLE 1960). The ratio in the breccia 12034 and fines 12070 of 4.1 is close to the values in the rocks when the statistical uncertainty is considered. The K/U ratio of the rocks which ranged from 1900 to 3100 is larger than that reported by LSPET (1970) and comparable to the range reported in the Apollo 11 samples (O'KELLEY *et al.*, 1970a, PERKINS *et al.*, 1970a). We confirm the LSPET (1970) findings that the K/U ratio in the breccia and soil were one-half those of the crystalline rocks at the Apollo 12 site, a marked contrast to the Apollo 11 findings where the soil and rocks had about the same K, U, and Th content. These low K/U ratios in the soil and breccias, as stated above, offer a strong indication the material from which the soil was derived underwent extensive differentiation unique from the processes that formed the crystalline rocks at the Apollo 12 site.

It is interesting to note, although this may be an artifact of the small number of samples, that the K/U ratios of crystalline rocks measured here and by LSPET (1970) fall into several distinct groupings, 1800–2000, 2400–2500, and 2800 to 3100. The constant K content of the Apollo 12 rocks suggests that these rocks may represent samples from a separate basalt flow and the low K rock 12005 is a sample from an independent flow. If this proves to be the case, the K/U ratios may result from localized segregation from an initially homogeneous lava as suggested by COMPSTON *et al.*, 1970 for the group 2 Apollo 11 rocks.

The Th content of the double core tube 12025, 12028 (see Table 3) was constant within the uncertainty of the measurement to a depth of 9 cm and comparable to the Th content of the bulk fines 12070,13. A discontinuity in the Th content was noted in the 9.4 to 16.4 cm depth section of the core. The average Th content of the six samples 12028, 11, 13, 14, 16, 17, 18 was 3.2 ± 0.2 ppm, about one-half the value for overlying material. The uranium content of this section of 0.90 ± 0.09 ppm was also low compared with the bulk fines 12070, however, the Th/U ratio remained unchanged at 3.6 ± 0.4 . The existence of this discontinuity in the primordial radionuclide content of the core tube in the region of 9 to 16 cm depths indicates the soil is not well mixed to these depths and that a unique type of material was deposited during this period of regolith formation. The Th and U content of the core tube 12028 at depths below the 16.4 cm depth are significantly higher than the top of the core tube and the bulk fines while the Th/U content remains relatively constant.

The rare gas content of the type AB rock 12062 was reported earlier by LSPET (1970). On the basis of their rare gas concentrations and the primordial radionuclide measurements of this work, K–Ar and U–Th–He gas retention ages were calculated. This crystalline rock showed respective ages of 2.61 and 1.50 billion years, indicating a substantial difference in the rate of rare gas loss.

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