The Role of Exogenic Factors in the Formation of the Lunar Surface

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The formation of the surface of planetary bodies is determined by the interaction of endogenic and exogenic forces. Clarification of the mutual role of these forces is one of the most important trends in the geological sciences.

Progress in the study of lunar samples and in geological and morphological observations by man and by automatic equipment now make the solution of this problem for the Moon quite important. However, in spite of the abundance of factual material, the mutual role of these forces in many respects remains unclear. Therefore, it is important to separate from the complex of phenomena that portion in which the nature of the process can be firmly established.

However, the role of any process in geology cannot be studied without consideration of the specific time to which it relates. In studying the geological processes which formed the overall appearance of the Earth, we clearly see the periodicity or unevenness of the actions of various processes in a single region. However, for the Earth overall we are actually studying primarily the history of the Phanerozoic, i.e., the last 600 million years and, even if we include the little-studied upper portion of the Precambrian, we can judge only the last third of Earth's history. For this period of the planetary history of the Earth, we can in general assume a sufficient similarity of the active factors and proceed from the principle of actualism after introducing a few rather controversial corrections.

Stages in the Geological History of the Moon

The surface of the Moon preserves traces of much more ancient processes which encompass, perhaps, up to 90 percent of its planetary history. Under these conditions we can no longer consider the acting forces to be constant, but must distinguish at least three stages, which differ quite sharply as to the nature of the predominant processes (ref. 1).

Stage I, the continental stage, encompasses the period of time from approximately 4.5 to 4.0 billion years ago and can be called the pregeological stage, since there is no direct analogue on Earth. The pregeological stage of formation of the planetary body (ref. 2) from the gas-dust cloud ends with a powerful meteorite bombardment, in which the force of the impacts increases with growth of the planet. The thermal energy of the impacts is rapidly dissipated into surrounding space, so that the entire planet is not heated (ref. 3). However, each in-falling particle is simultaneously crushed, significantly heated, and subjected to loss of volatile components, which are concentrated at the surface of the planet if the gravitational field of the planet is capable of retaining them. The fraction of heat that remains in local foci of heating remains unclear, but obviously the process of differentiation can occur both from the top downward and from the bottom upward, when forming the primary crust of the planet. Apparently, at this stage of formation of the surface of the planet the concepts "exogenic" and "endogenic" lose their ordinary meaning and require special definition. Near the surface a zone of localized hot foci is formed through which great masses of matter pass in a process analogous to zone melting, the theory of which was developed by A. P. Vinogradov and his school for magmatic melting (refs. 4, 5, and 6).

It is now important to underline the following characteristic peculiarities of this stage in the history of the Moon:

1. The distribution of the largest impact craters of the Moon is relatively even over its surface and provides no basis for the assumption of the basic asymmetry of the visible and back sides of the Moon, which developed later (fig. 1).
2. During impact accretion, the matter of the Moon underwent significant and repeated conversion with significant losses of volatile elements and compounds.
3. The great majority of craters forming the surface of the lunar continents are of impact origin, complicated with later tectonic development of weakened jointed zones of circular structures, and in many cases accompanied by quiet effusion of lava, which fills the impact structure.
4. As a result of the powerful impact-explosive processes the predominant type of continental rock is the widely distributed impact breccias.

It is also important to emphasize that, regardless of the stage of formation of the Moon, each impact crater in the dense rock is surrounded by a zone of crushing, which extends one or two radii beyond the limits of the visible crater and continues significantly further out in the form of networks of radial and circular cracks. Such cracks, which may extend hundreds of kilometers in depth around the large craters, form weakened crustal zones, through which the tectonic stresses of the planet are primarily relieved

