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MOONQUAKES AND LUNAR TECTONISM*

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Abstract. With the succesful installation of a geophysical station at Hadley Rille, on July 31, 1971, on the Apollo 15 mission, and the continued operation of stations 12 and 14 approximately 1100 km SW, the Apollo program for the first time achieved a network of seismic stations on the lunar surface. A network of at least three stations is essential for the location of natural events on the Moon. Thus, the establishment of this network was one of the most important milestones in the geophysical exploration of the Moon.

The major discoveries that have resulted to date from the analysis of seismic data from this network can be summarized as follows:

(1) Lunar seismic signals differ greatly from typical terrestrial seismic signals. It now appears that this can be explained almost entirely by the presence of a thin dry, heterogeneous layer which blankets the Moon to a probable depth of few km with a maximum possible depth of about 20 km. Seismic waves are highly scattered in this zone. Seismic wave propagation within the lunar interior, below the scattering zone, is highly efficient. As a result, it is probable that meteoroid impact signals are being received from the entire lunar surface.

(2) The Moon possesses a crust and a mantle, at least in the region of the Apollo 12 and 14 stations. The thickness of the crust is between 55 and 70 km and may consist of two layers. The contrast in elastic properties of the rocks which comprise these major structural units is at least as great as that which exists between the crust and mantle of the earth. (See Toksőz *et al.*, p. 490, for further discussion of seismic evidence of a lunar crust.)

(3) Natural lunar events detected by the Apollo seismic network are moonquakes and meteoroid impacts. The average rate of release of seismic energy from moonquakes is far below that of the Earth. Although present data do not permit a completely unambiguous interpretation, the best solution obtainable places the most active moonquake focus at a depth of 800 km; slightly deeper than any known earthquake. These moonquakes occur in monthly cycles; triggered by lunar tides. There are at least 10 zones within which the repeating moonquakes originate.

(4) In addition to the repeating moonquakes, moonquake 'swarms' have been discovered. During periods of swarm activity, events may occur as frequently as one event every two hours over intervals lasting several days. The source of these swarms is unknown at present. The occurrence of moonquake swarms also appears to be related to lunar tides; although, it is too soon to be certain of this point.

These findings have been discussed in eight previous papers (Latham *et al.*, 1969, 1970, 1971) The instrument has been described by Latham *et al.* (1969) and Sutton and Latham (1964). The locations of the seismic stations are shown in Figure 1.

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1. Characteristics of Lunar Seismic Signals

Signals having both man-made and natural origins have been detected by the Apollo seismic network. The man-made signals are generated by astronaut surface activities and the impacts of the LM ascent stage and the third (S–IVB) stage of the Apollo booster from each mission. The natural signals are moonquakes and meteoroid impacts. Several hundred natural events are recorded per month. Most of these are very small moonquakes (see Moonquake Swarm Activity).

All natural and artificial (LM and S–IVB impacts) seismic signals are similar to each other, but are strikingly different from normal terrestrial seismic recordings. Two examples are shown on compressed time scales in Figure 2. Their most striking characteristic is exceedingly long duration. Signals from the larger man-made impacts continue for over 4 hr. All signals show gradual increase and decrease in signal intensity. The lunar signals are complex with little correlation between any two components of ground motion. The succession of body-wave and surface-wave phases familiar on Earth records is absent or very weakly developed in the lunar signals. These lunar signal characteristics appear to be adequately explained by assuming the presence of a heterogeneous surface layer that blankets the Moon to a probable depth of several km with a maximum thickness of 20 km. Seismic waves with the observed wavelengths are intensively scattered within this zone. Seismic wave velocities and absorption of seismic energy are both quite low in the scattering zone. It is probable that the acoustic properties of this zone can be attributed predominantly to cratering processes and the nearly complete absence of fluids in the material. The lower boundary of the scattering zone is the depth below which the rock, conditioned by pressure, transmits seismic waves without significant scattering.

The presence of the scattering zone accounts for two features of lunar seismic signals that earlier puzzled the experiment team: (1) the absence of normal surface waves (Love waves and Rayleigh waves); and (2) the poor definition or total absence of identifiable surface-reflected body waves, particularly from deep Moonquakes.

