served 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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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

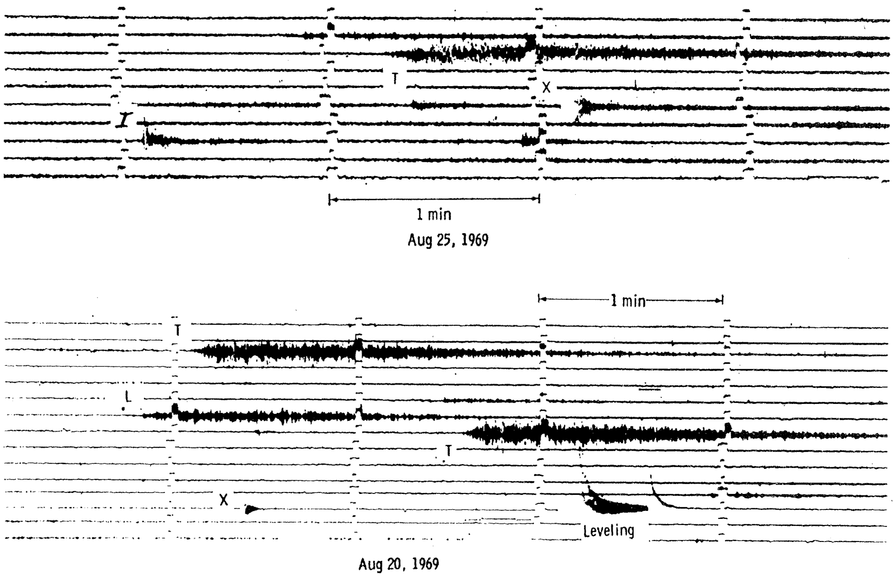

Fig. 1. Seismograms from the short-period (SP) seismometer showing signals of types I, T, X, and L.

the long-period (LP) and SP seismometers. For L events detected by the LP seismometers, little phase correlation between components is observed. The spectral peaks related to L events are broad, with frequencies of spectral maxima ranging between 1 and 6 hz. About 83 L events have been identified on the Apollo 11 records. Nearly all events thus far observed on the Apollo 12 records are of the L type, and the signal received from the impact of the LM ascent stage is also classified as L. The signal from the LM impact is shown in Fig. 2, along with the two largest L events recorded to date during the Apollo 12 mission.

An important result of the experiment is the discovery that the background noise level on the moon is extremely low. Before PSEP data were obtained, the level of lunar background noise was uncertain by several orders of magnitude. According to one popular hypothesis, the large diurnal thermal variations within the lunar surface material produced stresses that would lead to spallation and fracture and, consequently, to a high level of background noise. Another hypothesis proposed that meteoroid impacts were sufficiently numerous to create a significant continuous noise level. Still another hypothesis cited the absence of an atmosphere, oceans, and cultural activities to support the contention that the background noise level on the moon would be much lower than the level on the earth. Apollo 11 and 12 experience now suggests that the last of these is most accurate. The noise level is frequently below the threshold sensitivity of the instrument (0.3 nm at 1 hz) and far below the noise level at any known earth site.

The following possible source mechanisms for the observed signals are suggested: (i) venting gases from the LM and Portable Life Support Systems and circulating fluids within the LM (types B, M, and T); (ii) thermoelastic stress relief within the LM and PSEP structures (types I and X); (iii) instrumental effects (thermal effects, telemetry dropout, and the like); (iv) meteoroid impacts on the LM, the PSEP, and the lunar surface (types I, X, and L); (v) displacement of rock material along steep lunar slopes; (vi) moonquakes. Mechanisms i and ii are quantitatively important on the Apollo 11 seismograms because of the proximity of the LM to the seismometers and because of the single-package construction of the entire experiment. The differences in the Apollo 12 configuration make these sources relatively unimportant in the data being received from that instrument. Mechanism iv is thought to be a source of significant activity on both missions. The question of the existence of mechanisms v and vi is still open.

