COMPARISON OF THE ANALYTICAL RESULTS FROM THE SURVEYOR, APOLLO, AND LUNA MISSIONS*

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Abstract. The principal chemical element composition and inferred mineralogy of the powdered lunar surface material at seven mare and one terra sites on the Moon are compared. The mare compositions are all similar to one another and comparable to those of terrestrial ocean ridge basalts except in having higher titanium and much lower sodium contents than the latter. These analyses suggest that most, if not all, lunar maria have this chemical composition and are derived from rocks with an average density of 3.19 g cm^{-3}. Mare Tranquillitatis differs from the other maria in having twice the titanium content of the others.

The chemical composition of the single highland site studied (Surveyor 7) is distinctly different from that of any of the maria in having much lower amounts of titanium and iron and larger amounts of aluminium and calcium. Confirmation of these general characteristics of lunar highland material has come from recent observations by the Apollo 15 Orbiter. The inferred mineralogy is 45 mole percent high anorthite plagioclase and the parent rocks have an estimated density of 2.94 g cm^{-3}. The Surveyor 7 chemical composition is the principal contributor to present estimates of the overall chemical composition of the lunar surface.

Analytical information for the principal chemical elements is available at present from eight sites on the Moon. The location of these sites, their characteristics, and the nature of the analytical technique used, are summarized in Table I. All of the locations except one are in mare-type regions distributed widely on the lunar surface. These mare-type regions are characterized by much smoother terrain and a lower albedo than are the highlands or terrae of the Moon. Although the Frau Mauro landing site of Apollo 14 would appear from telescopic pictures of the Moon to be highland in brightness, the actual landing site was a mare-type locale with albedo in the same range as the previous mare landing sites of the Apollo and Surveyor missions (USGS, 1971). The only chemical analysis from a highland location comes from the Surveyor 7 mission to a site outside the crater Tycho.

The phrase 'principal chemical elements' is used here to denote the elements usually present in rocks in amounts greater than about 0.3 atom percent. They comprise the elements O, Na, Mg, Al, Si, Ca, Ti and Fe. These elements constitute about 99% of the atoms, and, therefore, determine the gross chemical nature of the lunar surface. The analyses compared in this report are those of the powdered material at a given site. It is felt that, in the case of the principal chemical elements, the chemical composition of

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TABLE I

Locations on the Moon from which chemical composition data are available

Mission	Date	Selenographic coordinates			Geographical area	Type of area	Type of analysis
		Long.	Lat.	Ref.			
Surveyor 5	1967, Sept. 11	23.20°E	1.42°N	(a)	Mare Tranquillitatis	Mare	in-situ α scattering
Surveyor 6	1967, Nov. 10	1.37°W	0.46°N	(a)	Sinus Medii	Mare	in-situ α scattering
Surveyor 7	1968, Jan. 10	11.44°W	40.97°S	(a)	outside Crater Iycho	Terra	in-situ α scattering
Apollo 11	1969, July 20	23.43°E	0.69°N	(b)	Mare Tranquillitatis	Mare	returned samples
Apollo 12	1969, Nov. 19	23.34°W	2.45°S	(c)	Oceanus Procellarum	Mare	returned samples
Luna 16	1970, Sept. 19	56.18°E	0.41°S	(d)	Mare Foecunditatis	Mare	returned samples
Luna 17	1970, Nov. 17	35°W	38°N	(e)	Sea of Rains (NW Mare Imbrium)	Mare	in-situ X-ray fluorescence
Apollo 14	1971, Feb. 5	17.5°W	3.7°S	(f)	Frau Mauro formation	Mare	returned samples

(a) Jaffe (1969).
(b) LSPET (1969).
(c) LSPET (1970).
(d) Vinogradov (1971).
(e) *Sky Telesc.* (1971) March, p. 155.
(f) LSPET (1971) *Science* **173**, 681–3.

this material represents the average of a given area of the Moon better than does the composition of individual rocks.

This is supported by the observations made on the Surveyor, Apollo and Luna missions. These showed that most of the lunar surface is covered by a fine powdered material. Rocks, or even fragments greater than 1 mm size, are rather rare. The astronauts on the Apollo missions found only a few fragments in a scoopful of lunar soil. This finely broken-up material extends down to of the order of meters in depth.