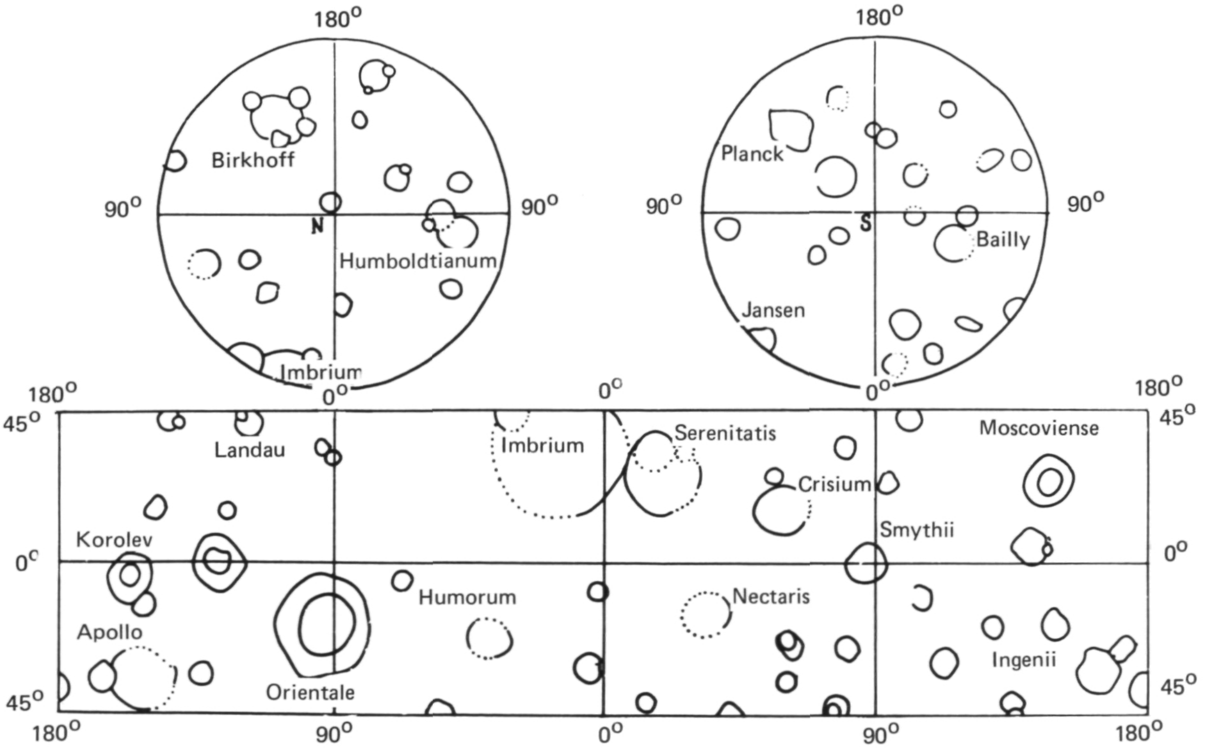

Figure 1.—*Distribution of the large circular structures on the surface of the Moon. Considering subsequent lava effusions, the densities of large craters on the visible and back side of the Moon are approximately equal.*

to form the characteristic circular structures. As the mass of the Moon grows because of the last impacts at the end of accretion, the zone of fragmented rock is buried, and the system of inherent jointing may manifest itself, in spite of subsequent lithification of the deep zones and development of magmatic processes.

Stage II in the development of the Moon is the maria or volcanic stage which encompasses the period from approximately 3.8 to 3.0 billion years ago and is characterized by extensive fusion of the interior and extensive effusion of superheated, but already degassed, basaltic lava. The asymmetrical distribution of the maria and the incomplete agreement between maria and ancient impact structures on the surface of the Moon basically reflect the internal causes of this process, although there are alternative explanations (ref. 7). This process develops during the sharp reduction of the meteorite flux, and the relative role of purely exogenic factors drops sharply. Apparently, some of the explosive volcanic craters can be related to the general type of this period although they could not be very widespread because volcanic action was the quiet effusion of basaltic lava, which filled the depressions and bottoms of impact craters, primarily on the visible side of the Moon.

Stage III, the postmaria or exogenic stage, lasts approximately 2.5 to 3.0 billion years and is essentially no different from the current stage. It is characterized by the extinction of magmatic activity on the surface, except perhaps for isolated points that are not decisive. Internal activity of the Moon is manifested primarily by the presence of vertical tectonic movements. With this general background of the absence or extremely weak manifestation of planetary magmatism, the leading role is also taken by relatively slight exogenic factors that continually operate over the entire surface of the Moon for billions of years. Their action in purest form is best seen on the surface of the lava flows of the lunar maria, which do not have their structure complicated by ancient crater forms that are repeatedly superimposed upon each other in the continental areas of the Moon. Since the task of the present report is to analyze the role of exogenic factors, it is natural that many propositions of our report will be developed on the basis of analysis of phenomena that can be studied on the lava plains of the maria.

The relatively slight cratering of the maria surfaces facilitated the development of the concept of the recent nature of the process of lava effusion and overestimation of the possible role of postmagmatic phenomena at the present time and in the recent past. In spite of convincing data on the ancient nature of lunar magmatism that have been obtained by direct study of lunar rocks, these concepts still exist.

The Regolith on the Lunar Surface

The processes of surface formation are reflected in the development of relief and deposits correlated with it. One characteristic representative is the regolith. The lunar regolith is a friable covering layer of clastic material, including rocks and fragments of all sizes, that is displaced from its point of initial deposition (fig. 2). The friable, slightly cohesive nature of the material is an obligatory characteristic of the regolith. It is determined by the thermodynamic conditions of

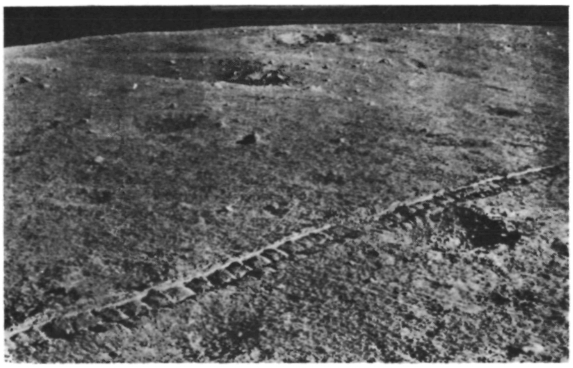

Figure 2.—*The regolith surface in the region of operation of Lunokhod 1 in the western portion of Mare Imbrium. The foreground shows the wheel tracks of the Lunokhod. The track width is about 20 cm.*

the lunar surface, primarily the presence of free volume.

The regolith blankets the forms of lunar macrorelief and mesorelief. On the plains of the lunar maria the average thickness of the regolith is several meters. In the continental regions, the average thickness of the regolith is generally significantly greater. The thickness of the regolith depends greatly on its position in the relief. In depressions, particularly at the foot of slopes, it probably reaches dozens of meters while on the surfaces of peaks and on slopes it sometimes decreases to some dozens of centimeters. On individual areas of the steep slopes of tectonic depressions (Straight Rille in Le Monnier crater, Hadley Rille) and certain other formations, local outcrops of bedrock are observed.

The greatest influence on the formation of the lunar regolith is the formation and evolution of small craters (with diameters less than several kilometers), which control the form and relief of the lunar landscape. The regolith includes ejecta from these craters and friable material moved by the combination of slope processes. As secondary components, the regolith contains thin ejecta layers from large, distant craters and extralunar (meteorite) material. The single-stage ejecta related to large-scale impacts and combined into rather large, extensive geological bodies such as the Fra Mauro formation, are lithified, i.e., they are not friable and therefore should not be included as part of the regolith. The presence of true volcanic ash in the lunar regolith has not yet been noted, but is improbable because of the facts just mentioned and can represent only a very slight admixture to the products of impact crushing.

