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APOLLO 16 GEOCHEMICAL X-RAY FLUORESCENCE EXPERIMENT: PRELIMINARY REPORT

Abstract: The lunar surface was mapped with respect to Mg, Al and Si as Al/Si and Mg/Si ratios along the projected ground tracks swept out by the orbiting Apollo 16 spacecraft. The results confirm the observations made during the Apollo 15 flight and provide new data for a number of features not covered before. The data are consistent with the idea that the moon has a widespread differentiated crust (the highlands). The Al/Si and Mg/Si chemical ratios correspond to that for anorthositic gabbro through gabbroic anorthosites or feldspathic basalts. The X-ray results suggest the occurrence of this premare crust or material similar to it as the Descartes landing site.

An integrated geochemical package was carried in the Command and Service Module during the Apollo 16 flight to the Descartes highland area. This package which was identical to the one carried aboard Apollo 15 included the X-ray, gamma-ray and alpha particle spectrometers. These experiments were flown to extend our observations to larger areas of the moon and to allow us to extrapolate from the data obtained on the surface to the rest of the moon. Thus, the purpose of the orbital mapping experiment and in particular the X-ray fluorescence experiment on which we are reporting here was to tie together the information obtained from the analysis of the returned lunar samples from the various sites to the global geochemical picture.

There was some overlap of orbital coverage between the two missions so that reproducibility of our results between the two missions could be studied and thus tied together. The total coverage for these two missions is greater than 20 percent of the total moon's surface. The Apollo 16 mission provided data for a number of features not previously covered for example Mare Cognitum, Mare Nubium, Ptolemaeus, Descartes area and Mendeleev as well as a number of other areas. One fact of considerable interest was the fact that the X-ray experiment was able to obtain a large number of data points over the Descartes landing site (see Fig. 1 and Table 1) while the astronauts were gathering samples on the surface. Our results will hopefully show how representative these were of the Descartes area.

Unlike the high inclination orbit of Apollo 15, the Apollo 16 flight path was nearly equatorial (9 deg. inclination) so that the projected areas covered were somewhat smaller than during the 15 flight. Although the original flight plan called for a plane change the exigencies of the mission did not permit this, consequently some of the ground coverage was lost.

The details of the X-ray experiment have already been described (1, 2, 3). The solar monitor on the Apollo 16 had an additional beryllium filter in front of the detector window to enable us to look at the high sun X-ray fluxes without observing the detector gainshifts experienced on the 15 flight.

The X-ray experiment was turned on initially at 80 hours into the mission and operated for about 12 hours in elliptical orbit (approx. 60 x 10 nautical miles). It was turned on again at 106 hours into the mission with the spacecraft then flying in a circular orbit of about 60 nautical miles above the lunar surface. As in the Apollo 15 flight, the estimated field of view for each data point used in this report is about 60 x 80 nautical miles. The data were reduced during the mission in the manner described in the Apollo 15 report. Thus it was possible to draw conclusions about the Descartes site and to report these to the crew while they were on the surface.

As indicated above, there was a region of overlap between the Apollo 15 and 16 tracks. This was mainly between 50 and 100 east longitude and covered such areas as Mare Fecunditatis, Mare Smythii, Langrenus, the highlands west of Smythii, etc. It is encouraging that for these areas, the Al/Si and Mg/Si chemical ratios for both flights agreed to better than 10 percent. This agreement makes it very encouraging to draw comparisons between the two flights. It also demonstrates that the sun's X-ray spectral distribution which produces the lunar fluorescent X-rays, was about the same on both missions. This in fact has been confirmed by examination of the Solrad data available for those periods.

Figure 1 shows the variation of Al/Si and Mg/Si intensity ratios plotted along the projected Apollo 16 ground tracks. These tracks have been divided into areas based in part on obvious geologic featured and in part on intensity contours. Because of the relatively low inclination of the orbit and the repetitive ground tracks there is a high density of data points plotted along the ground tracks. Thus the values shown represent the averages of a substantial number of points.

The results are tabulated in considerable detail in Table 1. A brief summary of our observations follows:

1) Our early reports, given while the mission was in progress of very high Al/Si ratios in the Descartes area have been confirmed by the analysis of some of the returned lunar samples (4). The statements made by members of the preliminary analysis team are that "analysis of the Descartes soils shows a surprisingly high concentration of aluminum oxide compared with samples returned from other sites visited by other Apollo missions." The values reported of 26.5 percent of aluminum oxide, agree very well with our own estimates (see Table 1). It appears reasonable from Fig. 1 that some of the material sampled at Descartes is similar to the eastern limb and farside highlands. This conclusion is further justified by the fact that the Mg/Si concentration ratios for some of the returned materials is about 0.18, close to our values of 0.19 ∓ 0.05. The eastern limb and far side highlands as shown in Table 1 are about 0.16 - 0.21.

