The Surface Abundance and Stratigraphy of Lunar Rocks From Data About Their Albedo

V. V. Shevchenko
Shternberg State Astronomical Institute, Moscow, U.S.S.R.

The data of ground-based studies and surveys of the lunar surface by the Zond and Apollo spacecraft have been used to construct an albedo map covering 80 percent of the lunar sphere. Statistical analysis of the distribution of areas with various albedos shows several types of lunar surface. Comparison of albedo data for maria and continental areas with the results of geochemical orbital surveys allows us to identify the types of surface with known types of lunar rock. The aluminum/silicon and magnesium/silicon ratios as measured by the geochemical experiments on the Apollo 15 and Apollo 16 spacecraft were used as an indication of the chemical composition of the rock. The surveys had a surface resolution of about 150 km, which is comparable in order of magnitude to the resolution of the albedo map, which is equal to 50 km on the lunar surface. This dependence allowed a preliminary estimate to be made of the distribution of rocks of various types over the surface of the Moon. The relationship of the relative aluminum content to the age of crystalline rocks allows a direct dependence to be constructed between the mean albedo of areas and the age of the rocks of which they are composed.

The nature of the spatial distribution of optical parameters of the lunar surface indirectly reflects the peculiarities of the current nature and genesis of the Moon. Furthermore, it is possible, on the basis of territorial unity, to compare optical parameters with structural peculiarities and chemical composition of the covering material. Establishment of reliable qualitative and quantitative dependences allows, in turn, extension of data obtained for the limited areas where spacecraft operated, to larger areas of the visible and back hemispheres of the Moon.

It is particularly interesting to investigate the mean regularities, using data that encompass a large portion of the lunar surface. In this connection, an albedo map covering 80 percent of the entire lunar surface was used (fig. 1) as the primary information. The map was constructed in an original scale of 1:10 million based on the results of processing Earth-based and orbital surveys. The albedo of the areas of the back hemisphere was determined from measurements made on photographs produced by the Zond 6 and Apollo 13 spacecraft (ref. 1). The measured values of brightness were reduced to true full Moon. On the map is a system of isolines drawn with an interval of values $\rho_0 = 1.0$ percent, showing the distribution of albedo in the range from < 6 percent to > 18 percent.

The reliability of the results of comparison depends to a great extent on the agreement of the spatial resolution of the data studied. Therefore, in order to study the dependence of albedo on chemical composition of the surficial material, data were used from the selenochemical orbital survey. The indicators of chemical composition of rocks used in this case were the relative contents of aluminum and magnesium along selected flight paths.

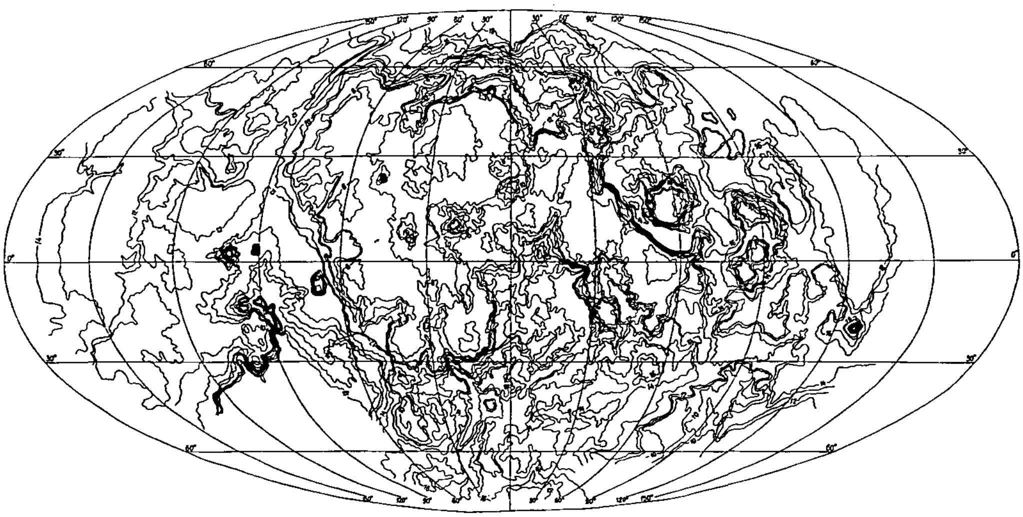

Figure 1.—*An albedo map for 80 percent of the lunar surface, drawn according to data from Earth-based studies and Zond and Apollo spacecraft.*

