
Cosmogenic radionuclides produced in the lunar surface by solar and galactic protons are employed to study both the recent and ancient cosmic ray irradiation history and to characterize lunar surface processes such as erosion of rocks and mixing of soil. (1) Radionuclide measurements in Apollo 11 and 12 samples indicated the relative contributions of solar and galactic protons to the cosmic ray flux at the lunar surface. Measurements of $^{26}$Al and $^{22}$Na depth gradients in whole rock, rock slices and core tubes from Apollo 12 have provided the necessary information to define the average intensity and energy spectrum of solar protons incident on the moon. The best fit for incident protons above 10 MeV, using the kinetic energy power law to describe the solar proton spectrum is:

$$dJ/dE = KE^{-3.0}$$

Where $J$ is the proton flux, $E$ is proton energy and $K$ a constant related to the particle intensity. From radionuclide and cosmic ray energy spectrum considerations, the average proton flux with energy greater than 10 MeV incident on the moon for the last few million years has been $60 \text{ p/cm}^2\text{-sec}$. The fact that the observed $^{26}$Al and $^{22}$Na depth concentration gradients can be described by the same proton energy and intensity spectra indicates the solar activity has remained relatively unchanged for at least the last million years.

Although the Apollo 11 and 12 lunar sample studies have greatly increased our knowledge of lunar processes and the cosmic radiation history, it is far from complete. A study of the suite of Apollo 15 samples near the St. George crater at the Apennine Hadley site has been particularly illuminating in revealing the history of some of the processes which occurred at this site as well as confirming the rates of lunar soil mixing. Rock chips from the surface of a large boulder and samples of surrounding and underlying soil were studied. Two chips (15205 & 15206) from the top surface of the boulder together with soil samples from beneath the boulder (15231), adjacent to the boulder (15211), and about 0.5 (15231) and 10 meters (15091) from the boulder were studied. The results of the radionuclide analyses are summarized in Table 1. Conclusions based on these analyses must be qualified somewhat because chemical analyses have not yet been reported; however, the following history of the boulder and soil appears evident. The boulder has been on the lunar surface in its present position for about one million years. This is evident from the fact that while the $^{22}$Na concentrations in the boulder chips are at saturation, the $^{26}$Al concentrations are at approximately one-half to two-thirds of their saturation value. This rather short lunar surface life is also attested to by the fact
that the soil (15231,1) directly beneath the boulder has a higher $^{26}\text{Al}$ concentration than its saturation value for its rather highly shielded location (minimum of 20 g/cm$^2$). This high concentration requires that it was exposed to saturation before the boulder covered it about one million years ago. The "soil fillet" (15211,2) adjacent to the boulder has a primordial radionuclide composition which is essentially identical to that of nearby soil samples, yet is far different from that of the boulder. This requires that the soil fillet originated almost entirely from nearby soil rather than from erosion of the boulder. This well developed soil fillet around the boulder helps to confirm our previous conclusions\(^{(1)}\) that soil mixing through the first two or three centimeters of depth occurs rather well on a time scale of 100,000 years through micrometeorite bombardment. Soil projectiles which were ejected by micrometeorite bombardment and which struck the boulder would form the observed fillet.

Two very interesting lunar specimens were collected at Station 9 of the Hadley Apennine site (see Table 2). Sample 15501,2 was a soil clod from the ejecta blanket of an apparently young crater.\(^{(2)}\) Our measurements show saturation with respect to $^{22}\text{Na}$, however the $^{26}\text{Al}$ concentrations indicate a surface age of only 0.75 to 1 million years. A possible alternate explanation for the low $^{26}\text{Al}$ concentration is a very high erosion rate; however, such a low concentration would require an erosion rate on the order of centimeters per million years.

Rock 15556, a highly vesicular basaltic rock, showed an unusually high $^{26}\text{Al}$ concentration which was adequately justified by its low density and the fact that it was only very slightly recessed in the lunar soil. Soil samples which were taken from trenches at stations 6 and 8 have been analyzed (see Table 2). Samples 15041,14 and 15031,14 represent top and bottom soil samples from the trench at station 8. Our previous observations of both rock and soil cores have shown that where the chemical composition of the major target elements for $^{26}\text{Al}$ and $^{22}\text{Na}$ are reasonably constant, the $^{26}\text{Al}$ to $^{22}\text{Na}$ ratio decreases by as much as twofold in the first 20 g/cm$^2$ of depth. The fact that the $^{26}\text{Al}$ to $^{22}\text{Na}$ ratio is the same at the surface as at the trench bottom suggests a very different chemical composition for soil from the two levels. Such a difference, however, is certainly not suggested by the primordial radionuclide concentrations. The approximate twofold increase in $^{54}\text{Mn}$ concentrations with depth, and the approximately fourfold decrease in the $^{56}\text{Co}$ with depth are in accord with the expected galactic cosmic ray flux buildup with depth and the solar cosmic ray attenuation with depth, respectively. The rather low concentration of $^{46}\text{Sc}$, $^{48}\text{V}$ and $^{56}\text{Co}$ were to be expected because of the lack of major solar flares for several months prior to the Apollo 15 mission.

A few of the radionuclide measurements of Apollo 14 samples are summarized in Table 3. The comparison of the observed $^{26}\text{Al}$ content of Rock Slice 14310,187 with the predicted value based on the average incident proton spectrum, the rock's chemical composition and the $^{26}\text{Al}$ excitation functions indicates this rock was at the surface for at least the last two or three million years. This is of particular interest, since preliminary track measurements\(^{(3)}\) suggested that the rock might have had a relatively short lunar surface.
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age. Rock sample 14321.40 is a 700 gram surface specimen of the 9 kilogram football sized breccia. The $^{22}$Na and $^{26}$Al concentrations in this section indicate saturation, however, the $^{26}$Al is somewhat low and may be the result of losses of surface material which are known to have occurred during the cutting of this specimen. Soil sample 14163.0 has substantially lower $^{22}$Na and $^{26}$Al concentrations than are present in the top two or three centimeters of lunar soil. This indicates that the sampling depth for this specimen was approximately 8 centimeters. Some of the Apollo 15 samples were counted one to two weeks after return to Earth. Measurements of the $^{40}$K (16.1d) in these samples indicated that it could be entirely accounted for by galactic cosmic ray production, thus demonstrating a negligible solar cosmic ray contribution over the past several months. In the case of $^{56}$Co its concentration is about 10 fold higher than could result from galactic cosmic ray bombardment, indicating a substantial residue from the January 24, 1971, solar flare.

The primordial radionuclide concentrations of Apollo 15 soil samples fall in a range between those at the Apollo 11 and Apollo 12 sites. (Table 4) The K, U and Th content of soil samples near Hadley Rille (stations 2 and 9) are lower than those at the landing site (station 8) and station 6, indicating that the wide differences which were observed between the Apollo 11 and 12 sites can also occur locally on a scale of a few kilometers. The K, U and Th content of the Apollo 14 soil sample is two to four-fold higher than those at the Apollo 12, and 15 sites while the K/U ratios (1200-1500) are comparable suggesting that the magmatic differentiation indicated by these ratios is characteristic of a large portion of the lunar surface. The Th to U ratios of Apollo 14 and 15 soil are about 4, in agreement with observation on Apollo 11 and 12 soils.

REFERENCES:

