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Apollo 15 Geochemical X-ray Fluorescence Experiment: Preliminary Report

Abstract. *Although only part of the information from the x-ray fluorescence geochemical experiment has been analyzed, it is clear that the experiment was highly successful. Significant compositional differences among and possibly within the maria and highlands have been detected. When viewed in the light of analyzed lunar rocks and soil samples, and the data from other lunar orbital experiments (in particular, the Apollo 15 gamma-ray spectroscopy experiment), the results indicate the existence of a differential lunar highland crust, probably feldspathic. This crust appears to be related to the plagioclase-rich materials previously found in the samples from Apollo 11, Apollo 12, Apollo 14, Apollo 15, and Luna 16.*

The recent Apollo 15 mission included a large complement of orbital experiments, of which three were components of an integrated geochemistry experiment. These three experiments, involving gamma-ray, x-ray, and alpha particle spectrometers, were included to obtain a geochemical map of the moon along the projected paths swept out by the orbiting spacecraft.

This report presents some of the preliminary results from the survey of the lunar surface obtained with the x-ray spectrometer. Although measurements of Al/Si and Mg/Si ratios were made, only the Al/Si ratios will be reported here. The Mg/Si ratios are important but more difficult to calculate and will be reported at a later date.

The Apollo x-ray experiment is based on the production of characteristic x-rays due to the interaction of the solar x-rays with the lunar surface. It appears from a number of calculations (*1*) that the typical solar x-ray spectrum is energetically capable of producing measurable amounts of characteristic x-rays from all the abundant elements up to about atomic number $Z = 14$ (Si). Furthermore, during brief periods of more intense solar activity when the solar flux "hardens" (higher fluxes of more energetic x-rays) it should be possible to observe radiation from elements of higher atomic number. Thus the secondary radiation excited from the lunar surface depends on the nature of the solar flux. It can affect not only changes in the fluorescent x-ray intensities but also changes in the relative intensities from the various elements. For example, should the solar spectrum harden, then there would be an enhancement of the intensities from the heavier elements relative to the lighter ones.

The instrument will be described briefly; a more detailed description can be found in documents detailing the Command Service Module (CSM) "J" series mission experiments (*2*). The x-ray detector assembly consisted of three large-area proportional counters with Be windows 0.0025 cm thick. Two of the detectors had large-area x-ray filters (Mg and Al foils) for energy discrimination among the characteristic x-rays of Al, Mg, and Si. A fourth detector was used as a solar monitor. A single collimator assembly was used to define a field of view of the three proportional counters as a single unit. The field of view was ± 30° full width at half maximum in two perpendicular directions. At orbital altitudes of 60 nautical miles (111 km) this field of view covered a sector approximately 60 by 60 nautical miles. The actual surface resolution defined by the collimators was also a function of the spacecraft motion and the time interval for data accumulation. Because the preliminary results in this report are based on 1-minute accumulation periods (the prime data are for 8-second intervals), one must consider each data point as representing a swath on the lunar surface of approximately 60 by 120 nautical miles. An eight-channel pulse height analyzer was used for each of the four detectors to obtain energy information. The filtered counters and the solar monitor covered a fixed energy of from 0.75 to 2.75 kev, whereas the unfiltered detector covered two energy ranges: 0.75 to 2.75 kev and 1.5 to 5.5 kev. The two gain modes of the unfiltered detector were operated alternately by a program built into the x-ray processor. The x-ray experiment was mounted in the Science Instrument Module. The proportional counter of the solar monitor was mounted on the opposite side of the spacecraft to continuously monitor the sun's x-ray flux simultaneously with the surface measurements.

The x-ray experiment was turned on by command module pilot A. Worden some 84 hours after the start of the mission, during the third revolution around the moon. About 100 hours of data were taken of the illuminated portion of the lunar surface during 84 revolutions. Lunar backside data were recorded on magnetic tape and telemetered while the spacecraft was on the forward side. The region covered ranged from about 150°E to 50°W.

