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Chemical Composition of the Lunar Surface in a Terra Region near the Crater Tycho

Abstract. *More precise and comprehensive analytical results for lunar surface material in a terra region have been derived from the data of the alpha-scattering experiment on Surveyor 7. The silicon content and the low sodium abundance are close to that of mare material. The abundances of titanium and iron are at least a factor of 2 lower, whereas the abundances of aluminum and calcium are significantly higher. The analytical results provide direct evidence for chemical differentiation in the moon and indicate a lunar crust of appreciably lower density than the whole moon and with lower density and higher albedo than lunar mare material.*

The alpha-scattering experiment on Surveyors 5 and 6 provided data on the chemical composition of the lunar surface at two mare sites: Mare Tranquillitatis (*1, 2*) and Sinus Medii (*3, 4*). The results at the Mare Tranquillitatis site are in adequate agreement with the analyses of the returned lunar samples from Apollo 11 (*5*). Surveyor 7, which landed in the terra region 30 km north of the crater Tycho (*6*), carried the same type of experiment, and preliminary results have been reported (*7, 8*). Processing of data from the Surveyor 7 mission has now been completed. More data have been used than were originally available. Our results are therefore more comprehensive and precise than those given in previous reports.

Earlier reports (*2, 4, 8, 9*) have described the technique of chemical analysis, the checks on instrument performance on the moon, the method of data retrieval and analysis, and the corrections that are applied for small changes in instrument characteristics during the mission, and they have discussed the precision and accuracy of the method. Only the special characteristics of the Surveyor 7 mission will be mentioned here.

Three lunar samples were examined on this mission: undisturbed lunar surface (sample 1), a small lunar rock (sample 2), and a trenched area (sample 3) prepared by the Surface Sampler (*8, 10*). The geometrical relationships of the samples to the instrument were different from those on previous missions (*8*) and therefore required laboratory mock-up studies and special computer analyses to achieve the most detailed interpretation of the lunar data.

Because the ^{242}Cm source strength was greater than on previous missions, there was a higher signal-to-background ratio than in previous experiments. The source quality was, however, somewhat poorer because of the greater thickness of the curium and the presence of a carbon coating used to minimize the transfer of radioactivity by aggregate recoil. The statistical accuracy of the data on each sample was limited by mission constraints and was less than on previous missions. Fortunately, the spacecraft and instrument survived the first lunar night sufficiently well so that additional data in the alpha mode were obtained on sample 3.

As in previous reports (*2, 4*), the energy spectra of the backscattered alpha particles and of protons from (α,p) reactions were analyzed in terms of a library of 13 elements. Table 1 presents the results for the three samples. The atom percent of each element is listed (after substraction of the small biases of the method) together with an estimated accuracy at the 90 percent confidence level. The estimated accuracy was obtained from the statistical error and the error of the method (*4*), with an additional estimated uncertainty for sample 2 included because of its peculiar geometry. The statistical errors were comparable to those on previous missions (*2, 4*). No value is given for carbon because, as this technique was implemented, results on terrestrial samples had been poor. An upper limit of 1 atom percent for carbon can be set for the samples examined on Surveyor 7. The values for sample 1 are well within the errors of the preliminary analysis of the data (*7, 8*).

The results for the two samples of lunar soil (samples 1 and 3) agree even within their statistical errors. This agreement indicates that the chemical composition of the topmost layer at the Surveyor 7 site is identical with the composition of material several centimeters below the surface. The data on the lunar rock (sample 2) give roughly the same composition; the lower magnesium and higher aluminum contents appear to be the outstanding differences. The slightly lower (by 20 percent) iron content is also of interest.

The two samples of lunar soil show significant amounts (0.3 atom percent) of fluorine. Although experience in analysis for fluorine by this technique is more limited than for other elements, similar concentrations of fluorine have been determined with adequate precision in terrestrial rocks. Analysis of the data with an even larger library (20 elements) confirms the results in Table 1 and indicates negligible

Table 1. Chemical analysis of Surveyor 7 samples (atom percent, on a hydrogen-free basis). All errors are at the 90 percent confidence level. The symbols for elements heavier than silicon represent groups of elements whose mass ranges are given in (*2*). The effective number of minutes of data collection in the alpha and proton modes for the samples are as follows: sample 1, 1723 (α) and 1674 (p); sample 2, 656; sample 3, 1218 (α) and 417 (p). Some of the time the instrument was operated with less than the full complement of detectors. For sample 1, some of the proton data below about 4 Mev were not used because of suspected noise; and for sample 2, the proton data below 2 Mev were not used because they were too sensitive to the exact geometry of the sample. The values for average soil composition (in atom percent) are averages of samples 1 and 3 with biases subtracted.