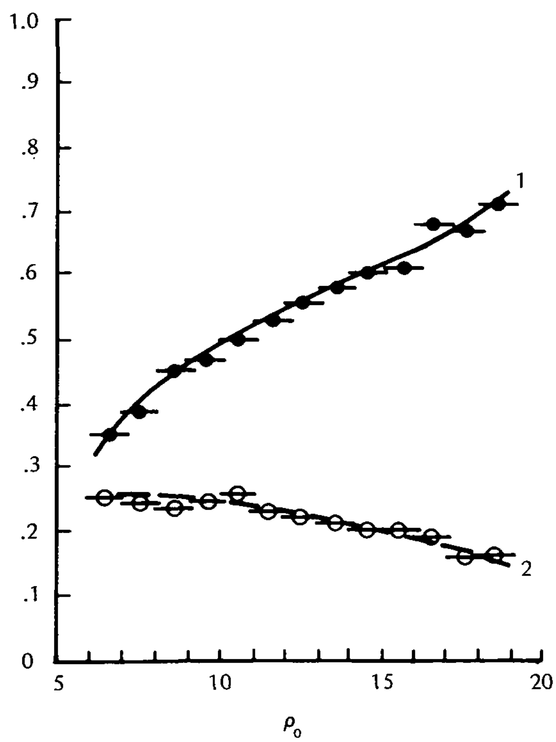

Figure 2.—*Curves showing the dependence of albedo on Al/Si (curve 1) and Mg/Si (curve 2).*

Figure 2 presents curves of the dependence of albedo on Al/Si (1) and Mg/Si (2). Curve (1) uses the mean values of Al/Si for the corresponding intervals of albedo ρ_0. The values of Al/Si are presented on the basis of individual measurements, representing the combined data from preliminary processing of the results of selenochemical surveying by the Apollo 15 and Apollo 16 spacecraft (refs. 2 and 3). In table 1 we present the number of individual measurements and the mean square deviations for the corresponding albedo intervals.

For the interval 17–18, the mean value of Al/Si was produced by use of two measurements with deviations of $\pm$ 0.040; interval 18–19 in this case corresponds to one measurement. Thus, curve (1) on figure 2 is the mean dependence of albedo on aluminum content in relationship to silicon with a mean deviation of individual Al/Si measurements of $\pm$ 0.040. Curve (2) corresponds to the dependence of albedo on relative content of magnesium (Mg/Si). The values of Mg/Si were taken from reference 4. The points used to construct curve (2) are mean values of Mg/Si for each albedo interval.

Table 1.—*The Mean Square Deviations and the Number of Measurements for Corresponding Albedo Intervals,* $\Delta\rho_0$

$\Delta\rho_0$	M	δ
6–7	29	± 0.049
7–8	29	.039
8–9	12	.040
9–10	6	.022
10–11	3	.030
11–12	6	.030
12–13	5	.037
13–14	9	.040
14–15	15	.058
15–16	10	.037
16–17	9	.059