The data have been reduced in a simple manner based on the energy discrimination afforded by the selected x-ray filters. Three simultaneous equations were written and solved by least-squares analysis, a procedure which permits easy estimates of statistical validity. The Al/Si intensity ratios were reduced to concentration ratios by a procedure which was in part theoretical and in part empirical. The theoretical calculations were based on an assumption of a coronal temperature of about 3×10^6 °K. Under these conditions we were able to calculate an x-ray energy distribution consisting of both continuum and characteristic lines which is consistent with our observations by means of the solar monitor of the solar x-ray flux. Using this calculated distribution, various compositions of lunar materials taken from the literature, and known fluorescence yields, we were able to derive a nearly linear relationship between Al/Si intensity ratios and Al/Si concentrations.

Empirically, the analysis of lunar

samples returned from Mare Fecunditatis (Luna 16) and Mare Tranquillitatis has provided us with information about the chemical composition of the two sites on which x-ray chemical mapping was performed. These two sites show relatively constant Al/Si ratios over large neighboring areas (see Fig. 1). For instance, at the Mare Tranquillitatis Surveyor 5 site the Al/Si concentration ratio was 0.35 for the regolith whereas at the Apollo 11 site some 32 km away the value of the Al/Si ratio for the soil was 0.37. Using the average concentration at these two sites, we calculated the Al/Si intensity ratio and found it to be within 10 percent of the orbital measured values. The calculated and measured values were thus in agreement within statistical error. With this agreement as a basis, the theoretically calculated relation (Al/Si intensity ratio versus Al/Si concentration) was used to estimate the concentrations shown in Table 1.

In Fig. 1 we have plotted Al/Si intensity ratios along projected ground tracks corresponding to revolutions 16, 25 through 27, 34, 63 through 64, and 72. Because of the close overlap, it was found useful to average some of the orbits. The agreement between values on the close ground tracks was, on the average, about ± 10 percent.

It can be seen from the map (Fig. 1) that there are very marked differences between the eastern limb highlands and the mare areas, the Al/Si intensity ratios varying by more than a factor of 2, being lowest in the mare areas and highest over the terrae (Table 1). The extremes vary from 0.58 to 1.37. The Apennines show intermediate values of 0.88, and the Haemus Mountains show a lower value of 0.83.

An interesting correlation between the Al/Si ratios and optical albedo values along a preselected ground track was obtained. Generally, the high Al/Si ratios correspond to higher albedo values. There are occasional deviations from these relations due to surface features (as, for example, a Copernican-type crater). It thus appears that one can use the x-ray data to infer something about the relation between albedo and composition. It may be possible for example to determine whether the albedo of a given feature results from chemical variation or from structure and age.

Table 1. Aluminum/silicon ratios.