Element	Sample 1	Sample 2	Sample 3	Average soil composition in	
				Atom %	Weight %
O	61.9 ± 1.3	61.4 ± 2.1	61.5 ± 2.0	61.8 ± 1.0	
F	0.29 ± 0.13	0.08 ± 0.23	0.31 ± 0.23	0.29 ± 0.12	
Na	0.51 ± 0.21	0.27 ± 0.36	0.46 ± 0.38	0.50 ± 0.20	0.7
Mg	3.6 ± 1.6	1.0 ± 1.9	3.6 ± 1.7	3.6 ± 1.6	7.0
Al	9.3 ± 0.4	11.7 ± 0.9	8.8 ± 0.6	9.2 ± 0.4	22.3
Si	16.1 ± 1.3	16.7 ± 1.4	16.6 ± 1.3	16.3 ± 1.2	46.1
"S"	0 ± 0.8	0 ± 0.9	0 ± 0.9	0 ± 0.6	
"Ca"	6.9 ± 0.7	7.3 ± 0.8	7.1 ± 0.7	6.9 ± 0.6	18.3
"Ti"	0.1 ± 0.5	0.1 ± 0.5	0 ± 0.5	0 ± 0.4	
"Fe"	1.5 ± 0.4	1.3 ± 0.4	1.7 ± 0.4	1.6 ± 0.4	5.5
"Zn"	< 0.06	< 0.14	< 0.18	< 0.07	
"Sr"	< 0.05	< 0.08	< 0.08	< 0.05	
Zr-In	< 0.05	< 0.05	< 0.09	< 0.05	
Sn-U	< 0.04	< 0.07	< 0.06	< 0.04	

amounts of nitrogen, phosphorus, and chlorine.

Column 5 of Table 1 presents an appropriate average of the data on the soil samples 1 and 3, with the estimated error. The amount of oxygen listed in Table 1 is higher than is needed to form normal lower oxides of the electropositive elements. However, the data obtained on the moon on this mission from a glass sample of known composition, when treated in the same manner, also gave a slight excess of oxygen. An oxide composition for lunar soil has therefore been calculated and is given in the last column of Table 1. In this calculation the apparent excess of oxygen was neglected and it was assumed that all the iron is in the ferrous state. Within the errors of the elemental analyses, a possible mineral composition of this terra material is 62 percent by weight feldspar (composition: 10 molecular percent albite, 90 molecular percent anorthite) and 38 percent pyroxene (representable by 32 molecular percent hedenbergite, 52 molecular percent enstatite, 16 molecular percent diopside). In view of the apparent absence of phosphorus in adequate amounts, the most reasonable mineral source for the fluorine is fluorite (CaF_2). The calculated density of void-free terra crystalline material at this site is then 2.96 g cm^{-3}. This value is not far from the values deduced from the preliminary Surveyor 7 results by Phinney *et al.* (*11*). For the lunar rock (sample 2) the chemical analysis indicates a mineral composition containing even more anorthite than is in the lunar soil, and a calculated density of 2.88 g cm^{-3}.

Although the Surveyor chemical analyses on this mission and on previous missions were very limited in number, they probably represent the average chemical composition of rather large areas on the moon. The pulverized nature of the lunar soil and the existence of a substantial fraction in the form of small glassy particles (*5*) confirm the importance of impact mechanisms (for example, by meteorites) in breaking up the lunar surface and spreading it over considerable distances. From detailed chemical investigation of returned samples from Apollo 11, Keays *et al.* (*12*) conclude, however, that only about 2 percent of the fine material is meteoritic. Thus, the material analyzed by the Surveyors can be taken as representing the average chemical composition of the lunar surface in the general areas of the landing sites.

Figure 1a presents a comparison of the abundances of the most important chemical elements in the soil at three locations on the moon (two maria and one terra). The preliminary examination of the returned Apollo 11 samples indicated that the elements shown in Fig. 1 make up about 99 percent of the material on the lunar surface at Mare Tranquillitatis (*5*); almost certainly, they comprise the great bulk of the material at the other sites also. The outstanding features of Fig. 1a are given below.

1) The two most abundant elements, oxygen and silicon, comprise the same fractions (to within better than 1.5 atom percent) of atoms on the lunar surface at all three sites. This agreement is especially significant for silicon; it implies that the silica content is the same at all three locations.