Surface waves, with wavelengths, of the order of the thickness of the scattering zone and smaller will quickly scatter into body waves within the scattering zone, and will thus propagate only to very short ranges. Surface waves long enough to propagate coherently (signal periods greater than about 5 s) would be generated only by events larger than any that have occurred during 20 months of observation. Such events must be rare.

A thin surface zone of intensive scattering coupled with a rapid increase of seismic velocity with depth will make the lunar surface a very poor reflector for seismic waves incident on the surface from the lunar interior. In such a structure, a very small proportion of the incident seismic energy follows the simple ray path of total reflection. Most of the energy is trapped in the surface region and leaks out slowly as from a primary surface source. As a result, no sharp increase of seismic energy is observed at a time when a surface-reflected seismic phase, such as PP or SS, is expected from an event at a large distance. Phases corresponding to surface-reflected P and S waves have been tentatively identified in several of the LM and S–IVB signals, but they are poorly defined.

Learning to distinguish between signals from meteoroid impacts and moonquakes is clearly a necessary first step in lunar seismology and is somewhat equivalent to the problem of distinguishing earthquakes from explosions on Earth. The criteria used for classifying seismic signals have been discussed in earlier papers (Ewing *et al.*, 1971; Latham *et al.*, 1971a, b). Briefly, the signal characteristics which are most useful in distinguishing a moonquake from a meteoroid impact are the presence or absence of an 'H-phase', and the time from the beginning of the signal to the maximum signal amplitude (rise time). Signals from moonquakes have relatively short rise times and contain the H-phase. The H-phase is a strong group of waves with a relatively sharp beginning, generally stronger on the horizontal components than on the vertical, suggesting a shear wave mechanism. The H-phase often contains lower frequencies than other portions of record, peaking near the 0.5 Hz natural frequency of the seismometers. The maximum amplitude of the moonquake signal envelope is either at or a few minutes after H (see Fig. 2).

In contrast with events containing an H-phase, are numerous events (designated C-events) which have very emergent beginnings, smoothly varying envelope amplitudes with relatively long rise times, and no abrupt changes in signal frequency and amplitude. These being also the characteristics of artificial impact signals, C-events are believed to be meteoroid impacts.

Some of the moonquake signals are found to fall into groups of matching signals (designated A events), members of each group having precisely identical waveforms. Ten groups of such matching signals (designated A_1 through A_{10}) have been found. This property has been discussed previously (Latham *et al.*, 1970, 1971 a, b; Ewing *et al.*, 1971) as indicating a repeating moonquake focus to be the source of each group of matching signals. The energy detected from one source, the A_1 zone, greatly exceeds that detected from the remaining nine focal zones. Most of the moonquakes occur during episodes of greatly increased activity, called moonquake swarms. Individual events of these swarms are very small and, unlike the category A moonquakes, do not match one another for those signals that are large enough to permit detailed comparisons of their waveforms.

2. Location and Focal Mechanism of Moonquakes

Moonquakes detected at the Apollo 12 and 14 stations prior to the Apollo 15 mission, are believed to have originated at no less than 10 different foci, although some of these may be quite close to one another. A single focus (A_1 zone), however, accounts for nearly 80% of the total detected seismic energy. Two moonquakes from the A_1 zone were recorded by the three stations of the Apollo seismic network during the first two perigee periods following activation of the Apollo 15 station: one moonquake at each perigee. Both moonquakes are small to intermediate in size relative to the range of A_1 signal amplitudes detected thus far. P-waves from these events arrive at station 12 1.8 s earlier than at station 14, but cannot be detected at station 15. Shear waves (H-phase) arrive first at station 12, and 3.4 s and 113.9 s later at stations 14 and 15, respectively. Using these arrival times and a lunar model derived from the artificial impact data, the epicenter (point on the surface directly above the moonquake focus) is located in Figure 1. The depth of the focus is approximately 800 km:

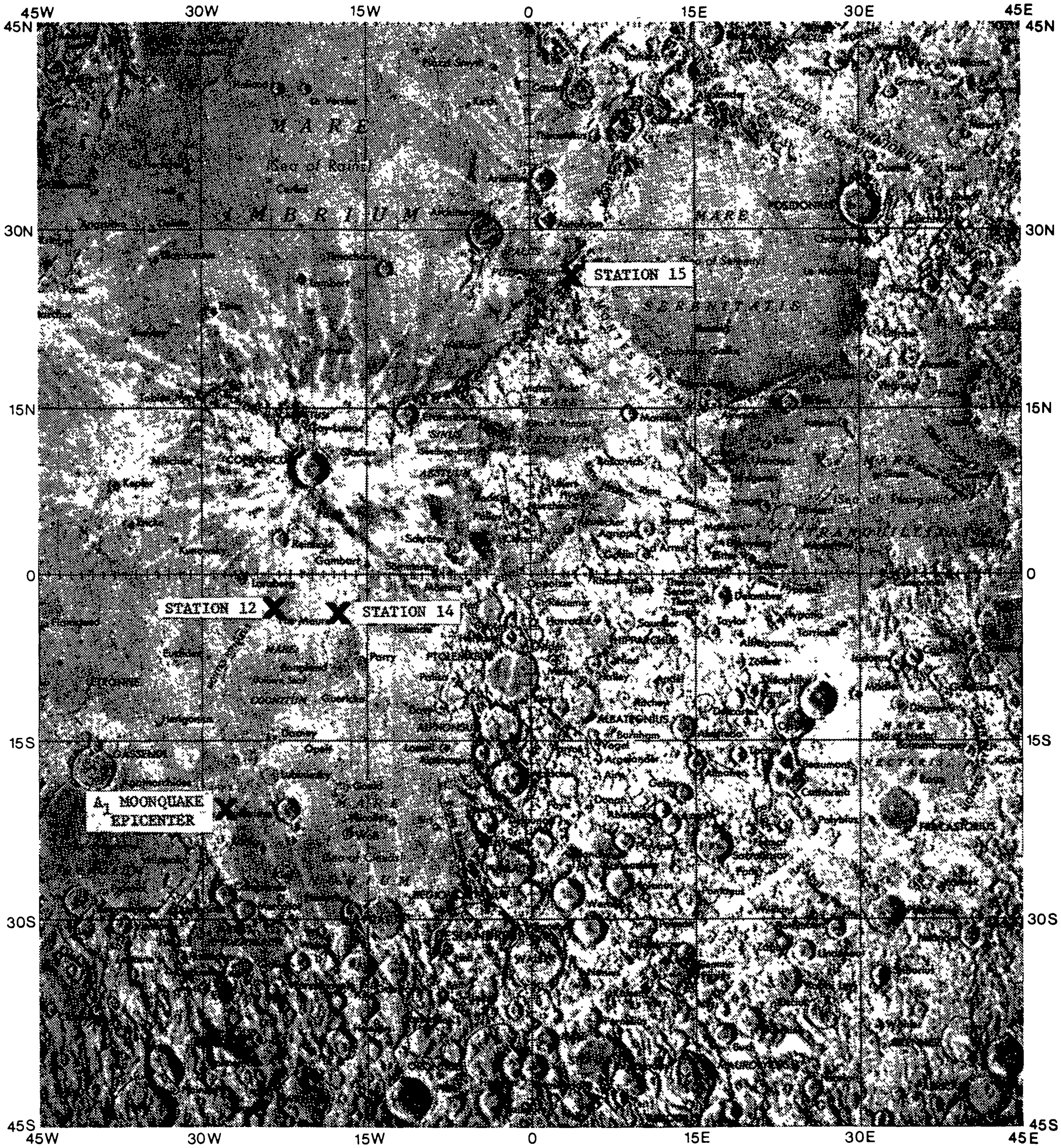

Fig. 1. Locations of the Apollo seismic network stations and the epicenter of most active source of moonquakes (A_1 zone).

a little deeper than any known earthquake. The remaining moonquake foci have not yet been located.

