Lunar Regolith at Tranquillity Base

Abstract. *The regolith at Tranquillity Base is a layer of fragmental debris that ranges in thickness from about 3 to 6 meters. The thickness of the regolith and the exposure histories of its constituent fragments can be related, by means of a relatively simple model, to the observed crater distribution.*

Tranquillity Base, the landing site of Apollo 11, is a relatively smooth and level part of the lunar surface in the southern part of the Sea of Tranquillity. At this site the lunar surface is underlain by weakly coherent fragmental material, the lunar regolith, which ranges in size from particles too fine to be seen with the naked eye to blocks more than a meter across.

Near the lunar module the surface of the regolith is pockmarked by abundant craters ranging in diameter from less than 2 cm to several tens of meters. A number of craters in the area, in the size range from 30 to 55 m, have sharply formed raised rims and anomalously shallow flat floors or floors with central humps. The floors of these craters are believed to have been formed on a more cohesive rocky substratum that underlies the regolith (*1*). We refer to this substratum as the bedrock. On the basis of the observed depths of the anomalous craters, the thickness of the regolith is estimated to range from 3 to 6 m. One of the anomalous craters, 33 m in diameter and 4 m deep, was visited by Armstrong, and a series of photographs were obtained of a low pile of coarse broken rock, which forms a central hump.

About 400 m east of the module is a prominent blocky-rimmed crater, informally named West Crater, which is about 180 m in diameter and about 30 m deep. West Crater is surrounded by a rim deposit of blocky ejecta which extends about 250 m out from the rim crest on all sides of the crater. Rays of coarse blocks extend up to several hundred meters beyond the continuous deposit of ejecta; one of these rays, with associated secondary craters, passes about 50 m north of the module. The surface of the regolith in the immediate vicinity of the module is relatively free of extremely coarse blocks, although some rock fragments nearby may have been derived from West Crater.

The size-frequency distribution of craters at and near Tranquillity Base has been estimated from Apollo 11 and Lunar Orbiter 5 photographs (Fig 1). The distribution of craters less than 100 m in diameter roughly follows a function, $F = \Phi c^{\mu}$, where F is the cumulative number of craters with diameter equal to or higher than c per 10^6 km^{-2}, c is crater diameter, Φ is a constant ($10^{10.9}$/m^{-2} 10^6 km^2), and μ is a constant (-2.00). This function, determined initially from Ranger photographs (*2*), has been found to fit the distribution of small craters at all Surveyor landing sites very closely (*3*). It is interpreted as the steady-state distribution of craters produced by repetitive bombardment of level surfaces on the moon.

The distribution of craters larger than a few hundred meters diameter in the vicinity of Tranquillity Base does not follow the steady-state distribution but can be fitted closely by another power function, $F = \chi c^{\lambda}$, where χ is $10^{12.9}$/m^{-2} 10^6 km^2 and λ is -2.93. The intersection of $F = \chi c^{\lambda}$ with $F = \Phi c^{\mu}$, at 141 m, is taken to be the upper limiting crater diameter of the steady-state distribution, here designated c_s. Soderbloom has shown (*4*) that the exponent μ of the steady-state distribution can be derived exactly and the constant Φ can be derived approximately, if a function close to $F = \chi c^{\lambda}$ is assumed to represent the distribution of all craters produced that are smaller than the steady-state limit.

The thickness distribution of the regolith can also be derived from the assumption that the function $F = \chi c^{\lambda}$ represents distribution of all craters that have been produced which are smaller than the steady-state limit. Under this assumption the difference between $F = \chi c^{\lambda}$ and $F = \Phi c^{\mu}$, at crater diameters less than c_s, represents the number of craters lost by erosion or burial as a result of repetitive cratering and other processes of material transport, such as mass wasting. The diameter of the largest crater that has just disappeared, as a consequence of these processes, is c_s. A crater of this size is lost partly by erosion of the rim but primarily by being filled in by debris derived from the rim and from more distant sources. The maximum thickness of the regolith in an area of 10^6 km is given by the original