2) Sodium is low (0.5 ± 0.1 atom percent) at all three places.

3) Although the errors on the magnesium abundances are rather large, there is no great variation in the magnesium content of lunar soil; in all three samples, it is about half as abundant as aluminum.

4) Aluminum and calcium are the next most abundant elements after oxygen and silicon. The abundances of these elements are essentially the same at the two mare sites; they are significantly higher at the terra site.

5) The largest relative variation is observed in the abundance of the elements heavier than calcium. The atom percent of iron is the same at the two mare sites (3.8) but is only 1.6 atom percent at the terra site. The high values of titanium at the two mare sites (2.2 and 1.0) are in sharp contrast to its absence at the terra site. This difference in the content of elements heavier than calcium between mare and terra sites was noted in the preliminary reports (*7, 8*).

The comparisons in Fig. 1a lead to conclusions, some of which were deduced even from the preliminary evaluations of the data (*7, 8, 13*). To the extent that the sites examined on the Surveyor missions are representative, these conclusions apply to other terrae and maria of the moon.

1) The assigned mineral composition at the terra site consists of appreciably more anorthite and less pyroxenes, ilmenite, and free silica than does the mineral composition of the mare sites.

2) The density of void-free crystalline material at the terra site is less than the density at the mare sites.

3) The higher albedo of the terra, relative to the mare, sites may be due, at least in part, to the lower abundances of the transition elements heavier than calcium at the terra site.

4) The low sodium content at all three locations suggests that the alkali elements were lost from all lunar material.

5) The suggestion by Anderson *et al.* and by Wood *et al.* (*14*) that some fragments in the soil at the Apollo 11 site came from the highland areas because their chemical composition resembles the composition of terra mate-

rial as determined in preliminary analysis by the alpha-scattering experiment (*7*, *8*) is supported by these more precise results.

The two major topographical provinces of the moon, the maria and terrae, have, since the 17th century, been likened to the ocean basins and the continental masses on earth. It is of interest, therefore, to compare the chemical differences between the maria and terrae with those of corresponding features on earth. Figure 1b presents the chemical composition of Pacific basalts (*15*) and an average composition of the North American continental crust (*16*) as representative of these features on earth.

On both the earth and the moon, the highlands (continents and terrae) are depleted in the heavy elements, iron and titanium, relative to the lowlands (ocean bottoms and maria). This depletion results in a lower density for highland material, which explains the generally isostatic relationship of the two provinces on earth and on the moon (*17*). On the moon, at all boundaries between the two, the maria are lower in elevation than the neighboring terrae; in addition, the maria are, on the average, 1.4 km lower in elevation over the visible face of the moon (*18*) than the terrae. Were it not for the effects of water and life on the earth, these differences in heavy element contents would undoubtedly lead, as on the moon, to a lower albedo for the dry ocean basins than for the continents.

The two parts of Fig. 1 indicate quite different chemical relationships on the moon and on the earth for the abundances of the lighter elements: the terrae of the moon are not enriched in silicon and sodium and depleted in magnesium, as are the continents of the earth. Instead, the terrae of the moon are enriched in aluminum and calcium, whereas on the earth the amounts of these elements are the same or are less on the continents than in ocean bottoms. The result is that, although the density relationship of the two provinces on the moon is the same as on the earth, the difference on the moon is smaller; the terrae density deduced here (2.96) is about 0.2 g cm^{-3} lower than that calculated for mare materials from alpha-scattering results (*4*).

Since the terrae represent about 80 percent of the lunar surface, the Surveyor 7 chemical analyses provide not only the first data on the chemical composition of the largest province of the lunar surface but also the first direct evidence for chemical differentiation in the moon as a whole. The distinct differences between the chemical composions of terra and mare sites (Fig. 1a) and the observed general isostasy on the moon (*17*) point to such differentiation. In addition, the density of terra material, 2.96 g cm^{-3}, inferred from the chemical analyses is, of course, much lower than the density of the whole moon, 3.36 g cm^{-3} (*19*). If it is assumed that, under pressure, the surface terra material would transform into garnet-containing rocks (*20*), the calculated density of the resultant material is 3.44 g cm^{-3}. To obtain the overall density of the moon, assuming the chemical composition to be the same as that of the terrae, the material below 100 km would have to be in this denser form. The pressure at this depth (<5 kilobars) is, however, much lower than the pressure considered necessary for this phase transformation (*20*). Thus, the chemical data suggest that the terrae constitute a crust that is distinctly different chemically from the interior of the moon. If the composition of the rock (sample 2) is taken as more representative of the terrae, the argument is even stronger for such a lunar crust. This proposal of a crust formed from a molten silicate phase is compatible with the implication that