The source of strain energy released as moonquakes is not known; but, if significant depth of focus for all moonquakes is verified by future data, it will have profound implications concerning the lunar interior. In general, this result would require: (1) that the shear strength of the lunar material at a depth of 800 km must be large

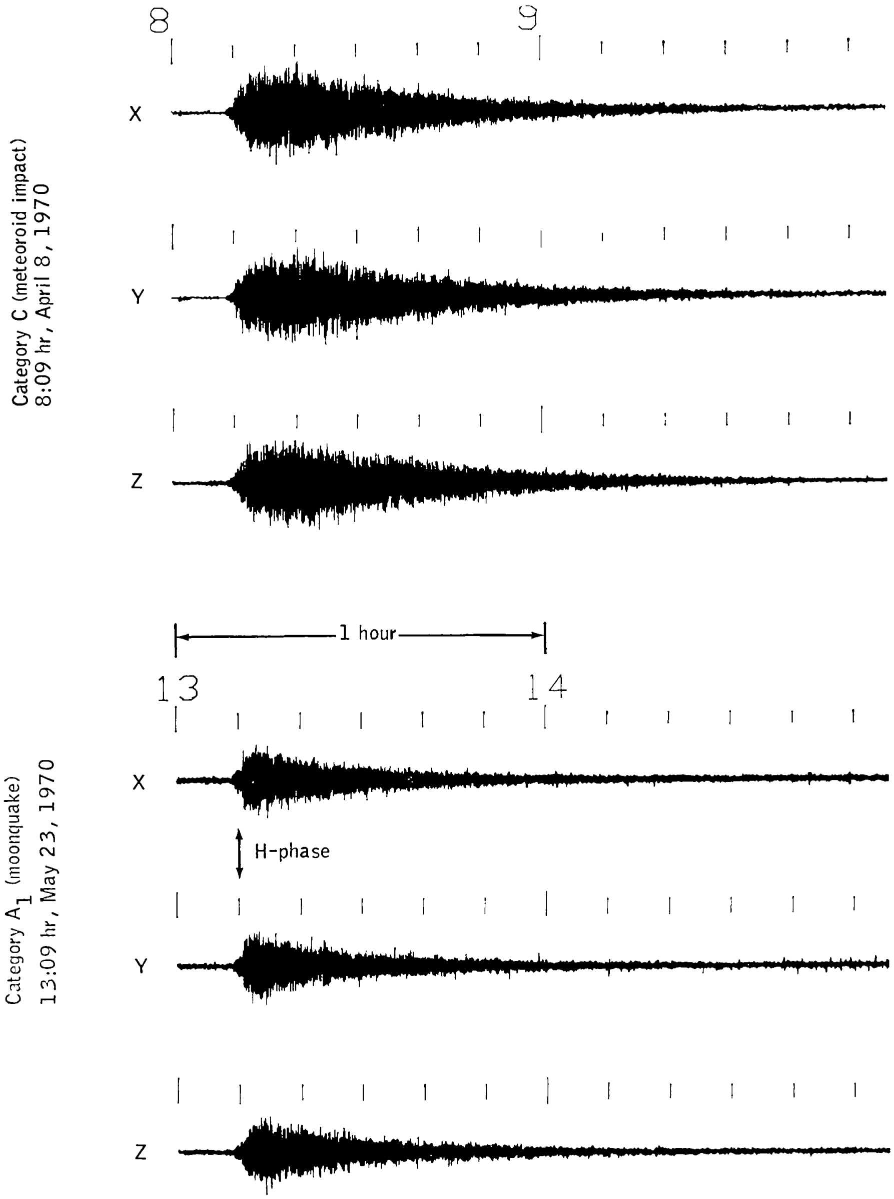

Fig. 2. Compressed time-scale records of two of the lunar seismic events believed to be of natural origin recorded at station 12. Z is the vertical component seismometer; X and Y are the horizontal component seismometers. The moonquake, event of 13:09 hr., May 23, 1970, originated within the zone of greatest activity (A_1 zone). The H-phase is prominent on the seismograms from the horizontal component seismometers for category A_1 events. This phase is tentatively identified as the direct shear wave arrival. The event of 8:09 hr., April 8, 1970, is believed to be a meteoroid impact (category C event).

enough to sustain appreciable stress; and (2) that maximum stress differences originate at this depth. These conditions place strong constraints on the temperature distribution in the deep lunar interior.