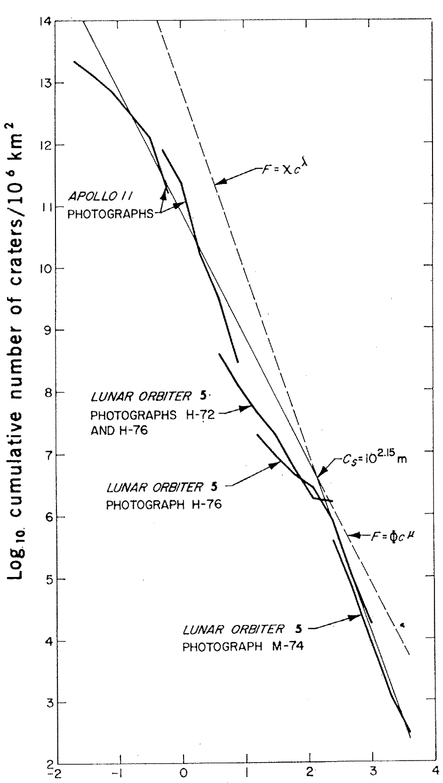

Fig. 1. Cumulative size-frequency distribution of craters on the lunar surface in the vicinity of Tranquillity Base, determined from Apollo 11 photographs and Lunar Orbiter 5 photographs. Curve shown for Lunar Orbiter 5 photograph M-74 is based upon unpublished data by E. C. Morris.

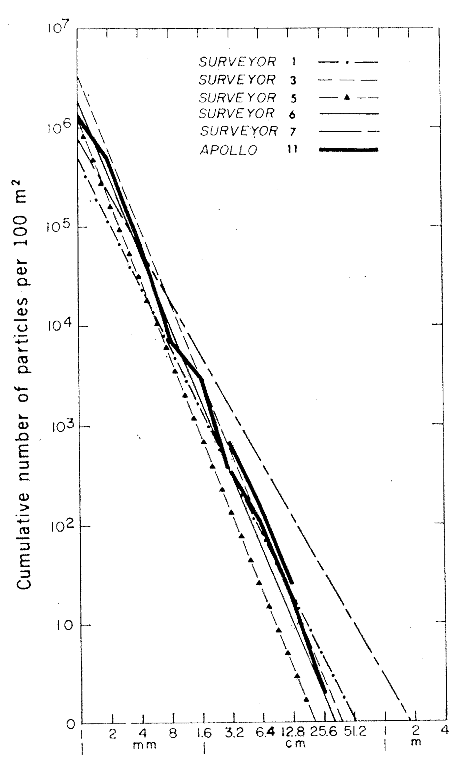

Fig. 2. Cumulative size-frequency distribution of surface particles at Tranquillity Base, compared with power functions fitted to observed size-frequency distributions of surface particles at the Surveyor landing sites.

depth of a crater with diameter c_s minus the original height of the rim. Elsewhere the base of the regolith is formed by segments of floors of smaller craters that have been filled in.

An approximate solution for the frequency distribution of regolith thickness has been given by Shoemaker *et al.* (*3*) as

$$H = \frac{100\,\lambda\,\pi\,\chi\,(1/q)^{\lambda+2}}{4(\lambda+2)A_m} \times [h^{\lambda+2} - h_s^{\lambda+2}], \quad h_{\min} \leq h \leq h_s \qquad (1)$$

where H is cumulative percentage of the surface underlain by a regolith of thickness equal to or greater than h, h is the thickness of the regolith, q is the ratio of the original depth (minus rim height) to diameter of the craters ($q \approx 1/5$), A_m is the total area of craters whose connected floors constitute the base of the regolith ($A_m \approx 2 \times 10^6$ km^2), h_s is the maximum thickness of the regolith ($h_s = qc_s$), and $h_{\min}$ is an artificially defined "minimum" thickness of the regolith

$$h_{\min} = q\left[c_s^{\lambda+2} + \frac{4(\lambda+2)A_m}{\lambda\,\pi\,\chi}\right]^{1/(\lambda+2)} \qquad (2)$$

Substituting the values for χ and λ at Tranquillity Base, we find the median thickness of the regolith to be 4.1 m.