The occurrence of similar L events during both the Apollo 11 and 12 missions greatly strengthens our present belief that, of the various types of signals described above, L events are most likely to be of natural origin. Equally important, the inclusion of the impact signal of the Apollo 12 LM ascent stage in this family shows that signals of the L type can be generated by impulsive sources on the moon. This observation suggests that all L events were produced either by meteoroid impacts or by shallow moonquakes. On this basis, comparing the various L phases with the LM impact signal, we conclude that few, if any, L events originated significantly farther from the seismometer than the LM impact, which occurred at a distance of 75.9 km.

The average rate of L events detected during the Apollo 11 recording period is 4 per day. This rate is consistent with the number of detectable signals from meteoroid impacts predicted by Laster and Press (*3*) and by McGarr *et al.* (*4*) for a high-Q moon. Thus it is possible that all of the observed L signals were produced by meteoroid impacts. Calculation of meteoroid flux based upon this hypothesis has not yet been completed.

Few, if any, of the observed signals have patterns normally observed in recordings of seismic activity on earth (with the possible exceptions of volcanic tremors and landslide signals). Distinct phases corresponding to the various types of body and surface waves are not as apparent in any of the recorded seismic signals, and most wave trains are of long duration with less phase correlation between components than in the case of the earth.

The unexpected long duration of most of the observed signals must be explained either by a prolonged source mechanism or as a propagation effect. Prolongation

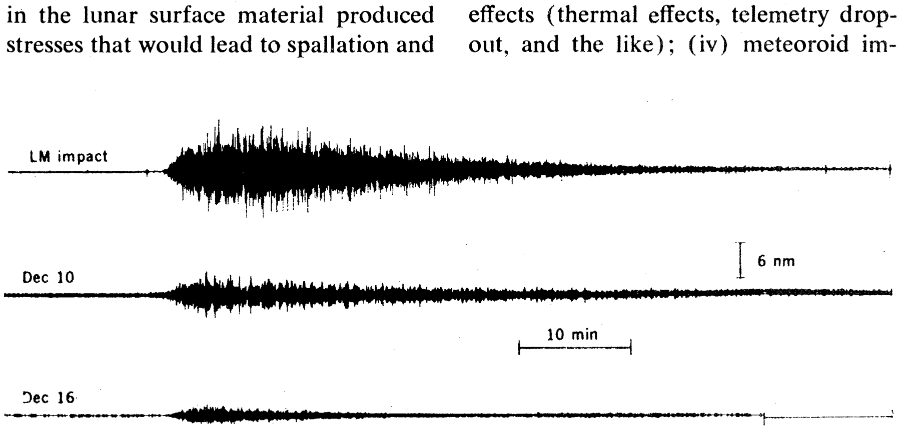

Fig. 2. Seismic signals received on the LP (long-period) vertical component seismometer from the LM impact and from natural sources on 16 December 1969.

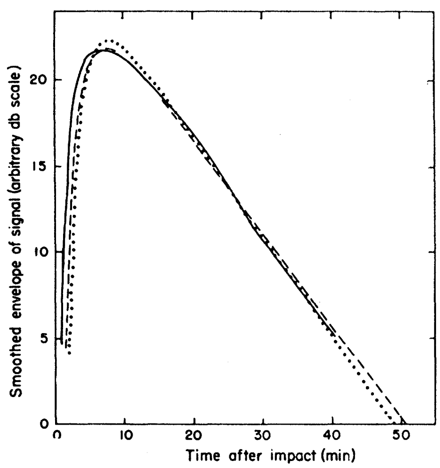

Fig. 3. Observed envelope of wave train received from the LM impact compared with the envelope predicted by diffusion theory. Solid line, observed; dashed line, two-dimensional ($vl = 5$ km^2/sec, $Q = 3600$); dotted line, three-dimensional ($vl = 7$ km^2/sec, $Q = 3600$ at 1 hz).

of an impact source might occur if the impact debris fell in the vicinity of the seismometers or if the debris triggered landslides. The small amount of debris thrown out by the LM impact weakens this hypothesis. A remote possibility is prolongation by collapse of "fairy castle" structures due to seismic waves excited by impacts.