The Relief and its Evolution

Small craters are the most typical forms of mesorelief and microrelief of the lunar surface. The peculiarities of their morphology and the nature of their distribution over the surface indicate that the overwhelming majority of the small craters are of impact formation and are related to the bombardment of the lunar surface with meteorite bodies.

The size distribution of craters in various homogeneous areas of the plains of the lunar maria is surprisingly similar. The model of this process is rather simple (refs. 8–11). The logarithmic curve of the dependence of crater density on size consists everywhere of two branches (fig. 3), one of which has a slope near − 2, the other near − 3. The steep lower sector of the curve corresponds to the primary distribution of craters and the averaged distribution law for meteorite masses. The smooth upper sections of the curve characterize the equilibrium surface saturation number of craters, where each new impact is compensated by the corresponding destruction of older craters. As a result, their number remains constant and the process leads only to reworking of the regolith. The point of intersection of the two branches of the curve is called the critical point and corresponds to the critical crater diameter that statistically reflects the age of the surface,

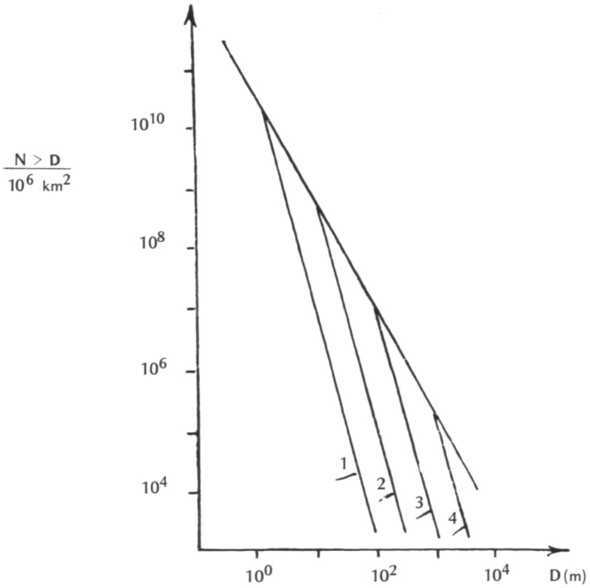

Figure 3.—*The crater frequency per unit surface area, as a function of crater diameter. Lines 1, 2, 3, and 4 are the frequency curves in the nonequilibrium portion of the Distribution at various times (isochrons). The flatter, upper limiting line is the curve for the equilibrium distribution.*

while the lower branches of the curve move parallel with time and form isochons. The actual realization of this model is complicated by secondary impact craters formed from local ejecta; by relief; and by the peculiarities of the geological structure of each specific region, as well as by possible unevenness of the meteorite flux, and other factors that require precising. In the first approximation, however, the model describes well the process of formation and evolution of craters on the lunar surface. The critical diameter of craters fluctuates from 2.7 m in the region of the young deposits from Tycho crater, through 50–200 m for the various maria of Imbrium and Eratosthenian age, and reaches 1000 m in the Fra Mauro formation, where the equilibrium density of small craters changes under the influence of the relief.

Craters form a continuous series of relief forms from fresh, sharply expressed, steep-sloped forms to more ancient, gently sloping formations. It is convenient to divide this series into five morphological classes, reflecting in increasing order the degree of destruction of primary forms: A, AB, B, BC, and C (fig. 4). The criteria for separation might be various morphological characteristics: steepness of slopes, sharpness of ridges, relative depths, etc. (refs. 10 and 12).

Study of the mutual superposition and intersection of craters of different morphological classes, in combination with exposure age data for crater ejecta, has made it possible to estimate, for the postmaria period of lunar history, the mean lifetime of craters with diameters of a few meters to several hundreds of meters on the mare plains (ref. 13) (fig. 5). As seen from figure 5, the evolution of the lunar craters and, consequently, the process of formation of á cover of friable deposits on the lunar surface, have been retarded in comparison with similar processes on Earth. Thus, a crater 10 m in diameter

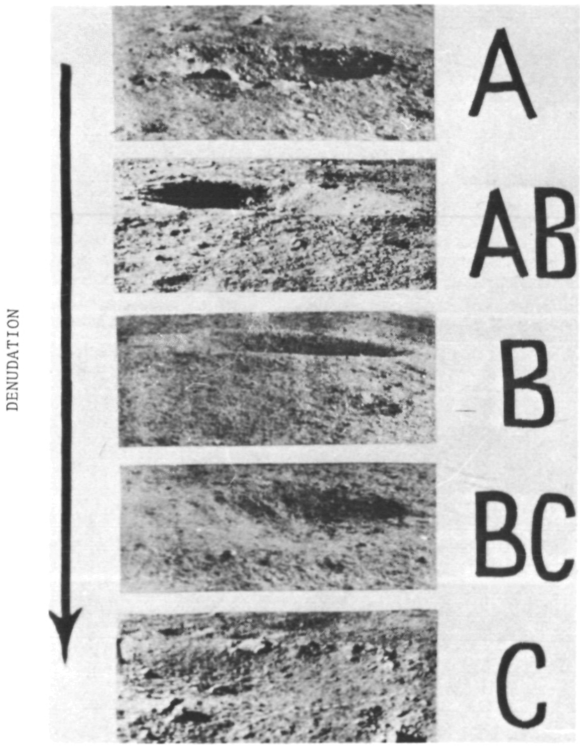

Figure 4.—*The morphological classes of small craters. The crater diameter on the photographs is 2 to 3 m. The images are from Lunokhod 1 and 2. The degree of destruction of the primary form increases from Class A to Class C.*