2) The observations made after the Apollo 15 flight of high Al and low Mg in the highlands and the reverse in the mare areas is confirmed in the Apollo 16 data. However there are exceptions for example Ptolemaeus has both high Al/Si and Mg/Si.

3) In both missions the Al and Mg values for the most part show an inverse relationship although this is not true everywhere as noted in 2 above.

Geologic Interpretation

The following preliminary interpretations of the X-ray fluorescence data is proposed subject to further detailed analysis of the intensity readings, study of returned lunar samples and photo interpretations of areas below the flight path. The major geologic result of the experiment is further support for the existence of a global lunar crust representing early geochemical differentiation of the moon. This support comes from the high Al/Si ratios measured at many highland areas on the far and near sides of the moon. Although the X-ray fluorescence experiment has covered less than a quarter of the moon's surface, the consistency of these data over nearly 230 degrees longitude and over 50 degrees of latitude (including the Apollo 15 data) provide strong support for the global nature of the crust.

The dominant material represented by the Apollo 15 X-ray fluorescence data were previously (Adler et al., 1, 2, 3) suggested to fall chemically in the range of anorthositic gabbro to gabbroic anorthosites, with probable occurrences of anorthosite, felsite and Kreep. The Apollo 16 data appears consistent with this interpretation and with the other lines of evidence concerning highland composition summarized by Lowman (5). Detailed study of the rock and soil samples collected at the Descartes landing site by the crew will provide invaluable ground truth that should permit more specific petrologic interpretation of the X-ray data at a later date.

One specific point of petrologic interpretation should be brought out here. The high Al/Si readings (1.5) over the Descartes site (Fig. 1) are close to those of the far side highlands which presumably represents premare crust. Although the Apollo 16 surface traverses were on Cayley and Descartes formations (both post Imbrium basin), there should be abundant fragments of this old, high aluminum crustal rock in the regolith samples.

Investigation of the widespread Cayley formation was one of the major objectives of the Apollo 16 mission. It is therefore of interest to note the X-ray intensities (Fig. 1) over the crater Ptolemaeus, whose floor has been mapped by Howard and Masursky (6) as Cayley formation. The Al/Si ratios measured over this crater appear to be intermediate between those typical of highlands and maria. If allowance is made for contamination of the crater floor with high alumina material brought from the surrounding area by mass wasting and ballistic transport, the X-ray results seem consistent with the interpretation of the Cayley formation, in at least this area, as volcanic rock (probably feldspathic basalt). If confirmed by detailed data analysis, this would provide further support for major vulcanism on the moon in the mare-basin-mare interval, demonstrating the more or less continuous nature of lunar volcanic activity in the first 1.5 billion years of the moon's history.

To summarize, the X-ray experiment on Apollo 16 has been successful. Additional evidence for the existence of a global differentiated lunar crust has been obtained, and the X-ray results indicate the occurrence of this pre-mare crust near the Descartes landing site. Further analysis of the data, comparison with samples returned from the Descartes site, albedo-composition correlations, and photointerpretation are in progress.

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Table 1

Concentration ratios of Al/Si and Mg/Si for the various features overflown during the Apollo 16 remote sensing geochemical mapping experiment.