The rocks which were brought back by the astronauts and by Luna 16 contain information – particularly about time scales of geological processes on the Moon – that are not easily available from the powdered material. However, their chemical composition can be quite misleading as regards the average chemical composition of the lunar surface, even in a given region. Thus, for example, the crystalline rocks from the Apollo 11 mission all had significantly more titanium than did the soil (Table II).

TABLE II

Titania content of Apollo 11 lunar material[a]

Samples	Wt. % TiO_2
Crystalline Rocks	
Group 1	11.88
Group 2	10.32
Breccias	8.87
Soil	7.50

[a] These data are from Levinson (1970).

TiO_2, at the 9–12 weight percent level, is not a minor constituent. Thus, the soil in Mare Tranquillitatis could not have been derived from the rocks brought back by the astronauts on this mission. This conclusion is supported by chemical analyses (*e.g.*, Tera *et al.*, 1970) for minor and trace elements of the samples from the Apollo 11 mission. Since most of the surface of a region is made up of the powdered material, the chemical composition of the soil represents the composition of Mare Tranquillitatis better than does the composition of the rocks. This can also be expected to be true at the other places on the Moon where chemical analyses are available.

Detailed examination of the fine material brought back by the Apollo and Luna 16 missions indicates that a significant fraction (20% or more) is in the form of glass. This precludes, for this component, the availability of the kind of detailed mineralogical information usually derived from microscopic petrological examination. It is fortunate that, on the Moon, a gross chemical composition probably has more significance than was expected: the pulverization and transport of material on the Moon by micrometeorite impacts provide an averaging over distances of the order of many kilometers. This suggests that gross soil analyses represent averages over many more rocks than can be brought back by even the most ambitious manned mission.

A comment should be made here about the contribution of meteoritic material to the lunar surface chemical composition. Several authors have concluded that this is of the order of 1.5 – 2% (Ganapathy *et al.*, 1970). It perturbs primarily the abundances of certain trace elements, but should be kept in mind for refinements in the abundances of the more abundant elements.

The lunar samples returned to Earth by the Apollo and Luna 16 missions can, of course, be analyzed and examined by the most refined modern techniques. Almost all the known chemical elements have been identified in this way in these samples. The in-situ chemical analyses performed on the Surveyor 5, 6 and 7 missions and on the Luna 17 mission were performed by special techniques. The Surveyor missions (Patterson *et al.*, 1969) determined the spectra of back-scattered alpha particles and the spectra of protons produced by (α, p) nuclear reactions and from these established the amounts of the principal chemical elements present in the lunar samples. The Luna 17 mission (Lunokhod-1, 1971) measured the number and energy of characteristic X-rays excited in the lunar soil by a tritium-metal X-ray source.

Although the chemical analyses obtained on these unmanned Surveyor and Luna missions are usually appreciably less precise than those on returned lunar samples, they represent half (4 out of 8) of the sites on the Moon from which information is available. Their accuracy is adequate to establish the gross rock type and even some of its special characteristics. In addition, the Surveyor 7 chemical analysis is, at present, the only one from a highland site on the Moon.

Finally, at the present stage of lunar and planetary investigations, a comparison between remote control analytical results and those obtained on returned samples can help make proper decisions about future exploration of the Moon, asteroids, and planets. In this connection it should be borne in mind that the capabilities of remote control analyses by various techniques are continually improving. The Surveyor missions represent the state of technology of one particular technique almost ten years ago. Not only could the accuracy for the principal chemical elements be improved today, but there are possibilities, also, of measuring some of the minor constituents. For example, the alpha-radioactive sources used on the Surveyor missions excite many X-rays in a sample. Using special modern detectors, the number and energy of these can be determined (Franzgrote, 1971). This makes possible the resolution of elements such as potassium and calcium, and iron and nickel, which are hard to determine separately by the classical alpha-scattering technique.

