Chemical Analysis of the Moon at the Surveyor VI Landing Site: Preliminary Results

Abstract. *The alpha-scattering experiment aboard soft-landing Surveyor VI has provided a chemical analysis of the surface of the moon in Sinus Medii. The preliminary results indicate that, within experimental errors, the composition is the same as that found by Surveyor V in Mare Tranquillitatis. This finding suggests that large portions of the lunar maria resemble basalt in composition.*

The first direct chemical analysis of lunar material was made by the alpha-scattering experiment aboard Surveyor V (*1*). The chemical analysis experiment on Surveyor VI was essentially a duplicate of the one on Surveyor V but was made at a different site. The theory, equipment, and operational sequence of this type of experiment have been described in detail (*1*, *2*). In this technique, the chemical composition of a sample is deduced from the energy spectrum of the large-angle scattering of alpha particles and from the spectrum of protons produced by nuclear interactions of the alpha particles with some of the lighter elements. Quantitative information is obtained about all elements heavier than lithium, but elements heavier than chlorine are not completely resolved.

Surveyor VI landed at 0101 hours G.M.T. on 10 November 1967 (*3*); the site was a heavily cratered mare-type area in Sinus Medii at selenographic coordinates 1.40°W longitude, 0.49°N latitude (*4*). About 4.5 hours after landing, the alpha-scattering instrument was activated. Initial measurements showed that the instrument had survived the launch and landing. An analysis of a polypropylene-grid-covered sample of glass of known chemical composition was then performed. Inspection of some of the data collected during 5.3 hours of operation in this phase confirmed that the instrument was capable of performing chemical analyses under lunar conditions. A command was therefore sent to release the sensor head from its stowed position on the spacecraft to the background-measuring position. Figure 1 (left) is a mosaic of television pictures taken just after the sensor head was released. The figure shows the area of the lunar surface later analyzed in this experiment. In the background position the sensor head was far enough from the surface to respond primarily to radiation from space. Data were collected for 6.25 hours and yielded a more precise determination of the background than was possible on the Surveyor V mission.

The background spectra for this experiment are similar to the ones obtained in the Surveyor V mission (*1*). In the alpha mode the background was considerably higher than it was in the Surveyor V experiment; poorer collimation of the alpha sources led to some scattering from the gold lining of the instrument. In the proton mode also the background was slightly higher, presumably because of less shielding from cosmic and solar particles by the more level terrain.

A command to deploy the sensor head onto the lunar surface was transmitted from a tracking station near Canberra, Australia, at 1208 G.M.T. on 11 November. Spectra sent by teletype to the Jet Propulsion Laboratory in Pasadena, California, showed that lunar-sample data were being received. Television pictures taken later confirmed that the sensor head was resting in a normal position on the lunar surface (Fig. 1, right). Data were accumulated normally except that for about 8 hours, at the highest operating temperatures, one of the four proton detectors was noisy and its output was blocked by command from Earth. During the period from 12 to 16 November there was no data accumulation because the temperature of the sensor head was above the operating limit of the instrument.

By 0330 hours G.M.T. on 17 November, spectra had been received for a total of about 30 hours. The instrument was then turned off in preparation for a hopping maneuver by the spacecraft. About 7 hours later the spacecraft's vernier engines were fired. Subsequent television pictures showed that the spacecraft had moved about 2.4 m and that the sensor head was upside down. This terminated the accumulation of data on the lunar surface on this mission.

The primary data of the experiment, recorded at the tracking sites, are not yet available. Some of these data, in the form of spectra received by teletype during the mission, have been processed in a preliminary way similar to that described in the Surveyor V report (*1*). These preliminary results, which must be assigned rather large limits of error, are based on data from approximately 13 hours of operation that have been subjected to preliminary certification and correction to nominal instrument response. They resemble in quality the data from Surveyor V. The gross data in the alpha mode show the characteristic decreases in intensity at about channels 27, 52, and 73, indicating, respectively, the presence of oxygen, silicon, and elements in the region of iron, cobalt, and nickel. In the proton mode, the decrease in intensity at about channel 63 and the broad peak at channels 80 to 100 are characteristic of the response when there is aluminum in the sample.

When the background observed under lunar conditions is subtracted and the results are analyzed by the techniques previously described (*1*, *2*), an eight-element library consisting of C, O, Na, Mg, Al, Si, "Ca," and "Fe" represents the data satisfactorily. Table 1 shows the deduced chemical composition of the sample of lunar mare surface material examined in the Sinus Medii landing site of Surveyor VI. The results are expressed in percentages of atoms heavier than lithium, since the method cannot detect hydrogen and helium and instrument parameters eliminate sensitivity to lithium. The errors are estimates based on our experience; they will be reduced later by more refined analyses of the complete data.