Lunar features	Intensity ratios*	Concentration ratios
Al/Si intensity ratios and calculated concentration ratios for various lunar features		
Mare Serenitatis	0.58 ± 0.04; rim, 0.71 ± 0.05	0.29 ± 0.02
Mare Imbrium	.59 ± 0.07	.30 ± 0.03
Mare Tranquillitatis	.70 ± 0.05; rim, .84 ± 0.04	.36 ± 0.02
Mare Crisium	.71 ± 0.02; rim, .80 ± 0.09	.37 ± 0.01
Mare Smythii	.73 ± 0.07; rim, 1.00 ± 0.11	.37 ± 0.04
Mare Fecunditatis	.73 ± 0.07; rim, 0.94 ± 0.14	.38 ± 0.03
Area northeast of Schröter's Valley	.64 ± 0.09	.32 ± 0.04
Area north of Schröter's Valley (Aristarchos Plateau)	.72 ± 0.07	.37 ± 0.03
Archimedes Rilles area (to Marsh of Decay)	.64 ± 0.03	.33 ± 0.01
Haemus Mountains	.83 ± 0.10	.43 ± 0.05
Apennine Mountains	.88 ± 0.01	.46 ± 0.01
Highlands east of Serenitatis to 40°E	.80 ± 0.08	.42 ± 0.04
Highlands between Crisium and Smythii	1.07 ± 0.13	.56 ± 0.06
Highlands west and south of Crisium	1.08 ± 0.11	.56 ± 0.05
Highlands between Smythii and Tsiolkovsky	1.16 ± 0.14	.60 ± 0.07
Highlands east of Fecunditatis	1.29 ± 0.23	.66 ± 0.11
Highlands east of Tsiolkovsky	1.37 ± 0.25	.69 ± 0.12
Al/Si concentration ratios of selected lunar samples		
Apollo 11, Mare Tranquillitatis, bulk soil (*8*)		0.367
Surveyor 5, Mare Tranquillitatis, regolith (*9*)		.350
Apollo 11, Mare Tranquillitatis:		
Average of low-K rocks (*8*)		.286
Average of high-K rocks (*8*)		.227
Apollo 11 and Apollo 12:		
Anorthositic gabbros (*7, 10*)		.637
Gabbroic anorthosites (*7, 10*)		.819
Anorthosites (*7, 10*)		.885
Apollo 12, Oceanus Procellarum:		
Average of soils (*11*)		.325
Average of type A rocks (*11*)		.239
Average of type AB rocks (*11*)		.219
Average of type B rocks (*11*)		.221
Dark 12013 (*12*)		.327
KREEP† (*12*)		.394
Noritic material (*7, 10*)		.416
Luna 16, Mare Fecunditatis:		
Bulk soil (*13*)		.416
Rocks (*13*)		.352
Surveyor 6, Sinus Medii, regolith (*9*)		.338
Apollo 14, Fra Mauro:		
Average of soils (*14*)		.413
Average of rocks (*14*)		.377
Surveyor 7, rim of Tycho, regolith (*9*)		.546

*Average of the values (± 1 standard deviation) obtained from the passes over each feature. †Potassium, rare-earth elements, phosphorus.

There are other correlations, but only preliminary comments can be made. An attempt has been made to plot Al/Si intensity values along a gravity profile obtained by Sjogren (*3*). It appears that the Al/Si intensity ratios vary inversely with gravity values; the lowest values are found in the regions of greatest positive anomalies.

Some tentative interpretations are possible, especially when the data are viewed in the context of earlier Apollo missions. These interpretations are based on comparisons of the relative Al/Si ratios with albedo values, regional geological data, and data from the analysis of the returned lunar samples. They are subject, at this stage of the analysis, to several limitations. First, the data plotted were read out at 1-minute intervals; this and the 60° field of view of the x-ray spectrometer mean that the Al/Si ratios refer to large areas. Second, the experiment is inherently a surface compositional measurement, providing no information, except for the mixing effect, of "gardening" on the subsurface composition below depths of about 0.1 mm. Subject to these limitations, we draw the following general conclusions about the moon's geology and evolution from the x-ray experiment.

1) The Al/Si ratios (Table 1) confirm that the highlands and maria do indeed have different chemical and mineralogical compositions. This conclusion, although expected, should be stated explicitly since there have been thus far only two sample-return missions (Apollo 14 and Apollo 15) to the highlands. Furthermore, it confirms that the albedo difference between highlands and maria is at least partially the expression of chemical difference. The x-ray experiment, with the evidence