Table III presents the results of chemical analyses of surface lunar fines for the principal chemical elements at the seven lunar *mare* sites that have been studied so far. Estimates of the accuracies of the Surveyor analyses are indicated; the accuracies of the analyses of the returned samples from Apollos 11 and 12 and Luna 16 are probably all less than 3% at the same confidence level; those from Apollo 14 are still preliminary and are quoted at $\sim$10%. The accuracy of the results from Lunokhod-1 (Luna 17) are not known. Although the Surveyor analyses for Ca, Ti, and Fe are, strictly speaking, for groups of elements with about the same atomic weight, assignment of the values primarily to the elements indicated appears justified on geochemical grounds.

TABLE III

Concentrations of principal chemical elements in lunar Mare material (fines)

	Percent by Atom						
Mission	Surveyor[a] 5	Apollo 11	Surveyor[a] 6	Apollo 12	Luna 16	Luna 17	Apollo 14
Reference	(a)	(b)	(a)	(c)	(d)	(e)	(f)
Element							
O	61.1 $\pm$1.0	59.87	59.3$\pm$1.6	59.9	(60.15)	(63.2)	(60.8)
Na	0.47$\pm$0.15	0.33	0.6$\pm$0.24	0.30	0.37	—	0.40
Mg	2.8$\pm$1.5	4.57	3.7$\pm$1.6	6.8	4.99	6.3	5.4
Al	6.4$\pm$0.4	6.30	6.5$\pm$0.4	6.3	6.95	5.7	7.7
Si	17.1 $\pm$1.2	16.31	18.5$\pm$1.4	16.0	15.97	15.7	17.5
Ca*	5.5 $\pm$0.7	4.92	5.2$\pm$0.9	4.1	4.99	4.4	4.3
Ti*	2.0 $\pm$0.5	2.19	1.0$\pm$0.8	0.9	0.98	$<$1.8	0.5
Fe*	3.8 $\pm$0.4	5.12	3.9$\pm$0.6	5.4	5.39	4.7	3.1

[a] For the Surveyor analyses, the elemental symbols Ca, Ti and Fe represent a range of elements (see text and Economou, 1970). The principal contributors are expected to be the elements listed. The quoted errors of the Surveyor analyses are estimates at the 90% confidence level.
(a) Franzgrote (1970).
(b) Averages of the more accurate of many lunar soil analyses reported in Levinson (1970).
(c) LSPET (1970).
(d) Vinogradov (1971).
(e) Lunokhod-1 (1971).
(f) LSPET (1971).

The comparison between the Surveyor 5 and Apollo 11 analyses, columns 2 and 3 of Table III, is particularly to be noted since both apply to Mare Tranquillitatis, at sites less than 30 km apart. It is seen that the agreement is just about within the Surveyor analytical errors except in the case of Fe, where the Surveyor answer is some 25% lower than the Apollo result.

The analytical results for all the maria lead to a similar geochemical picture – that of a silicate rock with Al and Ca each comparable to or greater than Mg, low Na (0.3 to 0.6 atom percent) and frequently high Ti (0.5 to 2.2 atom percent). The Fe content is also relatively high at 3.1 to 5.4 atom percent. These data indicate that the surface of the Moon in the maria is made up of chemically differentiated material – it does not have the chemical composition of the Sun or of chondritic meteorites. Both of these samples of primordial solar system matter have magnesium contents comparable to those of silicon, much higher than the amounts of aluminum and calcium.

Since the first chemical analysis of the lunar surface on the Surveyor 5 mission (Turkevich *et al.*, 1967), the compositions of the lunar maria have been compared with those of terrestrial basaltic rocks. The more extensive data available now make possible a more detailed comparison. This is done in Figure 1, where the amounts of