The nearly exact repetition of moonquake signals from a given focal zone over periods of many months requires that the focal zones be small, 10 km in diameter or less, and fixed in location over periods approaching two years. If moonquake foci were separated by as much as 1 wavelength, larger differences would be observed among moonquake signals.

As noted previously (Latham *et al.*, 1970, 1971a, b), the category *A* moonquakes occur in monthly cycles near times of apogee and perigee. This suggests that they are triggered by lunar tides. This hypothesis is strengthened by the observation that the total seismic energy release and the interval between the times of occurrence of the first moonquakes each month and perigee, both show 7-month periodicities which also appear in the long-term gravity variations. With a few possible exceptions, the polarities of signals belonging to a set of matching events are identical. This implies that the source mechanism is a progressive dislocation and not one that periodically reverses in direction. It is conceivable, of course, that detectable movements in one direction are compensated by many small, undetectable movements in the opposite direction. A progressive source mechanism suggests a secular accumulation of strain periodically triggered by lunar tides. Whether this strain is local, regional, or moonwide is an intriguing problem for further study. Several possible sources are (1) slight expansion of the Moon by internal radiogenic heating or slight contraction on cooling; (2) a gradual settling of the lunar body from an ellipsoidal form to a more nearly spherical form as the Moon gradually recedes from the Earth; (3) localized strains due to uncompensated masses; or (4) localized thermal stresses.

For samples of earthquake data, the cumulative amplitude curves often have a nearly linear slope known as the b-value. The *b*-values measured for tectonic earthquakes are normally close to 1. The *b*-values of moonquake data (Latham *et al.*, 1971c) are approximately 2. Higher *b*-values, as measured for moonquakes, are typical of one class of earthquakes – those associated with volcanic activity, which are presumably generated by subsurface movements of magma.

Laboratory experiments have demonstrated that high *b*-values are associated with microfracturing in rock samples subjected to small mechanical stresses (Scholz, 1968); and with cracking from thermal stresses induced by heating and cooling of samples (Warren and Latham, 1970). High *b*-values are also measured in laboratory tests when two surfaces are rubbed together under high pressure (Nakamura *et al.*, 1971). Thus, while no definite conclusion regarding the focal mechanism of moonquakes can be based on *b*-value data alone; comparison with laboratory experimental data and seismic measurements for earthquakes suggests that moonquakes may be generated by (1) thermal stresses, possibly of volcanic origin; (2) tectonic stresses at low stress levels; or (3) dislocations along pre-existing fractures. These suggestions are obviously of the most tentative nature, but they serve as hypotheses against which future data will be tested.

3. Moonquake Swarm Activity

One of the most significant discoveries of lunar seismology to date is the observation of moonquake swarms. Each swarm is a distinctive sequence of moonquakes closely grouped in space and time, generally containing no conspicuous event. Figure 3 shows the lunar seismic activity detected during the period April 7 to May 10, 1971 by the Apollo 12 and 14 LP seismometers. Two major and two or three minor moonquake swarms occurred during this internal. Other swarms were observed between May 16 to 20 and May 25 to 29. A moonquake swarm is characterized by an abrupt beginning and ending of activity. Events are recorded at a nearly constant rate of 8 to 12 per day during the swarm, as compared to 1 to 2 per day between periods of swarm activity. Swarm activity shows a semi-monthly periodicity. Thus, swarm events also appear to be triggered by lunar tides.