The seismic signal detected from the Apollo 12 LM impact (Fig. 2) demonstrated that prolonged wave trains can be produced on the moon by relatively small impulsive sources. This result is important to our interpretation of the long reverberation as a propagation effect. It could be explained by postulating extremely low attenuation (high Q) for the moon. Although the evidence for this is hard to deny, this phenomenon raises some difficult questions as to its mechanism. Regardless of the explanation of signal duration, the similarity between the impact signal and other prolonged signals suggests that the latter were produced by meteoroid impacts or by near-surface moonquakes at ranges mostly within 100 km of the seismometer.

One hypothesis that could explain the signal character of L phases is that the moon not only has a high Q but also is very heterogeneous, at least in its outer regions. Heterogeneity is also implied by surface evidence. The scattering of seismic waves that would occur through a highly heterogeneous material would tend to increase the duration of the observed seismic wave and to suppress the appearance of distinct phases within the wave train. A medium which shows high Q and high scattering efficiency is unlike anything observed within the earth. Cold blocks of different composition in welded contact might show these properties. A welded aggregate might scatter seismic waves and still maintain high Q. Whatever the mechanism turns out to be, it will provide important evidence concerning the origin and evolution of the lunar interior.

In a highly heterogeneous medium, seismic waves may be scattered to the extent that propagation might properly be described by diffusion theory in which seismic energy "flow" is proportional to the gradient of energy density. If we define a characteristic length, l, as the distance over which ½ of the outward radiating seismic energy is reflected back toward the source, the flow of seismic energy is given by

$$\frac{\delta E}{\delta t} = \tfrac{1}{4} v l \Delta^2 E \qquad (1)$$

where E is seismic energy density and v is the average velocity of propagation. This is the diffusion equation with diffusion constant

$$D = \tfrac{1}{4} v l \qquad (2)$$

The solution of Eq. 1 leads to amplitude-time functions shown in Fig. 3. It can be seen that diffusion theory accurately predicts the observed signal amplitude for times long in comparison with the direct travel time (approximately 23.5 sec). Although this result does not verify the scattering hypothesis, it is sufficiently encouraging to warrant further consideration. More detailed analysis of this problem will be given in the Apollo 12 Mission Science Report.

Alternatively, a velocity-depth function might be found which could explain the character of these signals by ray theory without resort to a scattering mechanism. Some preliminary calculations show that this may be a possibility.

In interpreting present data, we are not concerned with the structure of the moon's deep interior, since most of the recorded events appear to have occurred at relatively short ranges. The relatively thick zone of self-compaction in which elastic wave velocity increases with depth would be perhaps 20 to 40 km thick. The large increase in velocity with depth results in a surface sound channel which may carry the seismic energy of these events. The impact of the S-IVB (third stage of the Apollo booster) planned for April 1970 at a range of 200 km should enable us to extend our interpretation to depths approaching 50 km into the moon. It will also be of great importance to see whether the same propagation effects are observed in nonmaria (highland) regions.

Because of the high sensitivity at which the instrument was operated, many distinctive seismic events would have been detected if the moon had seismic activity and transmission characteristics similar to those of the earth. The fact that a large number of seismic events of familiar earth types were not observed during 21 days of operation is a major result. If lunar seismicity is much lower than that of the earth, this would imply the absence of tectonic processes within the moon similar to those associated with major crustal movements on earth. This, in turn, implies lower thermal energy in the lunar interior than is present in the interior of the earth. When a seismic array is established on the moon more details on structure and seismicity will become evident.

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