These preliminary results are slightly more detailed than those from Surveyor V in that they allow a crude breakdown of the elements heavier than silicon into "calcium" and "iron" portions. The presence of two distinct components is clearly indicated in the raw data by a slight drop in intensity in the alpha mode at about channel 62.

Table 1 also shows the results found by the same technique at the Mare Tranquillitatis site of Surveyor V (*1*). At both sites, by far the most abundant chemical element is oxygen; next in number of atoms is silicon; aluminum is very prominent in both samples. At present only upper limits can be assigned to the amounts of carbon and sodium present. The results of the two analyses are the same, well within their assigned errors.

The most important result of the chemical analysis experiment on the Surveyor VI mission is the finding of the same chemical composition at the

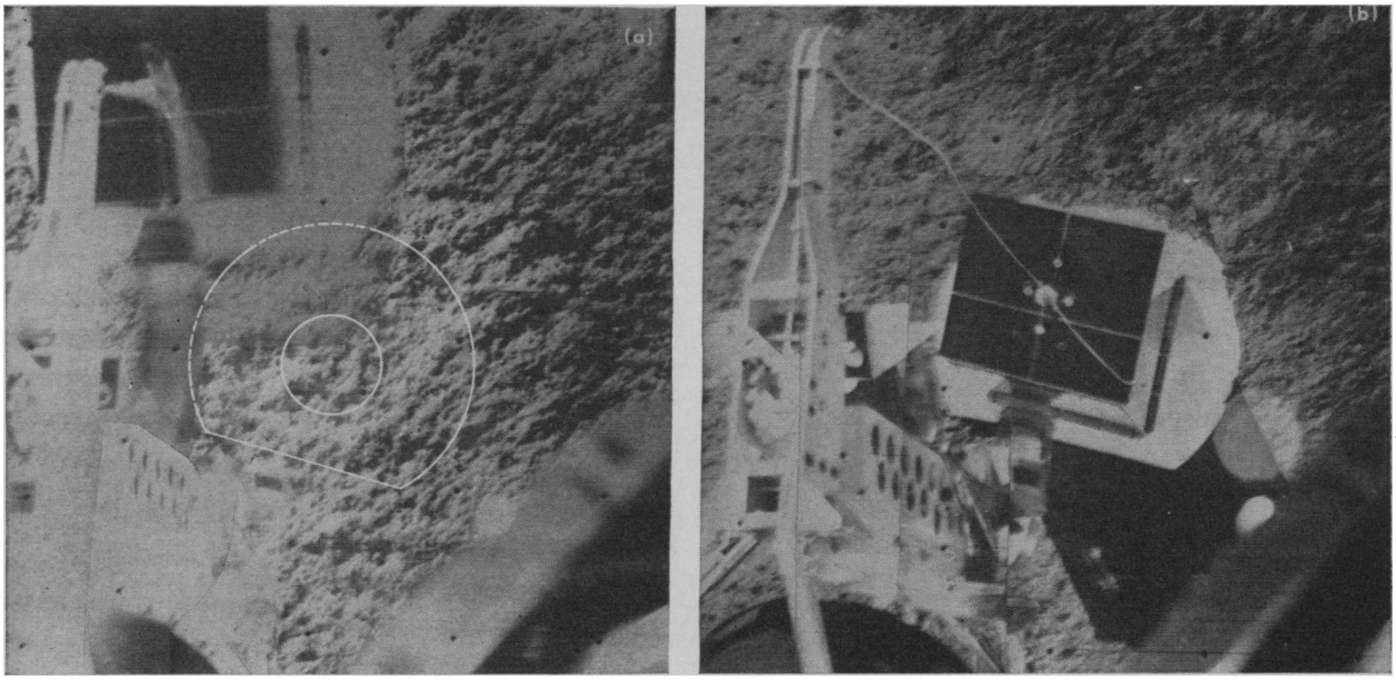

Fig. 1. (Left) Lunar surface analyzed by Surveyor VI. Mosaic of television pictures taken just after the sensor head was released from the stowed position. The circle shows the position of the opening in the sensor head after its deployment to the lunar surface. (Right) Alpha-scattering instrument on lunar surface.

landing site in Sinus Medii as was found in Mare Tranquillitatis (Table 1). This similarity is even more evident when one compares the data from the two missions at an earlier stage of analysis, when some of the systematic errors of the method are less important. In Fig. 2 the raw data from the two missions are compared after only background and small instrument corrections have been made. The data from Surveyor VI (both proton and alpha) have been normalized by a factor that brings the oxygen region of the alpha mode (channels 8 to 25) into coincidence with the data for that region from Surveyor V. This is done in order to take into account differences in source strength, duration of measurement, and possible differences in sample distances. The Surveyor V data are represented by the smooth curves; the Surveyor VI data are the points with associated statistical (1 σ) error bars.