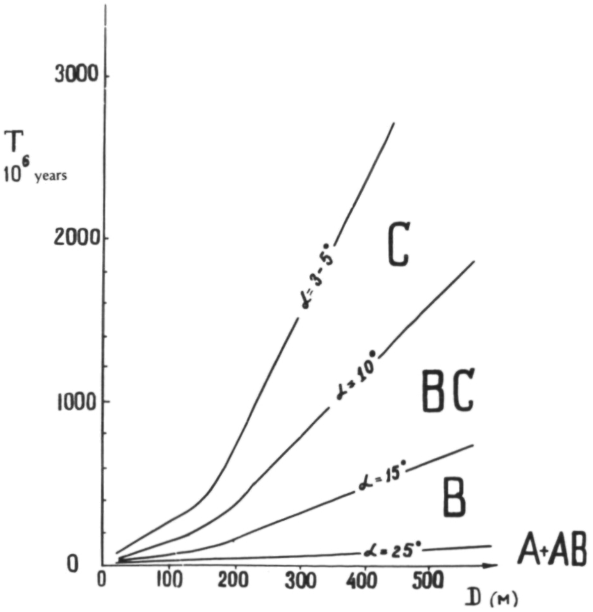

Figure 5.—*The potential lifetime of lunar craters. The lines separate fields of various morphological classes and show values of the maximum steepness of the Internal slopes of craters typical of boundaries between classes.*

has a statistical lifetime of about 25 million years, while a crater 250–300 m in diameter might even be preserved for about a billion years. The destruction rate of similar relief forms on Earth is approximately three orders of magnitude higher. The exposure time of matter on the lunar surface makes it possible for the important effects produced by the solar wind and cosmic rays to manifest themselves intensively (ref. 14). We will not study these effects in this article.

The processes that destroy lunar craters can be divided into two groups. The relative significance of these groups of jointly acting processes has not been reliably established. The first group includes the processes of impact-explosive crater formation, where the results depend on the scale of the phenomenon, and may either catastrophic or gradual (resulting from the addition of many small-scale phenomena).

The second group consists of processes involving the movement of matter downward along the slopes of craters under the force of gravity. On the steepest slopes in crater classes A and AB, both flowing and slumping processes develop (fig. 6). For class B craters, sliding phenomena are characteristic. In craters in classes A, AB, B, and, probably, BC, massive movement of clastic material down the slopes occurs, i.e., "creep." In craters of morphological class C, the significance of slope processes is apparently not great.

It should be emphasized that slope processes are observed with relatively small angles of inclination of the surface, significantly less than the angle of repose of lunar soil. The agents provoking the movement of the material downward along the slope are apparently moonquakes of both tectonic and impact origin, the ejection of material by micrometeorite impacts, and, possibly, the diurnal temperature fluctuations.

The processes that destroy noncrater lunar

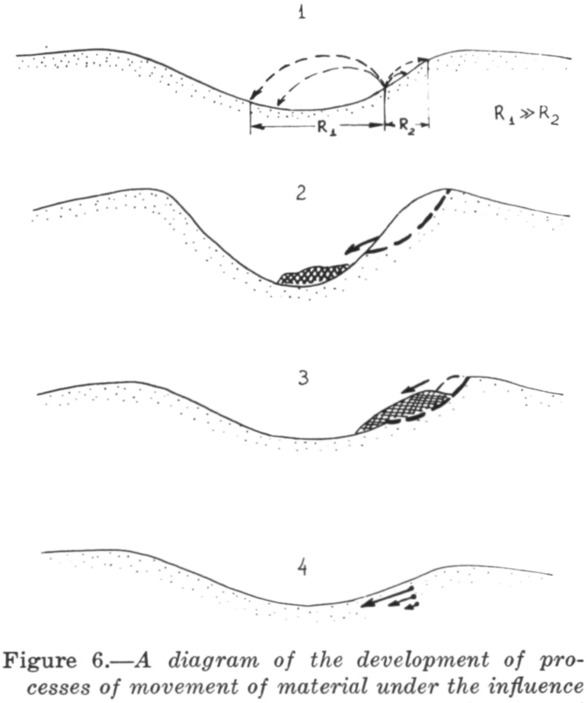

Figure 6.—*A diagram of the development of processes of movement of material under the influence of the force of gravity on the internal slopes of craters: 1, directed transfer by small impacts; 2, slumping; 3, flowing; and 4, mass movement such as "creep."*

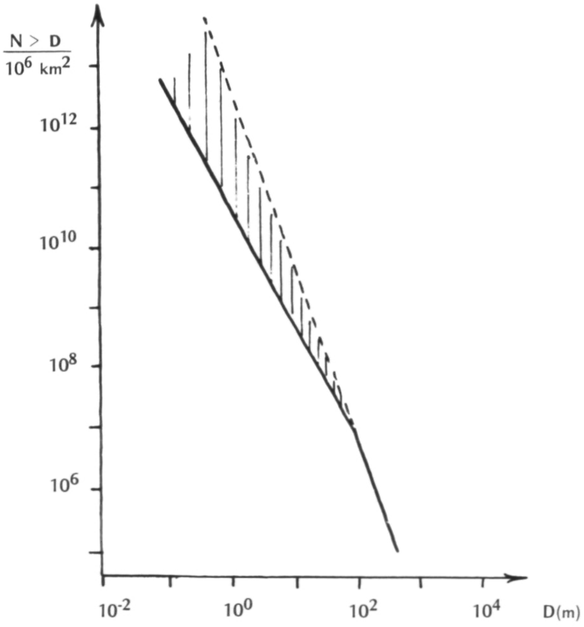

Figure 7.—*Density distribution of craters in regions studied by Lunokhod 1 and Luna 16 (solid lines on graphs). The dashed line shows extrapolation of the nonequilibrium distribution to reflect the total number of craters that once existed in this area. The hatched area corresponds to the portion of the crater population which has now disappeared.*

relief forms have in principle the same nature and are also determined by the joint effects of meteorite bombardment and slope processes. The predominant type of slope process is controlled by the steepness of the slope.