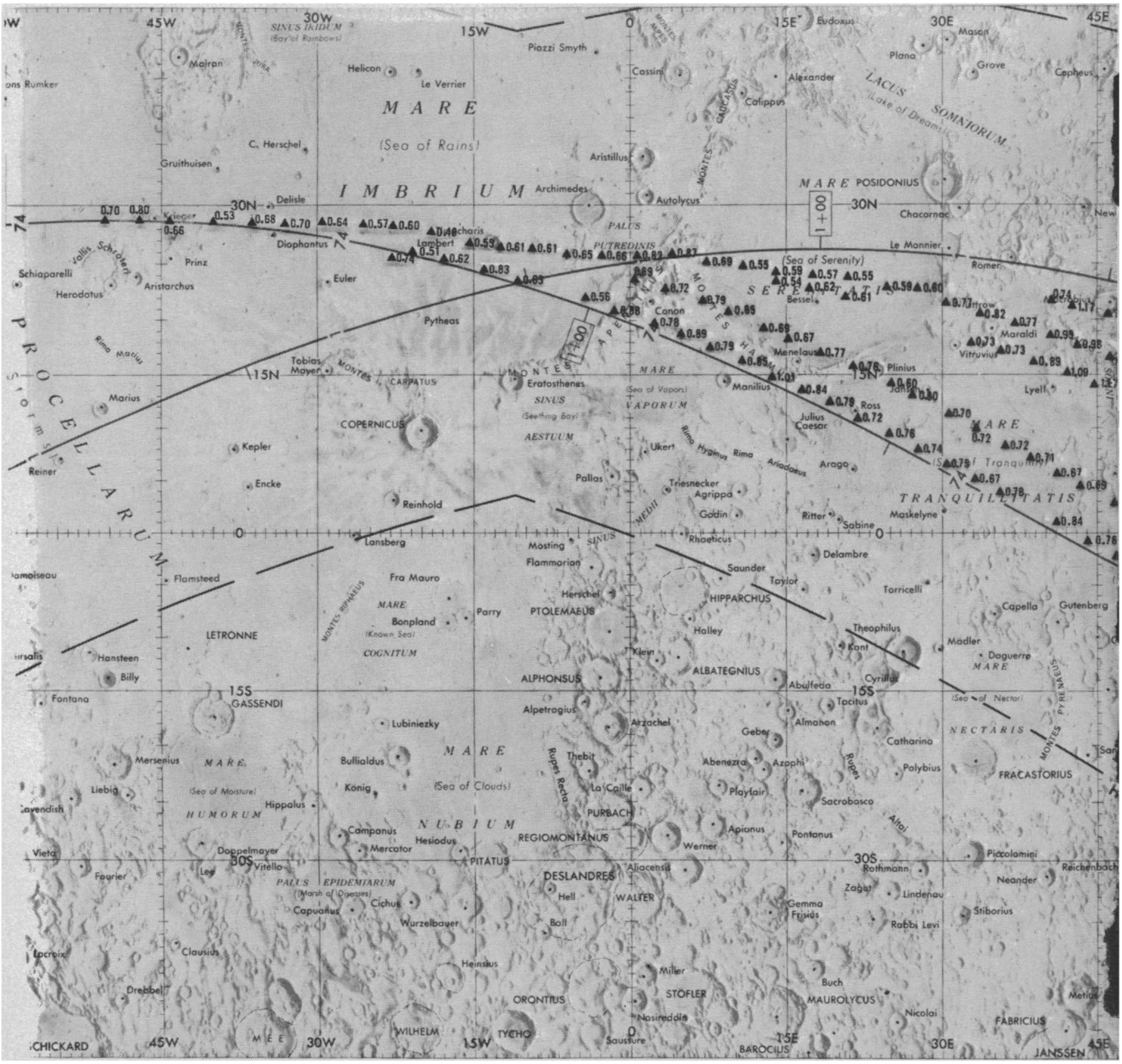