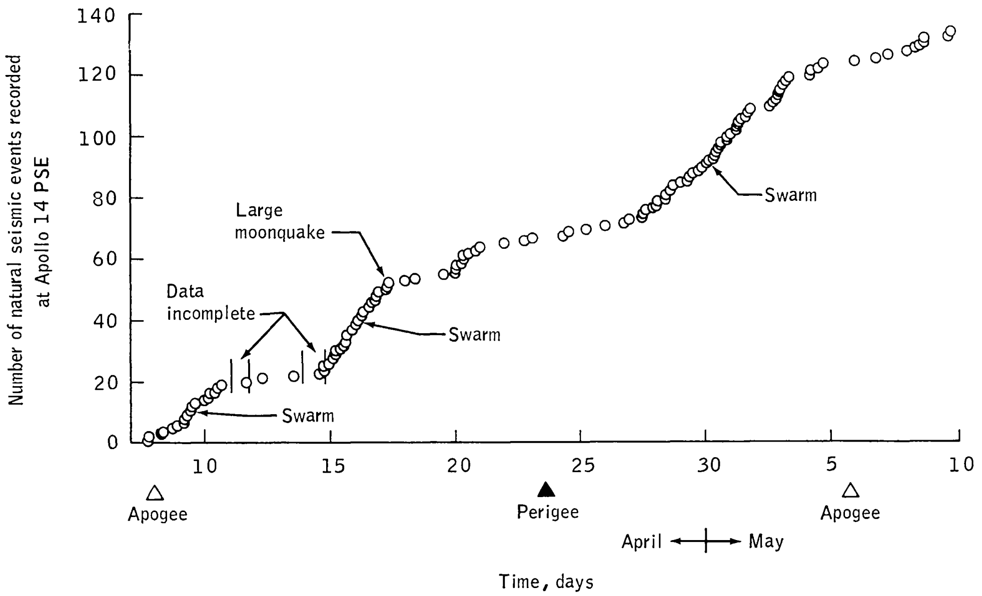

Fig. 3. Cumulative number of seismic events detected by the long-period seismometers at the Apollo 14 station as a function of time for the period April 7 to May 10, 1971. All events observed during this interval are included. Moonquake swarms appear as abrupt increases in the cumulative number of events. During periods of swarm activity, a rate of 8 to 12 events per day is observed as compared to the normal rate of 1 to 2 events per day.

Swarm events possess all of the characteristics of the category A moonquakes except one: they do not appear to have matching waveforms. Thus, while the pattern of activity strongly suggests that individual events of a given swarm are closely related, the moonquake foci must be distributed throughout a relatively large, active zone. By contrast, no large differences in the category A_1 moonquake signals recorded at station 12 have been observed over a period of 20 months. Thus, while the dimensions of the category A_1 focal zone is thought to be of the order of 1 wavelength (10 km) or less, the non-matching swarms events must be separated by at least 1 wavelength or more. From this, a swarm of thirty moonquakes must be distributed throughout a minimum voume of about 10^4 km^3, or they may occur within a planar or linear zone of larger dimensions.

The *b*-values, or slopes of the cumulative amplitude distributions, for the swarms discussed here fall in the range 2.1 to 2.4; close to the average value of 2 measured for the larger, periodic moonquakes.

An unusual swarm began on April 14 with recorded events occurring at a nearly constant rate of 12 per day while the average amplitude of the signals increased with time for a period of about 2 days. On April 17, following a 9 hr break in activity, three large moonquakes occurred, the last being the largest ever recorded. No significant aftershock activity was observed. The largest moonquake, though well-recorded by the Apollo 12 and 14 stations, preceded deployment of station 15, and its exact location therefore remains uncertain. However, by assuming that it occurred at a depth of 800 km, as estimated for category A_1 moonquakes, an epicenter of latitude 20° N and longitude 72° E is obtained. This location is about 2700 and 2900 km from the Apollo 14 and Apollo 12 sites, respectively. The Richter magnitude of this moonquake is about 2 to 3 depending on the method of calculation used. The largest category A_1 moonquake observed to date had a magnitude of about 1 to 2. The average swarm moonquake in this sequence was comparable in magnitude to a small to intermediate category A_1 moonquake. The buildup in the amplitude of events during the swarm suggest that they are indeed related. However, large moonquakes are not associated with any of the other swarms observed to date.

Similar swarms are common in volcanic regions of the earth where they often occur before, during and after eruptions. They are also observed in areas of geologically recent, but not current, volcanism. Sykes (1970) reports that earthquake swarms frequently occur along the crestal zones of mid-oceanic ridges which are centers of sea-floor spreading and abundant submarine volcanism. Swarms also precede most of the major volcanic eruptions in the Lesser Antilles (Robson *et al.*, 1962). They may also be observed in non-volcanic areas, where they are believed to represent minor adjustment of crustal blocks to local stress conditions. Sometimes, a swarm precedes a large tectonic earthquake. Whether related to volcanism or not, all earthquake swarms are thought to be of shallow origin. With such relationships in mind, the data on moonquake swarms and matching moonquakes will be examined with great interest as clues to present lunar tectonism.