Processes of Movement of Material

As already noted above, the formation and evolution of forms of lunar relief and the formation of the regolith cover are two aspects of the same process. The characteristic peculiarities of this process are vertical mixing of the regolith material and its horizontal displacement.

The formation of craters and their filling with friable material lead to a constant crushing and mixing of the regolith, which decreases in proportion to depth. We can gain an idea of this if the lower non-equilibrium portion of the curve characterizing the density of impact craters as a function of their size (fig. 7) is extended above the equilibrium portion of the curve. This extrapolation allows us to estimate the total number of craters that have been created in a given area and destroyed by later meteorite impacts. From this, it is easy to determine the intensity of mixing the regolith to any given depth (ref. 15). As seen from fig. 8, for a surface of Imbrian age, the number of generations of craters mixing the regolith down to a depth of a few millimeters reaches 1000; to a depth of 10 cm, near 100; and to a depth of 1 m, near 10.

Naturally, this does not mean that every particle of regolith in a given layer was located in the zone of impact this number of times, because the more powerful impacts are capable of burying regolith particles deeper than the active layer. Nevertheless, these estimates give a general idea of the degree to which impact action is active on the surface layers of the regolith.

In general, the vertical mixing of the regolith is a statistical process, and in some areas undisrupted masses of regolith may exist for extended periods of time. These peculiarities in the formation of the vertical structure of the regolith should lead to an irregular lens-like stratification in cross section that is coarser in the lower portion of the regolith cover.

The horizontal transport of regolith results from the motion of the material downward along the slopes and from the scattering of matter during explosions. The first process is significant within the limits of each specific form of relief. The range of transport in this case is determined by the length of the slopes, while the intensity of transport is determined by the difference in heights and by the steepness of the slope. Impact ejection can move material on the Moon over arbitrarily great distances, and even expell a portion of the impact products into interplanetary space. This phenomenon raises the problem of the material balance between the Moon and surrounding space.

Ejections of material during impacts are responsible for the formation of the bands of mixing of maria basalt and anorthosite-norite-troctolite rocks at the boundaries between maria and continental areas, with predominant displacement of the material toward the mare. The width of the band of

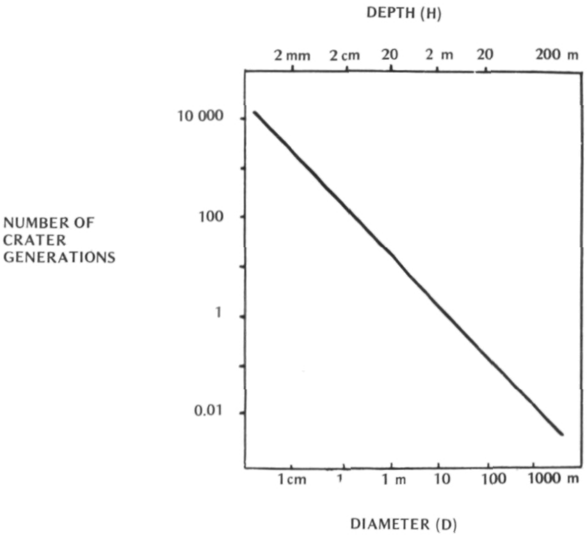

Figure 8.—*The number of generations of craters and the calculated depth of reworking of material by craters of various diameters, in regions studied by Lunokhod 1 and Luna 16.*

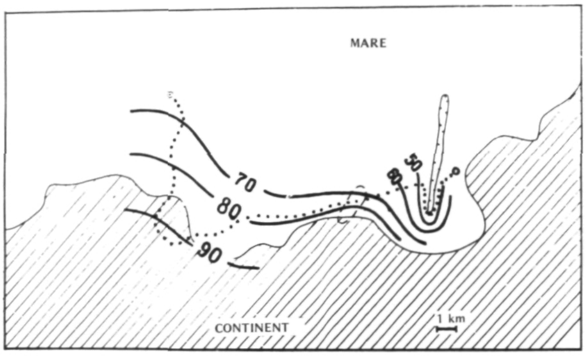

Figure 9.—*The fraction of continental material (wt.%) in the surface layer of regolith in the region of investigation of Lunokhod 2 (calculated from the results of chemical analyses by G. Ye. Kocharov and S. V. Viktorov (ref. 16)). The dotted line shows the path of Lunokhod 2. The decrease in admixture of continental material in the neighborhood of Straight Rille in the eastern portion of the path is related to intensive Transport of fine-grained material from the upper regolith layer into the rille.*

noticeable mixing may be a few dozen kilometers. This phenomenon can be illustrated in the landing area of Lunokhod 2, where typical maria surface relief is combined with a regolith of low-iron chemical composition (ref. 16) (fig. 9).