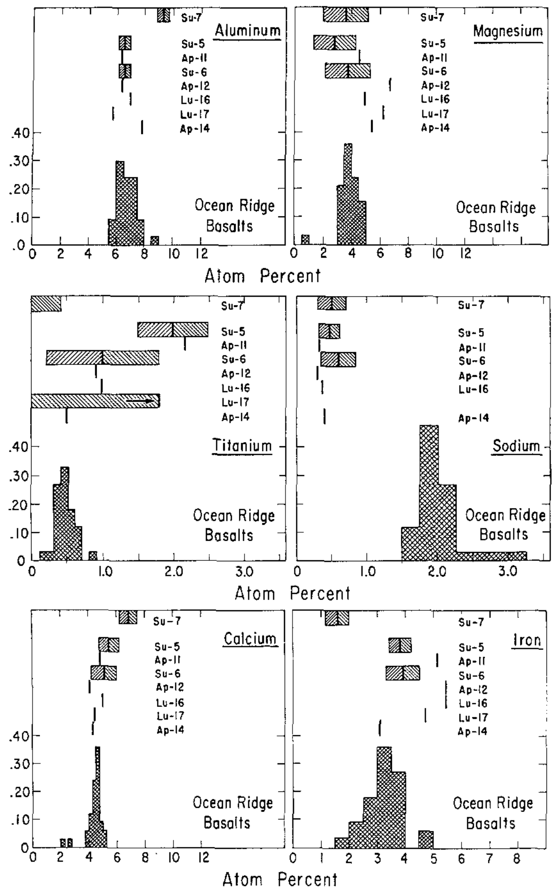

Fig. 1. Comparison of the amounts of some of the principal chemical elements in lunar mare material with the amounts in terrestrial ocean ridge basaltic rocks. The abscissae are in atom percent. The histograms are the distributions in the amounts of the element as determined by Kay *et al.* (1970). The shaded areas about the Surveyor analyses represent the 90% confidence range of these analyses.

Mg, Al, Ca, Fe, Ti and Na in the lunar maria are compared with the amounts of these elements in terrestrial ocean ridge basaltic rocks (Kay *et al.*, 1970). The comparison is not made for oxygen or silicon since these are not too sensitive indicators of rock type. There is, however, an indication that the amount of silicon in the lunar maria may be one to two atom percent lower than in terrestrial basaltic rocks.

Figure 1 shows that the Al and Ca contents of the lunar maria are well within the ranges observed by Kay *et al.* In the case of Mg and Fe, also, there is overlap, although some of the results from the lunar samples are higher than the distributions observed by Kay *et al.* Thus, for the six chemical elements present in amounts greater than three atom percent, the chemical composition of the lunar maria is adequately represented by that of terrestrial ocean ridge basaltic rocks. It is definitely incompatible with either the composition of terrestrial ultrabasic rocks or of meteorites or with that of the more evolved acidic granitic rocks of the Earth.

The principal differences between the chemical compositions of the lunar maria and those of terrestrial basaltic rocks are in the frequently high Ti and always low Na contents of the former. Both these aspects are well illustrated in Figure 1. Even larger differences in the amounts of less abundant elements have, of course, been noted (see, *e.g.*, LSPET, 1969, 1970).

The greatest variation in composition among the different maria is in the Ti content, which changes by a factor of four from the high value in Mare Tranquillitatis to the low value at the Apollo 14 landing site. Most of the variation in Mg content is contributed by the two Surveyor results for this element, where the errors are rather large. On the other hand, the Al content at all five sites is remarkably constant at 6.6 ± 0.6 (1σ) atom percent.

Considering the fact that the six maria sampled are widely separated on the Moon, these analyses suggest that most, if not all, lunar maria have this gross chemical composition. An average lunar mare chemical composition calculated on the assumption that each analysis is representative of its mare (the Surveyor 5 and Apollo 11 data for Mare Tranquillitatis were averaged) is given in column 2 of Table IV. These numbers differ by at most 0.5 atom percent from the results based on the Surveyor 5 and 6 and the Apollo 11 and 12 and Luna 16 missions (Turkevich, 1971).

Column 3 of Table IV gives the average lunar soil composition determined by the alpha scattering technique on the Surveyor 7 mission to a terra site outside the crater Tycho (Patterson *et al.*, 1970). Different terra sites on the Moon differ somewhat in their optical and topographical properties, and the Surveyor 7 landing site, in particular, is clearly in an ejecta blanket of the crater Tycho. However, this site is similar to other terra sites in having an appreciably higher albedo than do the maria, although this albedo is somewhat lower than that of most lunar terrae. In addition, the local

TABLE IV

Comparison of the chemical composition of lunar maria and terrae

	Percent by atom		
Element	Average Mare	Terra (Surveyor 7)[a]	Average lunar surface[b]
O	60.5	61.8 ± 1.0	61.5
Na	0.4	0.5 ± 0.2	0.5
Mg	5.2	3.6 ± 1.6	3.9
Al	6.6	9.2 ± 0.4	8.7
Si	16.7	16.3 ± 1.2	16.4
Ca	4.7	6.9 ± 0.6	6.5
Ti	1.1	0 ± 0.4	0.2
Fe	4.5	1.6 ± 0.4	2.2

[a] The errors are estimates at the 90% confidence level (see Patterson *et al.*, 1970). An amount of fluorine equal to 0.29 ± 0.12 atom percent was also found.