4. Moonquakes and Lunar Tectonism

As discussed above, it now appears certain that seismic energy release related to tides does occur within the Moon. However, the magnitudes of these events and their numbers are small in comparison to the total seismic activity which would be recorded by equivalent seismic station on earth. Estimated energy release from the largest moonquakes ranges between 10^9 and 10^{12} ergs. The total energy released by moonquakes, if the Apollo 12 region is typical of the entire Moon, is about 10^{11} to

10^{15} ergs per year. This compares with about 5×10^{24} ergs per year for total seismic energy release within the earth. Considerable uncertainty exists in this estimate, owing primarily to the difficulty of estimating the ranges of natural events and the possible contribution of small, undetectable moonquakes. However, the average rate of seismic energy release within the Moon is clearly far below that of the Earth. Thus, internal convection currents leading to significant lunar tectonism are probably absent. Further, the absence of conspicuous offset surface features and of compressional features such as folded mountains, is evidence against significant lunar tectonic activity; past or present. This conclusion is further strengthened by comparing heat flow and seismic energy release. The mechanism for generation of earthquakes is ultimately related to the flow of heat outward from the interior to the surface. The total annual heat flow for the Earth is approximately 10^{28} ergs; a factor of about 10^3 larger than the annual seismic energy release in the Earth. The total annual flow of heat for the Moon, assuming that the Apollo 15 measurement is representative of the average value for the entire lunar body (a very big assumption, but good enough for purposes of this discussion) is about 4×10^{26} ergs (Langseth *et al.*, 1972). This is a factor of between 10^{11} and 10^{15} larger than the present estimate of annual lunar seismic energy release. From this comparison it is evident that the dynamic response of the lunar interior to the available thermal energy is far below that of the earth. Presently, the outer shell of the Moon appears to be relatively cold, rigid, and tectonically stable compared to the Earth except for the minor disruptive influence correlated with lunar tides. However the presence of moonquake swarms suggests that there may be continuing minor adjustment to crustal stresses.

5. Conclusions

(1) Natural lunar seismic events detected by the Apollo seismic network are moonquakes and meteoroid impacts. The moonquakes fall into two categories: (1) periodic moonquakes, and (2) moonquake swarms. All of the moonquakes are small (maximum Richter magnitudes between 2 and 3). With few exceptions, the periodic moonquakes occur at monthly intervals near times of perigee and apogee and show correlations with longer-term (7-month) lunar gravity variations. They originate at not less than 10 different locations. However, a single focal zone accounts for 80% of the total seismic energy detected. The epicenter of the active zone has been tentatively located at a point 600 km SSW from the Apollo 12 and 14 stations. The focus is approximately 800 km deep. Each focal zone must be small (less than 10 km in linear dimension). Changes in record character that would imply migration of the focal zone or changes in focal mechanism have not been observed in the records over a period of 20 months. Cumulative strain at each location is inferred. Thus, the moonquakes apear to be releasing internal strain of unknown origin, the release being triggered by tidal stresses. The occurrence of moonquakes at great depths implies that (1) the lunar interior at these depths is rigid enough to support appreciable stress, and (2) that maximum stress differences occur at these depths. If the

strain released as seismic energy is of thermal origin, this places strong constraints on acceptable thermal models for the deep lunar interior.

(2) Episodes of frequent small moonquakes, called moonquake swarms, have been observed. The occurrence of such swarms also appears to be related to the lunar tidal cycle. The source of moonquake swarms has not been determined.

(3) The average rate of seismic energy release within the Moon is far below that of the Earth. Thus, internal convection currents leading to significant lunar tectonism appear to be absent. Presently, the outer shell of the Moon appears to be relatively cold, rigid, and tectonically stable compared to the Earth. However, the occurrence of moonquakes at great depth leaves open the possibility there may be very deep, weak convective motion. Moonquake swarms may be generated within the outer shell of the Moon as a result of continuing minor adjustments to crustal stresses.

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