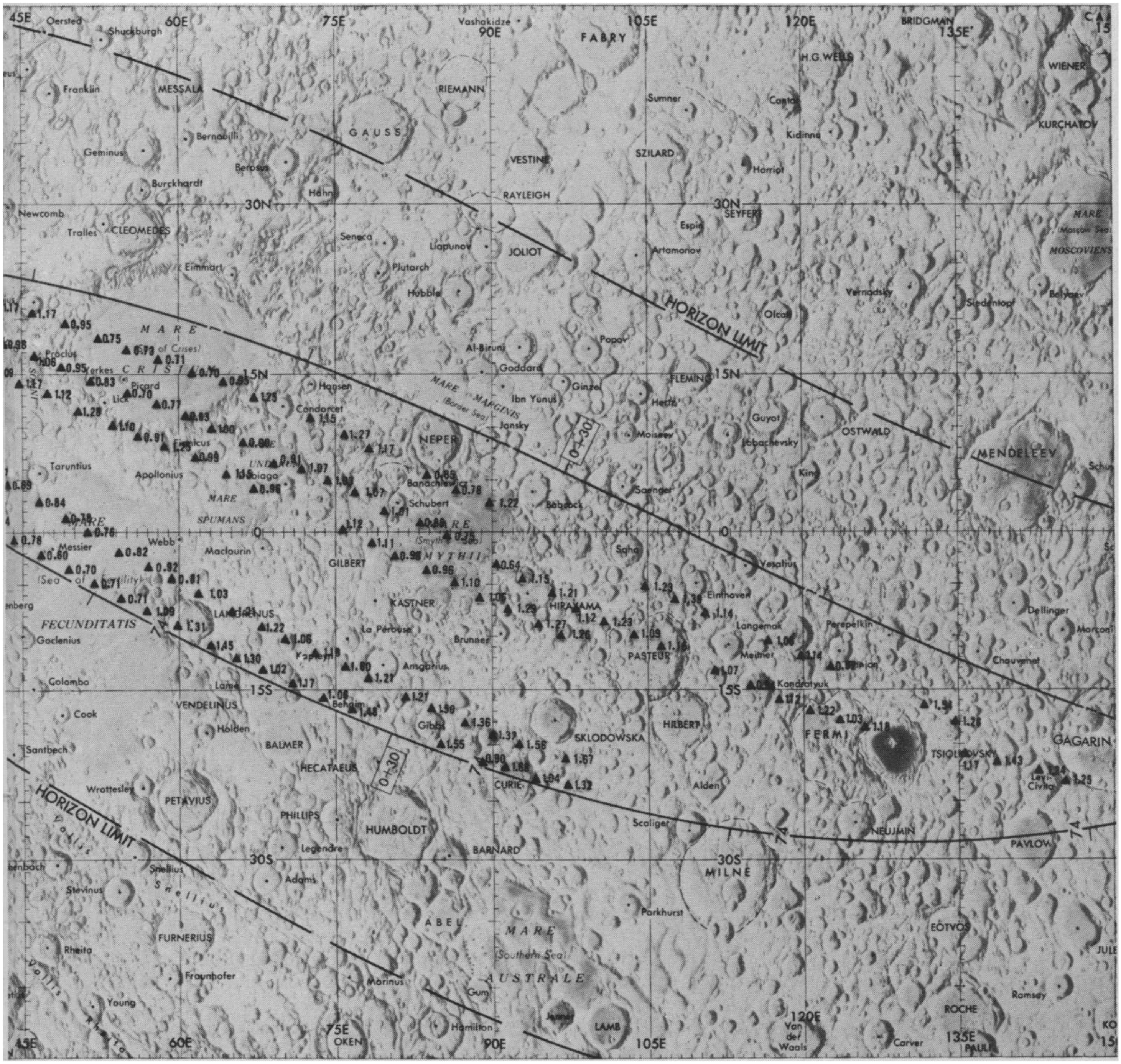