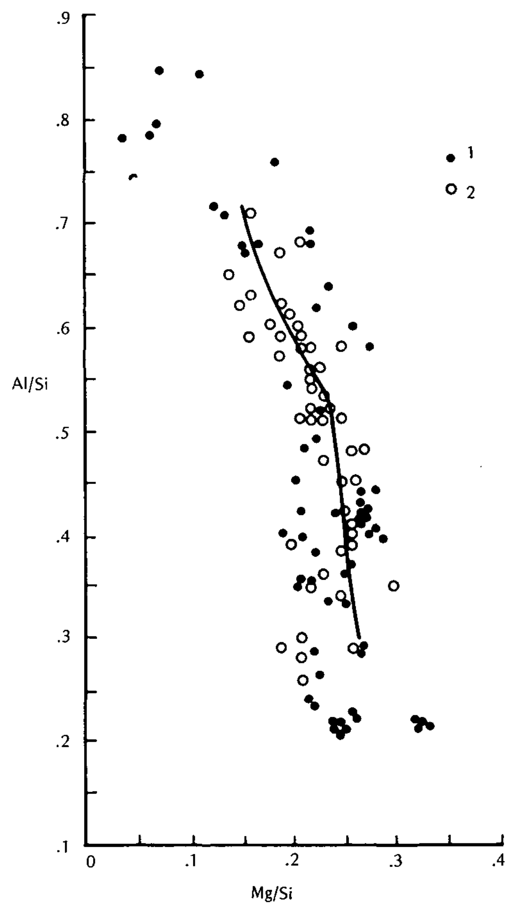

Figure 3.—*A curve showing the dependence of the relative contents of Al and Mg for surface rocks of identical albedo. The filled circles are for the analyses of returned samples and the open circles are for orbital data.*

One confirmation of the fact that albedo is a recognition indicator for rocks is the comparison in figure 2 of the dependence between the Al/Si and Mg/Si ratios and the results of selenochemical studies. Figure 3 presents a curve corresponding to the dependence of the relative contents of aluminum and magnesium for surface rocks of identical albedo (using the data of fig. 2). The individual points show the same relationship as do results of chemical analyses of specimens returned to Earth (filled circles "1") (refs. 5–13) and as do the results of selenochemical orbital study of individual sections (open circles "2") (ref. 4). Figure 3 shows that this curve actually reflects the mean relationship between Al/Si and Mg/Si. Consequently, the normal albedo can be considered a statistical mean indicator of rock type. This fact allows us to judge the distribution of lunar rocks of various types for 80 percent of the entire surface of the lunar sphere, i.e., that area covered by the measurements of normal albedo. Figure 4 shows a histogram of the albedo distribution. The histogram was constructed on the basis of a sample made from

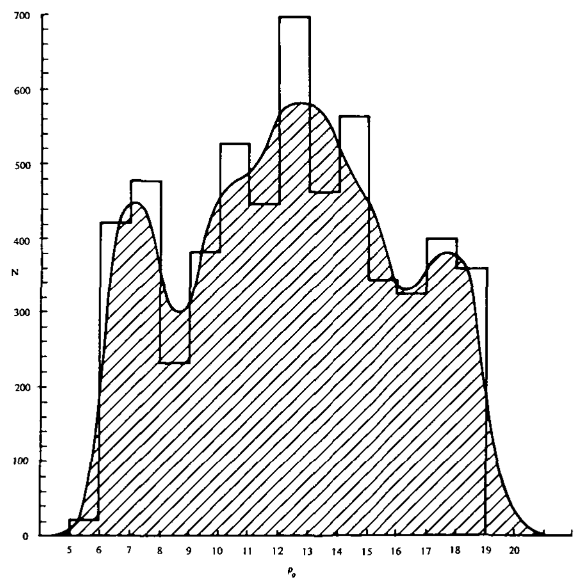

Figure 4.—*A histogram of the albedo distribution.*

Table 2.—*An Attempt to Identify the Maxima in Figure 4 With Known Rock Types, Using the Correlation Between Albedo and Al/Si Ratios*

Type of Rock	Al/Si	ρ_0(percent)	S(percent)
Maria basalts	< 0.40	< 8	16.4
Norites	0.40–0.55	8–12	28.0
Anorthositic Gabbro	0.55–0.65	12–16	36.4
Gabbroic Anorthosites	0.65–0.85	> 16	19.2

the albedo map by using an ideal system of points to create an even distribution of readings over the scale. The ordinate shows the number of points; the abscissa shows the corresponding normal albedo intervals. The smooth curve clearly shows four maxima within the distribution presented. Table 2 shows an attempt to identify the maxima with known types of lunar rock on the basis of the connection established above between albedo and chemical composition (with respect to relative aluminum content). The same table presents preliminary data on the area of the lunar surface within which the rock types mentioned are found. Anorthosites, for which Al/Si > 0.85, occupy a comparatively small area, amounting to less than 6 percent of the entire surface.