Feature	N*	Concentration Ratios	
		Al/Si ±1 σ	Mg/Si ±1 σ
Known Sea (19-29W)	8	0.38 ±0.11	0.40 ±0.29
Upper Part of Sea of Clouds (9-13W)	8	0.39 ±0.12	0.20 ±0.05
Mare Fecunditatis (42-57E)	80	0.41 ±0.05	0.26 ±0.05
S. of Fra Mauro (13-19W)	9	0.45 ±0.07	0.26 ±0.04
Mare Smythii (82-92.5E)	24	0.45 ±0.08	0.25 ±0.05
S. Edge of Mare Tranquillitatis Torricelli Area (26-30E)	21	0.47 ±0.09	0.23 ±0.05
E. Edge of Fecunditatis Largrenus (57-64E)	44	0.48 ±0.07	0.27 ±0.06
Ptolemaeus (4W-0.5E)	17	0.51 ±0.07	0.21 ±0.04
Highlands W. of Ptolemaeus to Sea of Clouds (4-9W)	16	0.51 ±0.11	0.25 ±0.12
Highlands W. of Mare Fecunditatis (37.5-42E)	29	0.52 ±0.07	0.24 ±0.05
Highlands W. of Smythii (72-77E)	35	0.57 ±0.07	0.21 ±0.03
W. Border of Smythii (77-82E)	33	0.58 ±0.08	0.22 ±0.04
E. of Descartes, Highland (20.5-26E)	23	0.58 ±0.07	0.21 ±0.04
S. of Sea of Foaming (64-72E)	45	0.58 ±0.07	0.25 ±0.04
Isidorus & Capella (30-37.5E)	38	0.59 ±0.11	0.21 ±0.05

*N is the number of individual data points used to determine the average Al/Si and Mg/Si values ±1 standard deviation and was obtained from the various passes over each feature.

Table 1 (continued)

Feature	N*	Concentration Ratios	
		Al/Si ±1 σ	Mg/Si ±1 σ
W. of Descartes, Highland (3-14E)	44	0.59 ±0.11	0.21 ±0.05
E. Border of Mare Smythii (92.5-97.5E)	17	0.61 ±0.09	0.20 ±0.06
Far Side Highlands (106-118E)	29	0.63 ±0.08	0.16 ±0.05
Descartes Area, Highland, Apollo 16 Site (14-20.5E)	30	0.67 ±0.11	0.19 ±0.05
E. of Ptolemaeus (0.5-3E)	12	0.68 ±0.14	0.28 ±0.09
Highlands (97.5-106E)	31	0.68 ±0.11	0.21 ±0.05
Farside Highlands, W. of Mendeleev (118-141E)	30	0.71 ±0.11	0.16 ±0.04

Al/Si & Mg/Si Concentration of Selected Returned Lunar Samples

Selected Lunar Samples	Al/Si	Mg/Si
Apollo 12, Oceanus Procellarum Average of Type AB Rocks (a)	0.22	0.22
Apollo 15, Hadley Apennines Average of Rocks (b)	0.22	0.27
Apollo 12, Oceanus Procellarum, Type B Rocks, Average (a)	0.22	0.37
Apollo II, Mare Tranquillitatis, High K Rocks - Average (c)	0.23	0.24
Apollo 12, Oceanus Procellarum, Type A Rocks - Average (a)	0.24	0.31

*N is the number of individual data points used to determine the average Al/Si and Mg/Si values ±1 standard deviation and was obtained from the various passes over each feature.

[a]Proceedings of the Second Lunar Science Conference (1971)

[b]LSPET (1972)

[c]Proceedings of the Apollo 11 Lunar Science Conference (1970)

Table 1 (continued)

Selected Lunar Samples	Al/Si	Mg/Si
Rock 12013 (a)	0.24-0.30	0.20
Apollo II, Mare Tranquillitatis, Average of Low K Rocks (c)	0.29	0.23
Dark of Rock 12013 (d, e, f)	0.33	0.22
Apollo 12, Oceanus Procellarum Average of Soils (a)	0.33	0.29
Surveyor VI, Sinus Medii, Regolith (g, h)	0.34	0.20
Apollo 15, Hadley-Apennines Soils (b)	0.34	0.30
Surveyor V, Mare Tranq. Regolith (i, h)	0.35	-
Luna 16, Mare Fecunditatis, Rocks (j)	0.35	0.21
Apollo 11, Mare Tranquillitatis, Bulk Soils Average (c)	0.37	0.24
Apollo 14, Fra Mauro, Average of Rocks (k)	0.38	0.26
Kreep Average (d, e, f)	0.39	0.21
Apollo 14, Fra Mauro, Soils (k)	0.41	0.26
Norite Material, Average (l, m)	0.42	0.20

[a] Proceedings of the Second Lunar Science Conference (1971)
[b] LSPET (1972)
[c] Proceedings of the Apollo 11 Lunar Science Conference (1970)
[d] McKay et al. (1971)
[e] Meyer et al. (1971a)
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[g] Turkevich et al. (1968a)
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[j] Vinogradov (1971)
[k] LSPET (1971)
[l] Wood et al. (1971)
[m] Marvin et al. (1971)
[n] Turkevich et al. (1968b)