Figure 2 shows good agreement of these primary data from the two missions in both alpha and proton modes in all energy regions. Most of the small systematic deviations, such as those near the regions of sharp change in intensity, are attributed to the slightly different energy scales of the two instruments.

The differences that exist are small relative to those to be expected from significantly different types of rock. For example, Fig. 2 also shows the response observed in a Surveyor-type instrument on exposure to terrestrial samples of dunite (USGS standard DTS-1) and granite (USGS standard G-2); again the responses are normalized in the oxygen region of the alpha

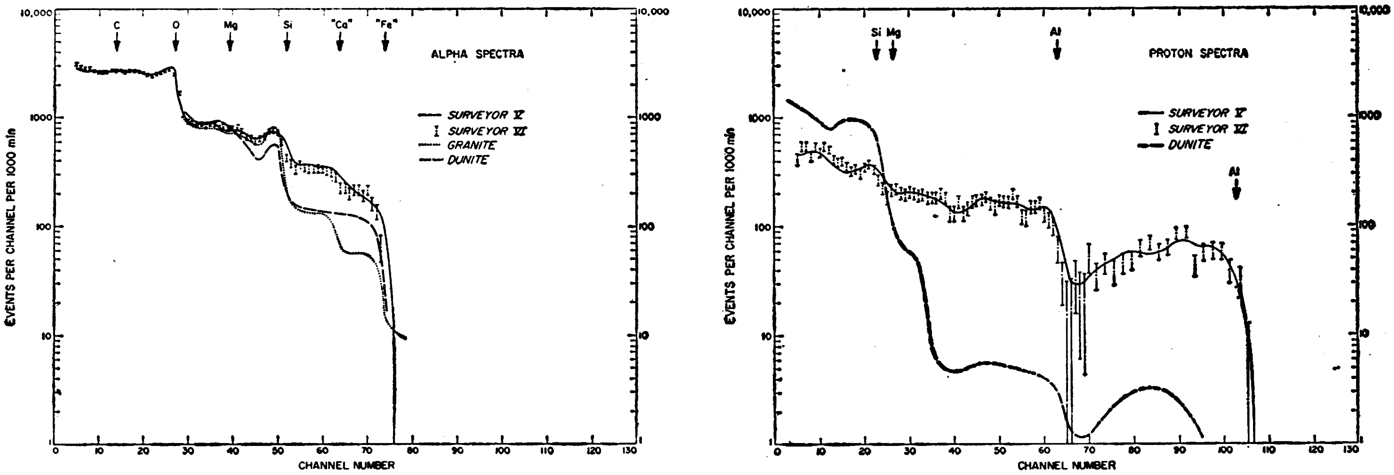

Fig. 2. Comparison of results from Surveyor V and Surveyor VI. (Left, alpha spectra; right, proton spectra). The smooth curves represent data from Surveyor V; the points with associated error bars represent data from Surveyor VI. In both instances the appropriate background has been subtracted. The Surveyor VI data have been normalized to the Surveyor V results in the region of channels 8 to 25 of the alpha mode. Also shown are the responses of a Surveyor-type instrument, similarly normalized, to samples of terrestrial dunite and granite.

Table 1. Chemical composition (percentages of atoms) of lunar surface at two Surveyor sites (preliminary results).

Element	Surveyor V (*1*)	Surveyor VI
C	< 3	< 2
O	58 ± 5	57 ± 5
Na	< 2	< 2
Mg	3 ± 3	3 ± 3
Al	6.5 ± 2	6.5 ± 2
Si	18.5 ± 3	22 ± 4
"Ca"*	13 ± 3‡	6 ± 2
"Fe"†		5 ± 2

* Elements having mass numbers between about 30 and 47; included, for example, are P, S, K, and Ca. † Elements having mass numbers between about 47 and 65; included, for example, are Fe, Co, and Ni. A lower limit of 3 percent "Fe" was set in the preliminary analysis of Surveyor V results (*1*). ‡ For the unresolved total of atoms with $28 < A < 65$.

mode. (The proton response from granite is not shown in Fig. 2; it is not significantly different from the lunar results.) Figure 2 demonstrates that the two lunar samples must have very similar compositions and differ from terrestrial dunites and granites.