This can be seen with equal clarity in the detailed study of the albedo along a line connecting the landing point of Luna 20 with the light continental regolith and the landing point of Luna 16 with the typical dark maria regolith. The study was performed at our request by V. I. Yezersky at the Khar'kov Observatory (fig. 10). We can see from the change in albedo that the zone of significant mixing is about 50 km here, while the downward transfer of material toward the mare, with an altitude difference of about 1 km, is approximately four times greater than the transfer upward in the direction of the continental area.

Formation of the Size Composition of the Regolith

When impact craters are formed on the surface, material which was formerly deposited at some depth is ejected. If the crater is large enough and penetrates below the regolith, it will partially crush the underlying rock and deposit large fragments of this material in the ejecta zone in the form of blocks. The ejected material is partially separated by size, with the smaller fractions tending to travel further. This results in the formation of blocky zones on the slopes of fresh craters, and also contributes to the coarsening of the regolith on the slopes of the lunar relief. The burial of stones accounts for the fact that large fragments are sometimes found in the regolith.

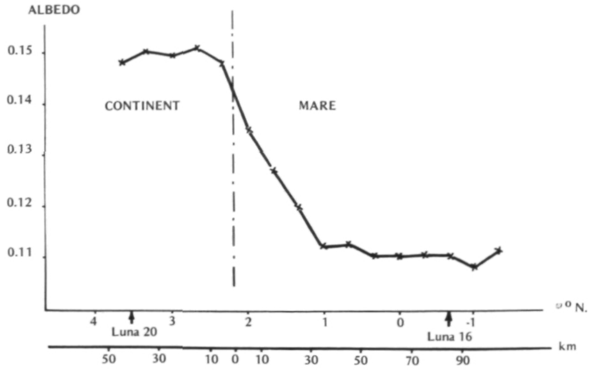

Figure 10.—*The photometric section along a line connecting the landing sites of Luna 16 and Luna 20. Produced by V. I. Yezersky at the Khar'kov University Astronomical Observatory.*

Systematic analysis of crater ejecta observations performed by Lunokhod 2 at the edge of Straight Rille and direct study of regolith cores show a significant increase in coarseness of the regolith material with depth, which results from its crushing at the surface (refs. 17, 18, and 19). This phenomenon can be illustrated by Lunokhod data on the granulometry of coarse fragmentary material from the surface layer of the regolith in typical geological conditions (fig. 11).

The situations studied are grouped into an evolutionary series by age. The ejecta from class A craters, 20 to 50 m in diameter, has a probable exposure age of not over a few millions of years. The material in the ejecta zone from class B craters of similar size has been exposed on the surface for 10 to 20 million years. Exposure time of the material near class C craters, 20 to 50 m in diameter, and in the space between, is not less than 50 to 100 million years. From the data presented in fig. 11 it also follows that the large fractions are crushed with more intensity than the smaller fractions.

In general, the formation of the granulometric composition of the regolith occurs under the influence of the opposing processes of disintegration and aggregation, primarily caused by meteorite bombardment. The role of aggregation increases in inverse proportion to particle size. In the initial stages of transformation of lunar surface material, disintegration processes dominate, i.e., crushing the primary rocks and their fragments, while as the exposure age of the surface increases and the particle dimensions decrease, the role of aggregation processing such as sintering, fusion, and remelting increases statistically. The superposition of these two constantly acting processes at a given stage of development leads to an equilibrium state of the granulometric composition of the fine-grained (less than 1 mm) portion of the regolith with a weighted mean particle size of about 60 μ (ref. 20). In these cases, it is customary to say that regolith has reached a granulometrically mature state. Judging from the results of investigation of the granulometric composition of samples with various exposure ages, the time required to reach the equilibrium state is approximately 100 million years (ref. 19).

Obviously, slope processes make a significant contribution to the formation of the granulometric composition of the regolith. Comparison of specimens from the upper layer (15 cm) of regolith returned by Luna 16 (mare plain) and Luna 20 (slope of a hill at the edge of the crater Apollonius C) shows that the regolith on the slope has approximately the same median diameter as on the plain, but is distinguished by a significantly lower degree of sorting (fig. 12).

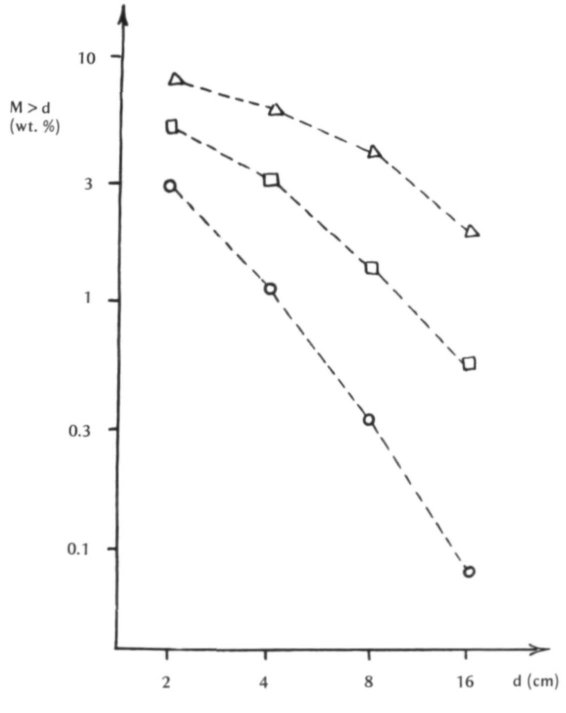

Figure 11.—*Dimensional composition of blocky material in ejecta from Class A craters (triangles), ejecta from Class B craters (squares) and ejecta on the surface, within Class C craters and in the space between craters (circles). The craters are 20 to 50 m in diameter. Calculations are based on results of the analysis of Lunokhod 1 panoramas.*