The regolith has been turned over to the median depth of 4.1 m by cratering just once since the mare surface was formed, presumably as a lava flow, at Tranquillity Base. At shallower depths, the regolith has been turned over repeatedly by the formation and filling of small craters. The time for turnover to any median depth less than median thickness of the regolith is given, to good approximation, by

$$t = \frac{4A_r q^{\lambda+2}(\lambda+2)}{\pi\,\lambda\,\chi(d^{\lambda+2} - h_s^{\lambda+2})} \qquad (3)$$

where t is time of turnover expressed as a fraction of the age of the mare surface at Tranquillity Base, $A_r = 10^6$ km^2, and d is the median depth of turnover. Solutions to Eq. 3 for median depths of turnover: for 1 mm, time of turnover is 0.00037; for 1 cm, 0.0031; for 10 cm, 0.027; for 1 m, 0.24. In these calculations the crater production function, $F = \chi c^{\lambda}$, has been extrapolated to crater diameters of the order of a few millimeters.

Craters or pits smaller than a millimeter have been observed on the rocks returned to earth by the Apollo 11 mission. Craters smaller than 4 mm in diameter commonly are glass-lined, whereas the craters larger than 4 mm are only rarely glass-lined and are commonly irregular in form. The small craters are generally abundant on rounded sides of the rocks and are less abundant or rare on angular sides. A light halo, probably produced by minute fractures, surrounds most of the small craters, and the rounded surfaces of most rocks are underlain by a light rind, about a millimeter thick, that probably has been produced by repetitive cratering. These observations suggest that repetitive bombardment by small particles has been an important mechanism of erosion of the rocks.

If the crater production function, $F = \chi c^{\lambda}$, is extrapolated to very small craters, the following expression for the expected lifetime of a rock fragment can be obtained by integration of the volumes removed by repeated small cratering events,

$$l_1 = \frac{50A_r(\lambda+3)D}{\pi\,\lambda\,\chi\,(c_{\min}^{\lambda+3} - D^{\lambda+3})} \qquad (4)$$

where l_1 is the mean expected lifetime, expressed in units of the age of the mare surface, of a rock fragment eroded by bombardment of particles that produce craters smaller in diameter than D; D is the initial diameter of the rock fragment; and $c_{\min}$ is the smallest crater considered in the integration. Relatively few particles smaller than 1 μm may be expected to form craters on the moon's surface, and a value of 10 μm has been somewhat arbitrarily adopted for $c_{\min}$. With the observed value of λ, an order of magnitude error in $c_{\min}$ has a relatively small effect on the calculated lifetimes. Solutions to Eq. 4 are listed in Table 1. A 10-cm rock fragment, for example, has a mean expected lifetime, if exposed continuously to small particle bombardment, of about 1 percent of the age of the mare surface.

Table 1. Mean expected lifetime of rock fragments expressed as fractions of the age of the mare surface at Tranquillity Base.

	Initial size of rock fragment			
	1 mm	1 cm	10 cm	1 m
Mean lifetime of rock eroded by small* particle bombardment	0.00034	0.0017	0.012	0.087
Mean lifetime of rock destroyed by large† particle bombardment	0.00026	0.0022	0.019	0.16
Mean expected lifetime of rock bombarded by both small and large particles	0.00015	0.00097	0.0073	0.056

* A small particle is defined as a particle that produces a crater of diameter smaller than the rock fragment. † A large particle is defined as a particle that produces a crater of diameter equal to or larger than the rock fragment.

In addition to being worn down gradually by small particle bombardment, a rock fragment may be catastrophically broken up or destroyed if it is struck by a sufficiently large or energetic particle. Experiments suggest that almost all rocks are destroyed if they are hit by a particle that would have formed a crater equal in diameter to the rock. Impacts by projectiles somewhat smaller or less energetic than those required for catastrophic disruption tend to produce extensive spalling from the sides of rocks (*5*). The recovery of some rocks in the Apollo 11 mission with one or two rounded, pitted sides and several angular sides suggests that splitting or fragmentation by large particle impact is a significant process of rock destruction. The outer parts of many of the rocks are broken by a series of concentric fractures into a series of exfoliation shells. These fractures may have been produced in part by impact spalling.