[b] See text.

topography is clearly similar to that of other lunar terrae, and the crater Tycho itself is in a vast terra region of the Moon. It is seen from Table IV that the chemical composition at this site is distinctly different from that of the maria. There is more than a factor of three fewer atoms of elements heavier than Ca (*i.e.*, much less Fe and very little, if any, Ti), and about a 40% increase in Al and Ca contents. The amount of Si is, within the Surveyor errors, the same as in the maria.

The applicability of this chemical analysis at one terra site on the Moon to other terra areas must, of course, be made with caution. Supporting this extrapolation, however, is the finding of fragments of similar compositions in the Apollo 11 soil (*e.g.*, Smith *et al.*, 1970; Wood, 1970) and in some of the Apollo 12 breccia rocks (*e.g.*, Anderson *et al.*, 1971) which have been attributed to highland material transported by meteorite impacts to the maria. More recently, experiments on the Apollo 15 mission, using X-ray detectors on the orbiting Command Module, established a higher Al/Si ratio over the highlands – including the back side of the Moon – than over the maria (Adler *et al.*, 1972). This supports the assumption that the Surveyor 7 chemical composition may be representative of all the lunar terrae. It has been pointed out (Turkevich *et al.*, 1968b; Phinney *et al.*, 1969; Patterson *et al.*, 1969) that these differences in chemical composition between the lunar terrae and maria may be the explanation for the albedo differences of the major topographical features of the Moon. For rocks on Earth, there is an inverse correlation between the albedo and the content (in the range being considered here) of the chemical elements heavier than calcium (primarily Ti and Fe) (Patterson *et al.*, 1969). On Earth, a major cause of darkening of rocks with larger amounts of these elements is the higher oxidation state of Fe; on the Moon where the rocks are characterized by a lower oxidation state than on Earth, it is partly due to the presence of the very dark mineral, ilmenite ($FeTiO_3$), although radiation effects involving these heavier elements may also contribute.

The lower amount of elements heavier than calcium in the lunar highlands also implies a lower density for the rocks there (see below) than in the maria, with a suggestion that isostatic adjustment has occurred in many regions of the Moon. For example, the recent Apollo 15 observations that the back side of the Moon is, on the average, about 2 km higher in elevation from the center of mass than the mean radius of the Moon (Michael and Blockshear, 1971) is consistent with the existence of a thicker crust of lower density material on the back side than on the front, where the higher density maria make up a larger fraction of the surface.

The average chemical composition of the lunar surface, on the assumption that the mare composition of column 2 of Table IV is applicable to 20% of the surface and the Surveyor 7 composition to the rest, is given in column 4 of Table IV. The differentiated character of the entire lunar surface (not only of the maria) is indicated by this average chemical composition.

Although an elemental chemical composition cannot provide the detailed information about rock type and mineralogy that can be obtained from examination of returned samples, some data of this type can be reasonably inferred from chemical analyses. This was first done using the early Surveyor analyses by Turkevich *et al.*

TABLE V

Normative mineral composition inferred from chemical analyses (mole percent)