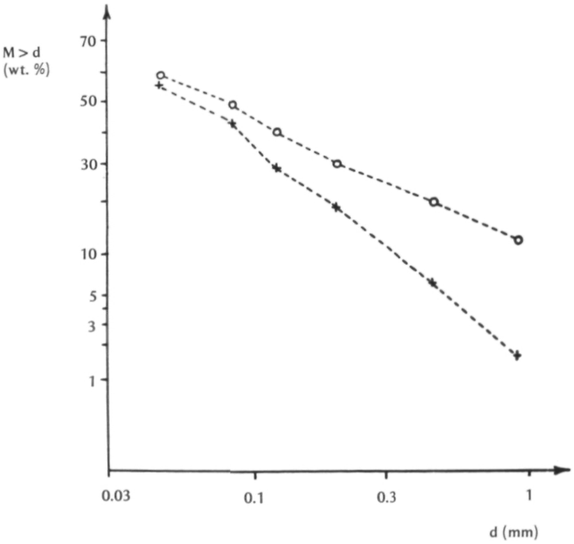

Figure 12.—*The size composition of the fine-grain regolith fraction from Luna 16 (crosses) and Luna 20 (circles). Top 15 cm of cores, sieve analysis.*

Regolith Lithology

Several types of particles can be distinguished in the composition of the regolith, which reflect the varying nature and degree of exogenic reworking of the initial material.

First of all, these include fragments of primary (in relationship to processes of regolith formation) rocks and the mineral grains which compose them. The presence of these particles reflects the process of crushing—the initial stage of alteration of material on the surface of the Moon. Their content (fig. 13) differs in various regolith samples and decreases significantly with increasing maturity of the regolith, while for a single sample it decreases with decreasing size of fraction. Thus, in a sample of mature mare regolith (Luna 16), for particles more than 0.5 mm in diameter we find about 20 percent fragments of primary rock, while in a sample of regolith whose particles are significantly younger in exposure age, obviously under the influence of slope processes (Luna 20), the fraction of fragments of primary rock increases to 50 percent (refs. 10 and 25).

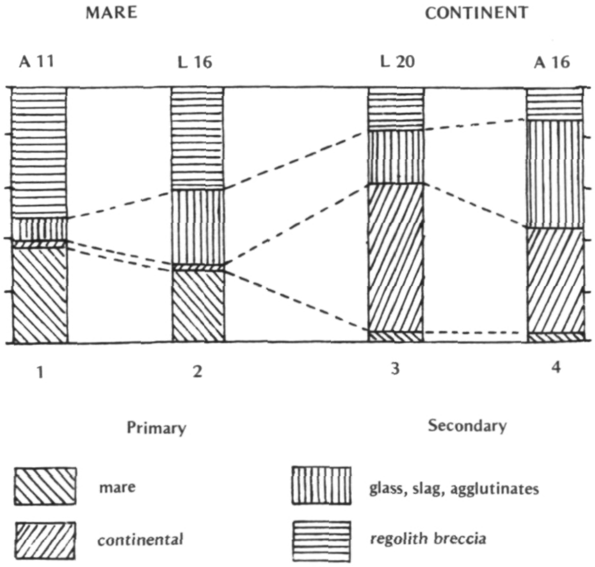

Figure 13.—*Lithological composition of regolith fragments: 1, Plain of Mare Tranquillitatus, Apollo 11 collection, fraction size: 1–5 mm (ref. 21); 2, Plain of Mare Fecundatatis, Luna 16 collection, fraction size: 0.25–0.425 mm and larger than 0.45 mm (refs. 22 and 23); 3, Continental Plateau to the north of Mare Fecundatatis, Luna 20 collection, fraction size: 0.25–0.50 mm and larger than 0.45 mm (refs. 22 and 24); 4, Continental Plateau of Descartes, Apollo 16 collection, fraction size: 0.25–0.50 mm (ref. 24).*

Rock fragments from the regolith at present are the only direct source of information about the composition of the lunar material. The primary rocks present in the form of fragments relate to two magmatic associations—maria ferrobasalts and the continental series of anorthosite-norite-troctolite rocks. The latter were generally brecciated by the intense early bombardment of the Moon by meteorite bodies.

The chemical composition and mineralogical-petrographic peculiarities of the fragments of these rocks indicate primary magmatogenic formation under conditions of a great deficit of volatile components, which is manifested in the very earliest stages of the geological evolution of the Moon accessible to our study. As noted above, an important factor in the loss of volatiles was probably local heating by collisions during the accretion of the Moon and directly related to the meteorite impacts which formed its surface. The early impoverishment in volatile components, as well as the basic nature of the lunar magma, which had low viscosity, do not allow us to assume any significant development of explosive volcanism in the history of the Moon or any significant admixture of pyroclastic material in the regolith.

Fragments of regolith breccia are typical regolith components. Many peculiarities of these particles—the general lithological composition of the fragments included in the breccia, the smooth form of most of the fragments, the presence of large quantities of glassy fragments, including glass spheres—definitely indicate their formation as a result of compaction and lithification of regolith material. The primary factor in lithification has apparently been the process of diffusion and partial melting at grain interfaces. The occurrence of this process probably requires a significant increase in the contact area, which is achieved by compaction of the friable mass of the regolith. Two mechanisms of such regolith lithification are possible: (1) rapid compression, with heating due to friction during compaction by impact phenomena; and (2) slow compaction of matter in the lower horizons of the regolith under the pressure of the overlaying masses in the specific conditions of the lunar vacuum. An important peculiarity of the regolith breccia which indicates the multistage nature of its formation, is the presence of multigeneration breccias, i.e., breccia fragments included in younger breccias. This peculiarity is observed on both macroscales and microscales. The content of regolith breccias, like the content of other secondary particles, increases with increasing exposure age and, for fractions larger than 0.5 mm in the Luna 16 and Luna 20 regolith, amounts to about 40 and 20 percent, respectively (fig. 13).