The mean expected lifetime of a rock fragment destroyed by large particle bombardment is given by

$$l_2 = \frac{4A_r}{\pi\,\chi\,D^{\lambda+2}} \qquad (5)$$

where l_2 is the mean expected lifetime, expressed in units of the age of the mare surface, of a rock fragment destroyed by a particle that would produce a crater of diameter equal to or larger than D, the diameter of the rock fragment. As shown in Table 1, the mean expected lifetime of a rock destroyed by large particle bombardment is of the same order as the mean expected lifetime calculated for small particle bombardment. The calculations suggest that, for rocks 10 cm in diameter and larger, small particle bombardment is the dominant process of rock destruction. This result is sensitive to the assumed crater diameter at which catastrophic disruption occurs but is consistent with the observation that most large rocks have well-rounded, pitted surfaces on most sides.

The true mean expected lifetime of a

rock must be calculated by combining the rate of erosion by small particles and the hazard of catastrophic disruption,

$$L = \frac{1}{1/l_1 + 1/l_2} \qquad (6)$$

where L is the mean expected lifetime, expressed in units of the age of the mare surface, of a rock fragment bombarded by both small and large particles. Solutions of Eq. 6 are listed in Table 1.

A typical exposure history of a rock fragment may be deduced by comparing Table 1 with solutions to Eq. 3. Most rocks, once they have been ejected onto the lunar surface, may be expected to be destroyed before they become buried in the regolith. A rock will tend to be buried if the local time of turnover to a depth equal to the diameter of the rock is less than the lifetime of the rock. According to the calculations presented above, this happens in only a minority of cases because the time of turnover to a given median depth is about three times as great as the lifetime of a rock of that dimension. A correction should be made, however, for the fact that a crater produced in the regolith by a given release of energy will be about six times as deep as a crater produced in bedrock. With this correction, a rock fragment may be expected to be buried, on the average, before it is destroyed. Most rocks that are buried are likely to be buried only at shallow depth and are likely to be reexhumed in a time given by the time of turnover to a median depth which is equal to the depth of burial.

The mean expected exposure age for a rock fragment of a given size is approximately the same as the mean expected lifetime of a rock of the same initial size. On the average, an observed rock will have started out about twice as large but still will have half its lifetime left. Exposure ages ranging from 10 to 160 m.y. were reported for rocks ranging in average dimension from 3 to 11 cm, on the basis of the preliminary examination of the Apollo 11 samples (*6*). If the age of the mare surface at Tranquillity Base is of the order of 4 b.y. (*6*), the mean expected exposure ages for rocks in this size range are 10 to 30 m.y. A few exposure ages substantially greater than the mean should be observed for rock fragments that have been buried at shallow depth or that have been derived by breakup of much larger rocks. Some rock fragments should also be observed with exposure ages substantially less than the mean.

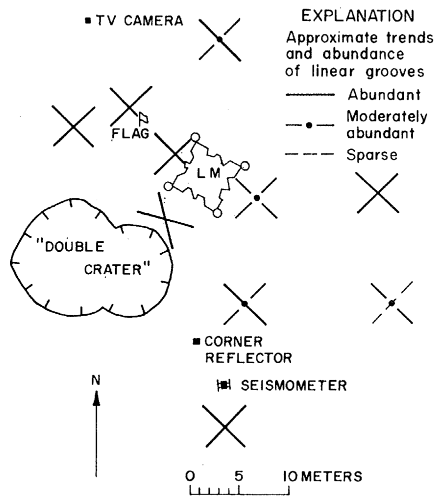

Fig. 3. Map of trend of linear grooves observed from extravehicular activity and module window photographs at Tranquillity Base.