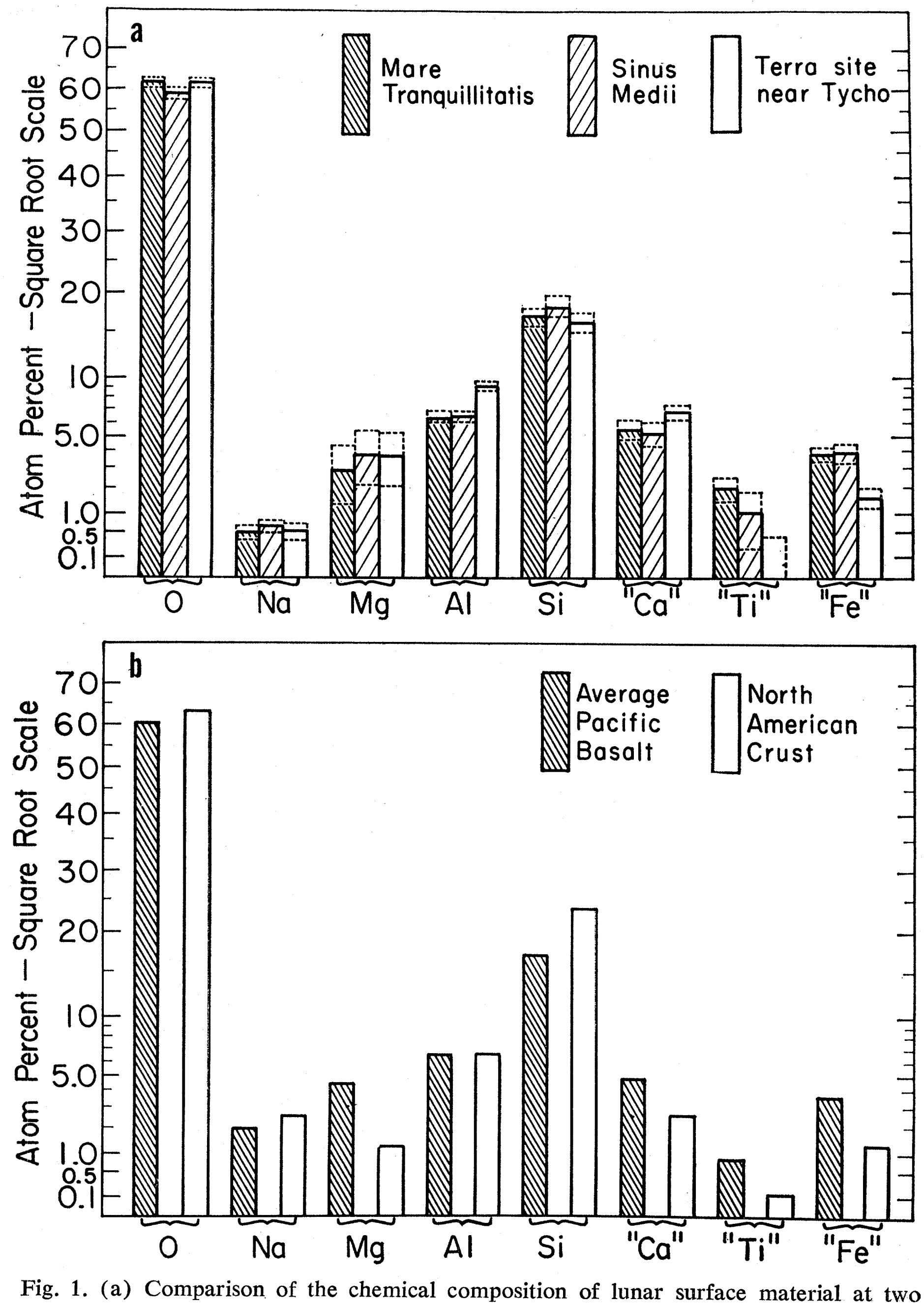

Fig. 1. (a) Comparison of the chemical composition of lunar surface material at two mare and a terra site. The dotted lines indicate the ranges covered by the estimated errors (90 percent). (b) Chemical composition of corresponding features on the earth.

the terra material contains a large amount of the mineral anorthite, which has low density and a high melting point. Similar ideas based on the preliminary results of this alpha-scattering experiment have recently been presented by Anderson *et al.* and Wood *et al.* (*14*).