Table 1 (continued)

Selected Lunar Samples	Al/Si	Mg/Si
Luna 16, Mare Fecunditatis, Bulk Soils (j)	0.42	0.27
Surveyor VII, Rim of Tycho, Regolith (n, h)	0.55	0.20
Luna 20, Apollonius Highlands	0.58	0.26
Anorthositic Gabbros, Apollo 11 and 12 (l, m)	0.64	0.21
Rock 15418, Apollo 15, Gabbroic Anorthosite (b)	0.67	0.15
Gabbroic Anorthosites, Apollo 11 and 12 (l, m)	0.82	0.074
Anorthosites, Apollo 11 and 12 (l, m)	0.89	0.038
Rock 15415, Apollo 15, Anorthosite Genesis Rock (b)	0.91	0.003

[a] Proceedings of the Second Lunar Science Conference (1971)
[b] LSPET (1972)
[c] Proceedings of the Apollo 11 Lunar Science Conference (1970)
[d] McKay et al. (1971)
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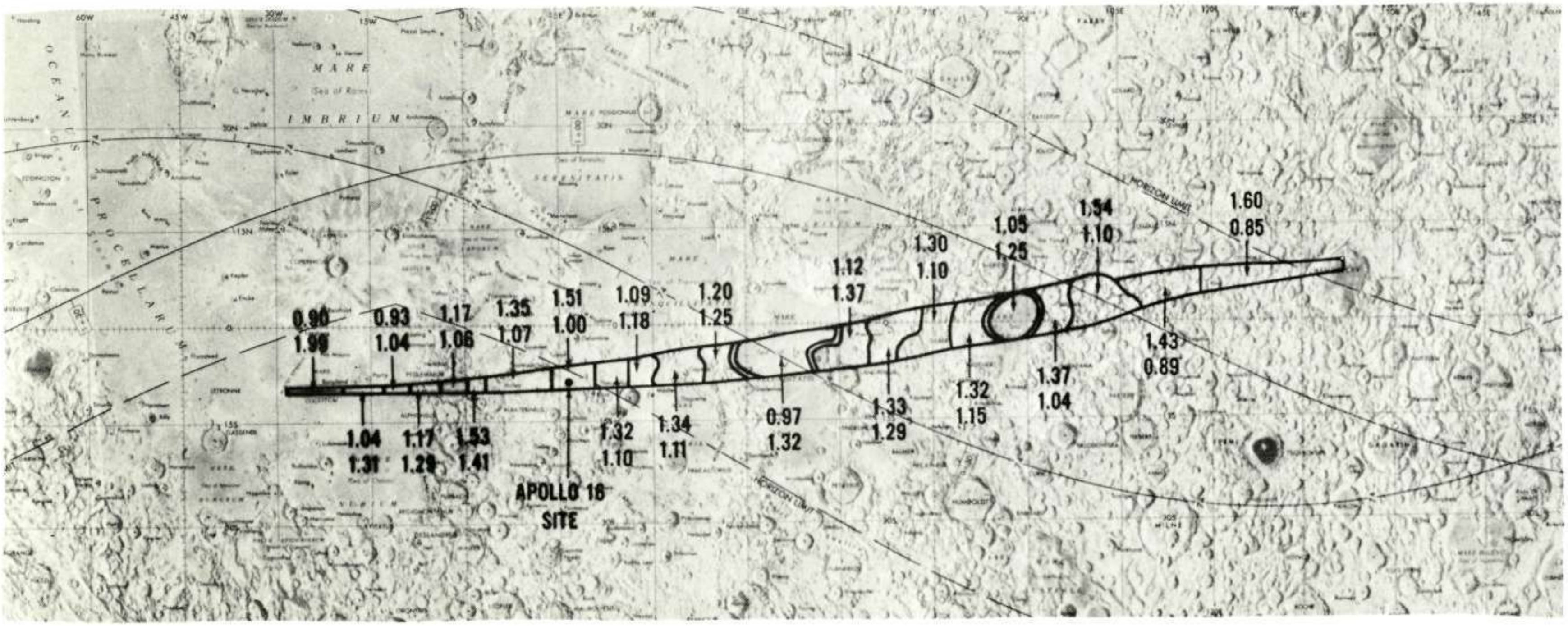

Fig 1 Al/Si and Mg/Si intensity ratios for specific areas along the Apollo 16 ground tracks. The upper values are Al/Si and the lower values Mg/Si.