The rough agreement between predicted and observed exposure ages suggests the extrapolation of the crater production function, $F = \chi c^{\lambda}$, to craters less than a millimeter in diameter is approximately correct.

Most rocks have been tumbled about on the lunar surface at least one or more times during their exposure to small particle bombardment. Small craters are generally found on all sides of a rock, showing that the bottom of the rock has been exposed at some time as a free surface. In the cases of three larger rocks whose position at time of collection during the Apollo 11 mission has been determined, one rock was oriented with the most rounded, pitted surface down, one rock was oriented on edge, with part of a heavily pitted, rounded side buried, and the third rock was oriented with the most rounded, pitted surface on top.

Rocks on the surface of the regolith may be tumbled by two somewhat different mechanisms: (i) A rock may be hit by one or more particles, which will impart sufficient angular momentum to turn the rock over. The efficiency of this mechanism depends on the degree to which the rock is embedded in the regolith. In many cases the impacting particles will destroy the rock, rather than turn it over. (ii) A rock may be thrown out of a crater. Rocks are tumbled most frequently by ejection from craters with diameters about twice as great as the tumbled rocks. This may be expected to occur about once in the lifetime of a rock, on the basis of the crater production function, $F = \chi c^{\lambda}$. However, $F = \chi c^{\lambda}$ has been determined for craters produced almost entirely in bedrock. For an impacting particle of a given energy, a crater produced in the regolith may be about twice the diameter of a crater in bedrock. If a correction is made for this difference, rocks may be expected to be tumbled about 10 times in their lifetime. The available evidence that most rocks collected in the Apollo 11 mission have been tumbled indicates that the mass flux of impacting projectiles is not dominated by very small particles.

The size-frequency distribution of rock fragments in the regolith at Tranquillity Base has been estimated from counts of fragments on the surface shown in Apollo 11 photographs (Fig. 2). The observed surface particle distribution is similar to that observed at other mare localities from Surveyor television pictures. This observed distribution follows fairly closely a power function with an exponent $\gamma = -2.4$. The size-frequency distribution of fragments in the regolith should be expected to follow a power function with about the same exponent as a power function which describes the size-frequency distribution of the impacting particles (*7*), or

$$\gamma \approx \lambda + 1 \qquad (7)$$

It may be seen that the agreement is rough, $\gamma = -2.4$ whereas $\lambda + 1 = -1.93$.

About half of the rock specimens returned in the Apollo 11 mission are fragments of microbreccia. The size-frequency distribution of the constituent particles of the microbreccia specimens is similar to the observed size distribution of particles in the regolith. Furthermore, the lithology and composition of the particles and the abundance of solar wind gases is about the same in the microbreccias as in the regolith (*6*). The inference seems secure that the microbreccias have been formed by induration of regolith material. This induration probably has been produced by shock compaction during formation of small and large craters in the regolith.

Some specimens of microbreccia exhibit a faint but distinct foliation that strongly resembles stratification. This foliation may be partly formed or enhanced by shock-produced shear, but in some cases there is a very slight sorting of fine and coarse particles in alternate layers. We believe the foliation is sedimentary stratification. Such stratification may be produced by deposition of successive layers of ejecta from small craters formed in the regolith. Stratification formed in this way will be preserved from destruction by repetitive cratering only where the rate of deposition exceeds the rate of turnover. This occurs primarily in the floors of craters that are gradually being filled and on fillets on the sides of rocks. Elsewhere the regolith is not stratified but has a rubbly structure (*8*) produced by repetitive cratering and turnover. This rubbly structure is also observed in some specimens of microbreccia.

The surface of the regolith at the Apollo 11 landing site is marked by intersecting sets of small shallow grooves. Most of the grooves are a fraction of a centimeter to a centimeter deep, about ½ to 3 cm wide, and 3 to 50 cm long a few were noted which are 2 to 3 m long. Where most strongly developed, the grooves are spaced 3 to 5 cm apart. One set of grooves trends northwest, another trends northeast. A few sets were observed that trend in other directions. The average trends and abundance of the grooves were estimated from ten surface photographs (Fig. 3). There appears to be no spatial or geometric relationship of the grooves to the location of the module or to local relief. Many of the grooves trend across small depressions and hummocks, with no apparent change in size, shape, or orientation.