The similarity of the results at the two Surveyor landing sites makes it improbable that the chemical composition found is applicable only to unique places on the moon. It is much more probable that they are representative of the large portions of the lunar maria that are similar in appearance and in optical and thermal properties.

Although the alpha-scattering technique provides no direct information about the chemical state of the elements identified, chemical experience indicates that the elements are combined with the oxygen that is present. The mean values given in Table 1, particularly in the case of Surveyor VI, indicate apparent deficiency of oxygen. However, well within the present limits of error, there is enough oxygen to combine with all the elements considered. Table 2 presents an example (not unique) of weight percentages of oxides that would be consistent with the analytical results from the two Surveyor missions. Such an oxide composition would imply a general chemical inertness of the lunar surface material. This inertness is consistent with the observed lack of chemical reaction with materials of the spacecraft, such as the aluminum footpads.

Table 2. An oxide composition consistent with the analytical results from Surveyors V and VI.

Oxide	Percentage by weight
Na_2O	*
MgO	5
Al_2O_3	13
SiO_2	50
CaO	15
FeO	16

* Presence of sodium has not been established with certainty; sodium oxide may be present in amounts as great as 3 percent by weight.

Table 2 illustrates the oxide composition of the bulk of the lunar material analyzed. Minor constituents, amounting to as much as 10 percent by weight, may be present. Moreover the analytical errors do not exclude the presence of some unoxidized metal or compounds decomposed by radiation. A limit to metallic iron, the most likely free metal, is placed at 0.25 percent by volume by the Surveyor magnet experiment (*5*).

It is improbable that the lunar material is a simple mixture of oxides. From our data a noncrystalline (vitreous or heavily damaged by radiation) state cannot be excluded. However, just as in terrestrial and meteoritic samples of this general composition, the oxides on the moon may be combined into more complex minerals. For example, a mixture of minerals of the feldspar and pyroxene classes is consistent with the oxide composition of Table 2. As the analytical errors are reduced and as the amounts of some of the minor constituents are established, the possible mineral composition will become more restricted. Even now the prediction of physical and chemical properties of lunar mare material, if made on the basis of known compounds and minerals consistent with the data of Table 1, should be more reliable than has been possible heretofore.

It was concluded on the basis of the Surveyor V chemical analysis (*1*) that the sample examined resembled most closely a rock of a basaltic type (a terrestrial basalt or a meteoritic basaltic achondrite). The results from Surveyor VI support this conclusion. In addition, the absolute and relative amounts of "Ca" and "Fe" determined in this mission are again most consistent with those in rocks of basaltic composition. As pointed out by Gault *et al.* (*6*), the finding of such a composition for a sample of lunar material suggests that the material is the product of cosmochemical processing such as the geologically produced differentiation of the material of the earth. The strong depletion of magnesium and enhancement of aluminum relative to silicon, in comparison with the values found in the solar atmosphere (or in chondritic meteorites or ultrabasic rocks), has been confirmed by the present results from Sinus Medii. Thus both Surveyor missions imply a chemically interesting history for lunar mare material.

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7. Work at the University of Chicago aided by subcontract JPL–NASA 951347 with the Jet Propulsion Laboratory; at the Jet Propulsion Laboratory, by NASA contract NAS 7-1000; and at Argonne National Laboratory, by the AEC. The instrument used was constructed mainly by personnel at the Laboratory for Astrophysics and Space Research and other personnel of the Enrico Fermi Institute, University of Chicago; these personnel and many others at Argonne National Laboratory, Jet Propulsion Laboratory, and Hughes Aircraft Company participated in testing of the instrument, its integration in the spacecraft, and its operation on the Surveyor VI mission.

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Littoral of the Northeastern United States: Late Quaternary Warping

Abstract. *Isobases constructed from recently published data are strikingly parallel to both the edge of the continental shelf off the northeastern United States and the Fall Zone. Our analyses suggest that the downwarping recorded by these isobases may be explained by Daly's hypothesis of a collapsing peripheral or marginal "bulge."*

Reading of a recent paper (*1*) concerning rise in sea level and crustal warping along the northeast coast and the adjacent continental shelf of the United States suggests that closer scrutiny of the data may yield further information. The authors concluded that

> If subsidence of the New England (Atlantic) shelf and coast with respect to other areas did occur, perhaps it can be attrib-