As indicated above, the differentiation process that produced this crust on the moon had some similarities to, but in general was different from, the process that occurred on earth. A particular difference was in the apparent behavior of uranium and thorium. On the earth, the granitic crust is enriched in these elements relative to the basalts. The Surveyor data on the alpha radioactivity of the lunar surface (*21*) indicate a lower uranium content at the terra site of Surveyor 7 than at Mare Tranquillitatis. The data of Luna 10 (*22*) also gave some indication of a lower content of radioactive elements in the terrae than in the maria. Thus, there is no evidence for an enrichment of uranium in the terrae of the moon. On the moon, in the absence of an oxidizing medium and water, it may be that both uranium and thorium followed the chemistry of +4 elements and stayed with elements such as titanium and zirconium. The rather high concentration of these elements, which appears to be a characteristic of mare material, may mean that on the moon, in contrast to the assumed situation on earth, the heat production due to the radioactive decay of the heaviest elements has been buried below the crust. At early times this factor could have been an important one in the history of the moon.

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Phobos: Preliminary Results from Mariner 7

Abstract. *Analysis of an image of Phobos on Mariner 7 frame 7F91 indicates that the martian satellite is larger and has a darker surface than had previously been thought. The limb profile measures 18 by 22 kilometers and is elongated along the orbital plane. Phobos has an average visual geometric albedo of 0.065 lower than that known for any other body in the solar system. It seems probable that Phobos did not form by accretion around primordial Mars, but was captured at some later time.*

An objective of the Mariner 69 television experiment (*1*) was to photograph one or both of the two martian satellites, Phobos and Deimos, under conditions which would lead to estimates of their physical size and reflectivity. Throughout the far-encounter sequences of photographs taken by Mariners 6 and 7, Phobos and Deimos moved in and out of the field of view,

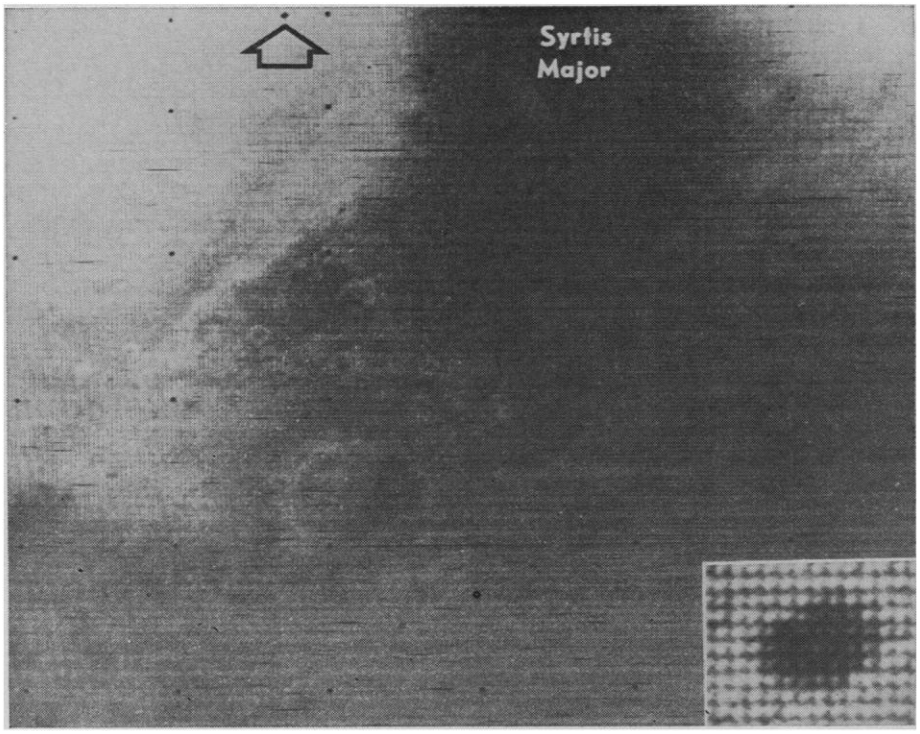

Fig. 1. Phobos as recorded on Mariner frame 7F91, with a × 15 enlargement (insert). A part of Syrtis Major is seen near the top. The phase angle is 22° and the range is 130,900 km to Phobos and 137,000 km to the martian surface.