Actually, the result produced relates only to the thin upper layer of lunar soil. Reflected radiation in the visible area of the spectrum, like fluorescence, radiation in the X-ray area, comes from the upper layer of lunar soil, less than 1 millimeter thick.

However, the heterogeneity of the surface structure of the lunar regolith practically means that the radiation recorded contains information on the material of deeper layers, which has been exposed or has been carried to the surface by crater-forming processes. It can be shown that the variations in albedo over significant areas reflect the peculiarities of the deep (down to several tens of kilometers) structure of the Moon. We know that on the global scale, areas of lunar matter with higher density occur in large depressions in the surface. In particular, it has been established that the level of areas of mascons averages 4 km below the level of the continents (ref. 14). Consequently, if there is a correlation between the reflectivity of matter and the absolute heights of the corresponding structures, the assumption stated above can be considered well founded. In one work (ref. 15), based on brightness measurements in the western portions of the Ocean of Storms made from the Zond 8 photographs, it was shown that along several profiles, each 500–600 km in length, there is a correlation between albedo and absolute altitude with a correlation factor of 0.790. A similar study was performed along the profile from the topographic survey, made with a laser altimeter (ref. 16) in the area from 140° E to 160° W (including the visible hemisphere) with the albedo map (fig. 1). Calculations of the correlation factor for 50 data points distributed at equal intervals along the profile yielded a value of $r = 0.798 \pm 0.051$.

The relationships between albedo of the lunar matter and chemical composition, as well as surface and depth distribution of lunar rock, allow us to use the reflectivity of lunar material as a stratigraphic indicator. In reference 1, data on the chemical composition and absolute age of specimens returned from various regions of the lunar surface have been used to produce a dependence between relative aluminum content in the rock and its crystallization time. Using the relationship of Al/Si with albedo, we can reveal the relationship between the albedo and the age of structures. Both of these dependences are presented in figure 5 (the abscissa has a double scale: top scale—albedo; bottom scale—relative aluminum content). The position of individual points on the graph in most cases corresponds to the mean data for the region when samples were collected. Thus, it is possible to determine a probable age of surface rock in various areas of the visible and back sides of the Moon. Since the described dependences are statistical in nature, the results are correct for structures covering significant areas. Small formations such as individual craters, aureoles, and ray systems are exceptions to the general rule.