		Surveyor 5		Apollo 11		Surveyor 6		Apollo 12		Luna 16		Surveyor 7	
Ilmenite		13.1		14.7		6.8		6.8		7.6		–	
$FeTiO_3$	il												
Plagioclase Feldspars		22.8		22.2		24.5		24.9		28.4		45.0	
$NaAlSi_3O_8$	ab		3.1		2.2		4.1		2.3		2.9		4.6
$CaAl_2Si_2O_8$	an		19.7		20.0		20.4		22.6		25.5		40.4
Pyroxenes		46.5		63.1		59.9		43.6		42.3		39.4	
$MgSiO_3$	en		16.4		12.9		15.0		8.3		13.2		22.9
$CaSiO_3$	Wo		18.3		30.6		25.2		20.3		15.5		11.0
$FeSiO_3$	fs		11.8		19.6		19.7		15.0		13.6		5.5
Olivine		–		–		–		24.8		21.8		15.6	
Mg_2SiO_4	fo		–		–		–		15.4		11.6		11.0
Fe_2SiO_4	fa		–		–		–		9.4		10.2		4.6
Quartz		17.7		–		8.8		–		–		–	
SiO_2	qtz		–		–		–		–		–		–
estimated density (gm cm^{-3})		3.15		3.27		3.14		3.17		3.22		2.94	

Average mare rock density: $\varrho = 3.19$ gm cm^{-3}

(1968a) and Phinney *et al.* (1969). A normative mineral composition is derived here following an order that minimizes the uncertainties due to the errors of the Surveyor analyses. The amount of ilmenite is determined by the Ti content. The amount of Al, with its relatively small error, determines the amount of plagioclase feldspar ($CaAl_2Si_2O_8$ and $NaAlSi_3O_8$ with the Na content determining the relative amounts of the two). The remaining atoms of Ca, Mg, Fe, and Si are assigned to pyroxenes and olivine or quartz. It is in the detailed assignment of the different types of pyroxenes and in the amounts of olivine or of silica minerals that the relatively large errors of the alpha scattering method for Mg and Si play the largest role. The results of the above procedure are shown in Table V for six of the lunar sites for which analyses are available.

The table illustrates, from a mineralogical standpoint, the similarities and differences among the different maria. The higher ilmenite content at Mare Tranquillitatis than at the other maria follows directly from the higher Ti content there. The constancy of the plagioclase contribution at 24.5 ± 2.4 mole percent is a consequence of the constant Al contents of the maria. The anorthite fraction of the plagioclase is constant at 88%, although here the inability of the alpha scattering method to distinguish between Ca and K must be remembered. Likewise, the detailed composition of the pyroxenes and the apparent considerable amount of silica minerals in the results from Surveyors 5 and 6 are less certain because of the rather large errors (and anticorrelation) attached to the Si and Mg results. The gross mineralogical characteristics inferred from the treatment of Table IV have actually been observed in the case of the powdered lunar material returned to Earth by the Apollo 11 and 12 and Luna 16 missions (LSPET, 1969; LSPET, 1970; Vinogradov, 1971).

The last column of Table V indicates that the material outside the crater Tycho is representable by negligible ilmenite, and a 50% increase in plagioclase content (again highly anorthitic) over lunar mare material. There appears to be no silica excess; in fact, some olivine content is suggested.

The bottom row of Table V gives the particle densities for the material making up the lunar fines at the different sites. They were calculated according to the procedure of Phinney *et al.* (1969), and represent estimates of the densities of the *average* rock from which these lunar fines were derived. These average densities at all five mare sites are relatively constant at 3.19 ± 0.06 gm cm^{-3}. The density of the corresponding terra material, as represented by the Surveyor 7 analyses, is significantly lower, 2.94 gm cm^{-3}. These numbers are in adequate agreement with the estimates made by Phinney *et al.* (1969) from the preliminary results of the Surveyor missions, namely 3.20 ± 0.05 and 3.00 ± 0.05 gm cm^{-3}.

A result of special interest from the Surveyor 7 chemical analysis is the apparent presence of 0.3 atom percent of F. Since the amount of P that would be required to have this F in the form of apatite was difinitely excluded by the analyses, this F may be in the form of CaF_2 or as a partial replacement for O in the silicates. Another possibility is that the fluorine found at the Surveyor 7 site is only on the surface of the regolith particles, perhaps the product of reaction with exhaling gases from the interior of the Moon. Fluorine-containing exhalations are often observed in regions of volcanic activity on the Earth (*e.g.*, Stefansson and Sigurjonsson, 1957). It will be of interest to see if any F is detected in particles that are more definitely of lunar highland origin than the ones that have been available so far on Earth.

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