One characteristic type of regolith particle not encountered in terrestrial formations is agglutinates—sintered aggregates of complex irregular shape. Like the breccias, the agglutinates contain all components of the fine regolith fraction, including fragments of crystalline rock and monomineral grains, but are distinguished by a significantly greater glass content and a high degree of surface melting. The composition of the agglutinates indicates that their source is fine-grained regolith material, while the basic textural peculiarities indicate that the most probable process of formation is melting and fusion of the components of the friable surface layer during micrometeorite impact (McKay refs. 20 and 26).

An obligatory component of the regolith is the various particles of secondary glass, whose content, like the agglutinate content, is a function of the exposure age of the sample. Many glass particles have nearly spherical shapes indicating the formation of such particles by cooling of a melt in free flight. The formation of the overwhelming majority of glass particles is a result of spraying and solidification of a melt formed in the central zone of meteorite explosions. Individual glass particles are diaplectic. Thus, the glasses reflect the most intensive stage of exogenic reworking of material on the lunar surface.

A special type of particle is fragments of meteorites which have fallen onto the Moon. These particles are rare, because of the extreme conditions of impact of meteorites with the lunar surface, and are represented primarily by iron-nickel chunks.

On the whole, the formation of the lithological characteristics of the regolith occurs under the influence of a complex variety of processes caused by the meteorite bombardment of the lunar surface. They include crushing, lithification, melting, and fusion of various intensities, as well as the process of horizontal transport, sometimes over significant distances, which allows us to study individual specimens and judge the structure of significantly larger regions.

The meteorite bombardment of the lunar surface is also reflected in the formation of many microcraters on the surface of individual regolith particles, which carry information both about the evolution of the regolith and about the parameters of the micrometeorite flux which reaches the surface of the Moon (refs. 27 and 28).

The condensation of material evaporated by impacts has some significance, but judging from the data presently available, this process is limited in morphological effect and is known by the formation, on the particle surfaces, of certain characteristic forms of microrelief (films and ridges of metallic iron) and rare crystalline forms. However, we can assume that further investigations will turn up additional morphological evidence about condensation processes on the lunar surface.

Chemical Composition of the Regolith

The basic features of the chemical composition of the regolith in the various regions of the Moon which have been studied are determined by the composition of the primary rocks of the region. The regolith and the locally underlying rocks differ significantly in secondary, but very important, details of their chemical compositions (ref. 29). These differences are related to the peculiarities of the processes of formation and evolution of the regolith and are determined by the addition of meteoritic material, the influx of material from other regions of the Moon, and the phenomena of selective evaporation during meteorite impacts.

The influx of meteoritic material is reflected in an increase in the content of a number of characteristic "meteoritic" elements in the regolith (Ir, Au, Ni, Ge, and certain others). In mature regolith from the Mare Imbrium plains the fraction of meteoritic material calculated as chondritic composition has been estimated to be on the order of 2 wt. % (refs. 30, 31, and 32).

The influx of material from other regions of the Moon due to horizontal transport by impacts has already been discussed in the earlier sections of this report. This process, in particular, causes certain increases in the content of Ca and Al in the regolith of the mare plains and an increase in the content of Fe and Ti in the regolith of the continental areas, as well as formation of the aforementioned zones of mixing at the boundaries between maria and continents where hybrid surface chemical compositions are found.

Local heating of material during high-speed impacts is a cause of a whole series of changes in the chemical composition of the regolith. Because of this process, the regolith in general and particularly those components subjected to the most intensive exogenic reworking are significantly impoverished in a number of highly volatile elements, including the alkalies and phosphorus (refs. 33, 34, and 35). However, the differentiation of material by evaporation involves not only the highly volatile elements contained in the primary rocks of the Moon in small quantities, but also the basic petrogenic elements, which have moderate volatility. Some of the glassy particles have lost at least 30 percent of the initial amount of silica which they contained as well as significant quantities of iron (ref. 36).

The loss of petrogenic elements due to selective evaporation has also been confirmed by increases in the heavy isotopes of a number of chemical elements (oxygen, silicon) in the fine fraction of the regolith as a whole, and particularly in its most highly reworked portion—the glasses and agglutinates (ref. 37).

For the regolith overall, as the degree of its exogenic reworking increases, this should lead to a regular change in its petrochemical type.

The peculiarities of the chemical and isotopic composition of the regolith in combination with the data of model experiments (refs. 35 and 38) demonstrate the important role of evaporation processes in the formation of regolith which lead to significant fractionations of the elements and their isotopes. One of the most important geochemical results of this phenomenon is that the ratio of daughter and parent isotopes becomes a function not only of age, but also of degree of exogenic reworking (ref. 39).

It is characteristic that an increase in the heavy isotope of elements in the regolith, in comparison with the primary rocks, is related to evaporation processes during the exogenic reworking of the surface and is observed for all the specimens studied. The universality of the influence of exogenic reworking provides grounds to suppose that this regularity is characteristic of the entire lunar surface.

If this assumption is correct, it may indicate a negative mass balance for the Moon at the current stage of its history.

Thus, analysis of various aspects of the structure, composition, and evolution of characteristic formations of the lunar surface leads to the conclusion that exogenic factors have played an important role in various stages of the geological history of the Moon, and that their role has become decisive over the past 2 to 3 billion years.

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