Basing our deductions on the overall struc-

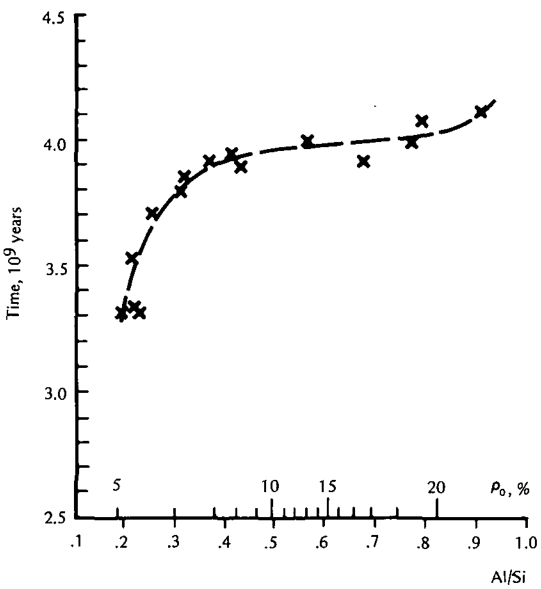

Figure 5.—*The age of lunar structures versus the Al/Si ratio and albedo.*

ture of the surface of the lunar sphere and considering the interrelationship of albedo, rock type, and crystallization time, we can draw the following preliminary conclusions. The contemporary lunar maria were formed within areas with predominantly noritic rock. At the present time, practically all maria are surrounded by zones of "dark" continental rock of probable noritic composition. Direct contact of the maria surface with light continental complexes, consisting of rocks of anorthositic type, is encountered very rarely. Within the limits of any given mare, sectors may be observed with variations of age of several hundreds of millions of years, eliminating the hypothesis of the catastrophic formation of the maria. This peculiarity indicates a very long and multiphased process of development of the maria areas. A general idea of the distribution of active processes on the Moon during various periods in history is given in figure 6. The integral curve of frequencies, constructed on the basis of the accumulated frequencies of albedo distribution (ordinate), based on the relationship of albedo to age (abscissa), shows the fraction of the entire lunar surface formed earlier than a given rock age. Figure 6 indicates that in the era before 4.0 billion years ago, active processes, accompanied by the melting of lunar matter with subsequent crystallization, covered the entire surface of the lunar sphere. During this time, the continental rocks of the anorthositic complex were primarily formed. During the next 0.1–0.2 billion years (formation time of norites), the active zone was gradually reduced, and during the last 3.0–3.5 billion years it has not exceeded a fraction of 1 percent of the entire surface of the moon.

The above-presented dependences of albedo on chemical composition and crystallization age are statistical in nature and are correct, as we have noted, for large territories. As concerns individual formations and small areas of the lunar surface, these dependences can be used for preliminary estimation only. Even in this case, however, the information is apparently of great interest for regions which have not been studied in detail by direct methods.

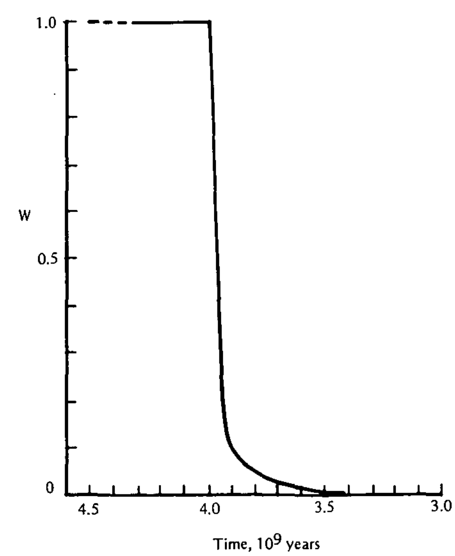

Figure 6.—*The distribution of active processes on the Moon during various periods in lunar history.*

References

1. SHEVCHENKO, V. V., *Astron. Zhurn.* In press.
2. ADLER, I., J. TROMBKA et al., *Science,* Vol. 175, No. 4020, 1972.
3. ADLER, I., J. TROMBKA et al., *Science,* Vol. 177, No. 4045, 1972.
4. ADLER, I., J. TROMBKA, et al., *The Moon,* Vol. 7, Nos. 3 and 4, 1973.
5. VINOGRADOV, A. P., *Geokhimiya,* No. 3, 1971.
6. VINOGRADOV, A. P., *Geokhimiya,* No. 7, 1972.
7. WOOD, J. et al., *Smithsonian Astrophysical Observatory, Special Report 307,* 1970.
8. WOOD, J. et al., *Smithsonian Astrophysical Observatory, Special Report 333,* 1971.
9. Summary of Apollo 11 Lunar Science Conference. *Science,* Vol. 167, No. 3918, 1970.
10. Preliminary Examination of Lunar Samples from Apollo 12. *Science,* Vol. 167, No. 3923, 1970.
11. Preliminary Examination of Lunar Samples from Apollo 14. *Science,* Vol. 173, No. 3998, 1971.
12. The Apollo 15 Lunar Samples: A Preliminary Description. *Science,* Vol. 175, No. 4020, 1972.
13. The Apollo 16 Lunar Samples: Petrographic and Chemical Description. *Science,* Vol. 179, No. 4068, 1973.
14. LEYKIN, G. A., M. P. POPOVA AND ZH. F. RODIONOVA, *Astron. Tsirk.,* No. 755, 1973.
15. LIPSKIY, YU. N., S. V. LANDAU, M. F. SHAVANOV AND V. V. SHEVCHENKO, *Kosmich. Issled.* In press.
16. WOLLENHAUPT, W. R. AND W. L. SJOGREN, *The Moon,* Vol. 4, Nos. 3 and 4, 1972.