The grooves may be produced by drainage of fine-grained surface material into fractures in the underlying bedrock or by vibration or jostling of joint blocks in the bedrock. If this interpretation is correct, it suggests that fine-grained regolith material is in direct contact with the bedrock. The drainage may be triggered or accelerated by tidal deformation or seismic disturbances. The lack of patterns that are radial or concentric to the module, or within craters, indicates that the grooves are not caused primarily by the descent exhaust or by downslope creep of material.

As the upper surface of the regolith is relatively rapidly changed by small cratering events, the grooves must be fairly young features or they must be frequently or continuously renewed. If they were not renewed, the lifetime of the grooves would be approximately equal to the time of turnover of the regolith to a depth equal to the depth of the grooves. The life expectancy of grooves 1 mm to 1 cm deep would be 0.0004 to 0.003 times the age of the mare surface.

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4 January 1970

Passive Seismic Experiment

Abstract. *Seismometer operation for 21 days at Tranquillity Base revealed, among strong signals produced by the Apollo 11 lunar module descent stage, a small proportion of probable natural seismic signals. The latter are long-duration, emergent oscillations which lack the discrete phases and coherence of earthquake signals. From similarity with the impact signal of the Apollo 12 ascent stage, they are thought to be produced by meteoroid impacts or shallow moonquakes. This signal character may imply transmission with high Q and intense wave scattering, conditions which are mutually exclusive on earth. Natural background noise is very much smaller than on earth, and lunar tectonism may be very low.*

The Passive Seismic Experiment is the principal means for determining the moon's internal structure, physical state, and tectonic activity and for relating these deductions to the various surface observations. Detailed investigation of the lunar structure must await the establishment and operation of a network of seismic stations; however, a single, suitable, well-recorded seismic event can provide information that is of fundamental importance and that could not be gained in any other way.

The Passive Seismic Experiment Package (PSEP) operated for 21 earth days at Tranquillity Base. It demonstrated that the goals of lunar seismic exploration could indeed be achieved.

The PSEP, which has been described elsewhere (*1*), was placed 16.8 m from the nearest foot-pad of the LM. Termination of the experiment resulted from failure of the system to execute commands from earth.

It became evident in the early stages of the experiment that the LM is a source of a great variety of seismic signals of unexpectedly large amplitudes, apparently generated by venting gases or circulating fluids, or both, within the LM. Thermoelastic deformation of the LM structure may also be a significant source of seismic noise.

Prior to the ascent of the LM, many signals corresponding to various activities of the astronauts, both on the surface and within the LM, were recorded, primarily on the short-period vertical (SPZ) seismometer. The astronauts' footfalls were detected at all points along their traverse (maximum range approximately 40 m). Signals were particularly strong when the astronauts were in physical contact with the LM. The velocity (compressional) at which such signals travel through the lunar surface material (debris layer?), as measured during a thruster test at the Apollo 12 site, is approximately 108 m/sec.

During the post-ascent period a great variety of high-frequency (2 to 18 hz) signals were recorded from the short-period (SP) seismometer. These signals have been separated into a number of descriptive categories based primarily upon the shapes of signal envelopes, the time-history of occurrence, and the spectral characteristics of each type. The following classification is tentatively assigned: (i) signals with impulsive onsets and relatively short durations (types I and X); and (ii) signals with emergent onsets and relatively long durations (types B, M, T, and L). Examples of seismic signals corresponding to several of these categories are shown in Fig. 1. Only the L events, which are believed to be of natural origin, are described below. The other signals are described elsewhere (*2*).

Type L signals have emergent beginnings and relatively long durations (up to 1 hour). The wave trains build up slowly to a maximum and then decrease slowly into the background. Of the various types of events, L events show the greatest variability in signal character, location of spectral peaks, and time of occurrence. They are observed on both