Fig. 1. Aluminum/silicon intensity ratios plotted along the projected ground tracks

from returned samples, indicates that there are at least two major types of materials exposed. The high Al/Si ratios of the highlands suggest they are related to the plagioclase-rich fractions of returned samples, whereas the low Al/Si ratios of the maria are consistent with the composition of the mare basalts. The distinct compositional differences between the maria and the highlands put limits on the extent of the horizontal transport. Were such a mechanism completely effective, the x-ray experiment would probably not detect compositional differences between highlands and maria because it "sees" only what is essentially the top surfaces. There has been perhaps some blurring of the mare-highlands contacts, as will be discussed in conclusion 3, probably by the cumulative effect of minor impacts.

2) As shown in Table 1, there is indication of chemical differences among the maria; the raw data suggest that the circular maria are relatively lower in Al/Si ratios than the irregular maria. If real, these differences may throw light on the origin of the mare basins, since the circular maria are characterized by mascons and apparent ejecta blankets, whereas the irregular maria are not. The data require more refinement to confirm this conclusion. However, they are consistent with the recent work of Soderblom (*4*), who found that the circular maria ("red") could be distinguished from the irregular maria ("blue").

3) There appear to be systematic chemical variations within the individual maria, in particular, Mare Crisium and Mare Serenitatis. The raw data suggest that the edges of these maria have relatively higher Al/Si ratios than the



corresponding to revolutions 16, 25 through 27, 34, 63 through 64, and 72. [Note overlap in gutter] centers. These variations may be real, a possibility supported by the systematic albedo patterns in Mare Serenitatis (*5*) and more indirectly by the work of Soderblom (*4*), who found several spectral subtypes of both "red" and "blue" maria. However, two factors confuse the picture at this time. First, because of the relatively large field of view of the x-ray experiment, intensity readings near mare rims include contributions from the nearby highland areas. Second, the mare regolith near the borders may contain substantial amounts of ejecta from nearby highlands. Study of the prime data, taken at 8-second intervals, may clarify this result.

4) The Imbrium ejecta blanket [Fra Mauro and Alpes Formation (*6*)] and possibly other ejecta blankets may be chemically different from the highlands outside such ejecta blankets. An obvious interpretation of this difference, if it is real, is that the mare basin ejecta blankets represent less Al-rich material derived from some depth in the moon. However, the ejecta blanket areas covered by the x-ray spectrometer, in particular in the Haemus Mountains south of Mare Serenitatis, included substantial areas of highland mare material [shown as Eratosthenian mare by Wilhelms and McCauley (*6*)]. It is thus unwise at this time to draw firm conclusions about the composition of the mare basin ejecta.

5) The x-ray data support the belief that the moon has a global Al- or plagioclase-rich crust whose formation was the first major geochemical event of the moon's geologic evolution after its formation. The data tend to support the suggestion of Wood (*7*) of widespread cumulates of plagioclase. Despite the preliminary nature of these data, one can pinpoint areas on the lunar highlands that have Al/Si ratios corresponding to analyzed materials rich in plagioclase. As shown in Table 1, the anorthositic gabbros have Al/Si ratios of 0.64, gabbroic anorthosites 0.82, and anorthositic fragments 0.89.

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Primordial Radioelements and Cosmogenic Radionuclides in Lunar Samples from Apollo 15

Abstract. *Two basalts, two breccias, and two soils from Apollo 15 were analyzed by nondestructive gamma-ray spectrometry. The concentrations of potassium, thorium, and uranium in the basalts were similar to those in the Apollo 12 basalts, but the potassium : uranium ratios were somewhat higher. Primordial radioelements were enriched in the soils and breccia, consistent with a two-component mixture of mare basalt and up to 20 percent foreign component (KREEP). The abundance patterns for cosmogenic radionuclides implied surface sampling for all specimens. The galactic cosmic-ray production rate of vanadium-48 was determined as* 57 ± 11 *disintegrations per minute per kilogram of iron. Cobalt-56 concentrations were used to estimate the intensity of the solar flare of 25 January 1971.*

The Apollo 15 mission has presented a unique opportunity to study the geochemistry of lunar surface materials by nondestructive gamma-ray spectrometry. The area explored was large and geologically diverse, and the improved sample documentation was supported by live television coverage. In addition, the Apollo 15 manned lunar landing, unlike previous missions, was not closely preceded by an intense solar flare. Thus, the Apollo 15 material could be used in a study of the galactic cosmic-ray production rates of some short-lived radionuclides that previously were produced chiefly by solar cosmic rays. Finally, since no quarantine requirements were imposed on samples from Apollo 15, the preliminary examination at the Lunar Receiving Laboratory (LRL) was supplemented by measurements at other laboratories.

The first Apollo 15 samples for radioactivity determination (15016,0 and 15101,1) were received from the LRL on 11 August 1971, about 9 days after lift-off from the moon. Two weeks later another pair of samples was received (15495,0 and 15601,2). Additional samples (15285,0 and 15455,0) gave valuable data on long-lived radionuclides, but because of the long decay interval before measurement they yielded little information concerning short-lived species.

The equipment and techniques of nondestructive gamma-ray spectrometry are essentially those we developed for use during the Apollo 11 and Apollo 12 missions at the LRL (*1–3*). Spectrum libraries for all the samples except 15455,0 were obtained from replicas that accurately reproduced the electronic and bulk densities of the lunar