Reports

Moonquakes

Abstract. *Although the average rate of seismic energy release within the moon appears to be far below that of the earth, over 100 events believed to be moonquakes have been recorded by the two seismic stations installed on the lunar surface during Apollo missions 12 and 14. With few exceptions, the moonquakes occur at monthly intervals near times of perigee and apogee and show correlations with the longer-term (7-month) lunar gravity variations. The repeating moonquakes are believed to occur at not less than 10 different locations. However, a single focal zone accounts for 80 percent of the total seismic energy detected. This active zone appears to be 600 kilometers south-southwest of the Apollo 12 and 14 sites and deep within the moon. Each focal zone must be small (less than 10 kilometers in linear dimension) and fixed in location over a 14-month period. Cumulative strain at each location is inferred. Thus, the moonquakes appear to be releasing internal strain of unknown origin, the release being triggered by tidal stresses.*

Seismic stations were installed on the lunar surface by the Apollo astronauts at three locations during missions 11, 12, and 14 as part of an integrated set of geophysical experiments called ALSEP (Apollo Lunar Surface Experiment Package). The Apollo 11 station operated for about 21 days before a failure in the command receiving system terminated operation. Stations 12 and 14 have been operating since November 1969 and January 1971, respectively, and are presently operating concurrently. Each station contains four seismometers. Three of them form a matched set sensitive to long-period horizontal motion in two perpendicular directions (LPX and LPY) and vertical motion (LPZ). The natural period of these seismometers is adjustable by command to either 15 seconds or 2.2 seconds, and they are now being operated at 2.2 seconds. The fourth seismometer is sensitive to short-period vertical motions (SPZ) and has a natural period of 1 second. This seismometer is not functioning in the Apollo 12 station. Owing to the extreme quietness of the lunar surface and the high sensitivities of these instruments, it is possible to detect motions of the lunar surface as small as 1 Å. Digital data are transmitted continuously from the lunar stations to receiving stations on Earth and are stored on magnetic tape for analysis.

A large number of seismograph stations, such as those operating on Earth, is not practical for the lunar network, but some fundamental facts concerning the dynamics and structure of the moon and meteoroid flux can be derived from the relatively limited data at hand. Results from the Apollo seismic experiment have been presented by the seismic experiment team in seven reports (*1–4*). The experiment itself has been described by Latham *et al.* (*5*). Here we discuss events believed to be of internal origin, that is, moonquakes.

Seismic signals from 272 events of natural origin have been recorded by the LP seismometers of station 12 during the first 398 days of operation, an average of about one event every 1.5 days. During the first 44 days of operation, the Apollo 14 station LP components detected 79 events, 31 of which were recorded at the Apollo 12 station as well. Station 14 has recorded all events detected at station 12 during the period of simultaneous operation. The ratio of amplitudes at station 14 to those at station 12 averages about 2 to 1 for all events recorded at both stations. The ability of station 14 to record events not detected by station 12 is apparently a matter of higher sensitivity resulting from the weaker elastic structure of the lunar subsurface at station 14 as compared to station 12. This difference is consistent with known differences in the geologic setting of the two stations.

Hundreds of signals with a great

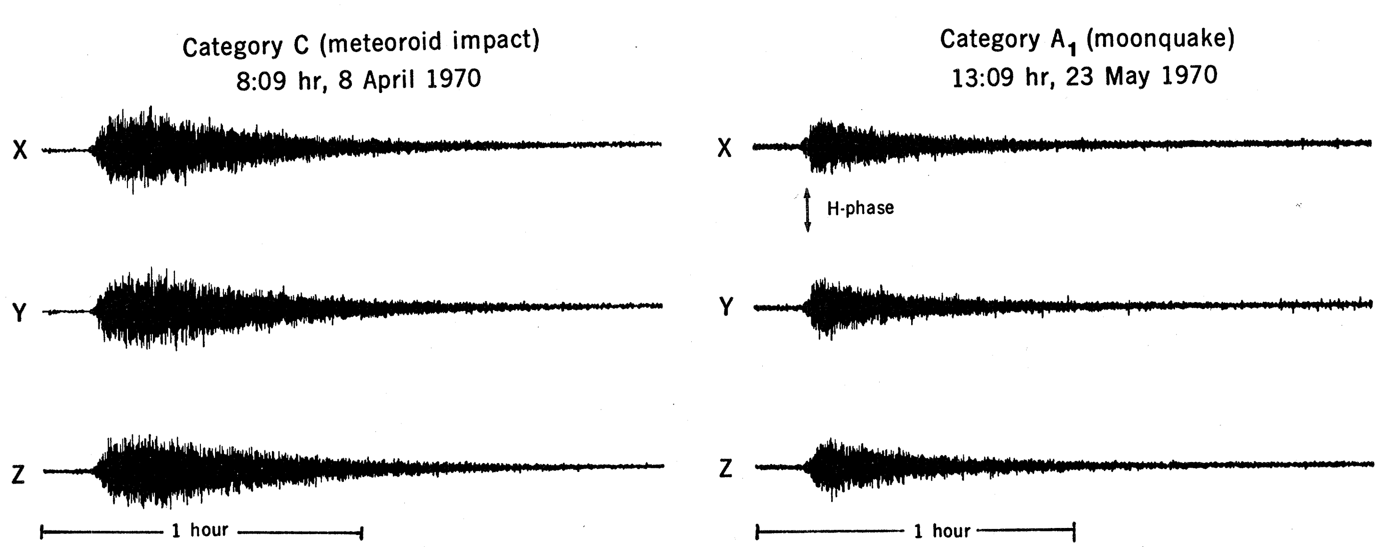

Fig. 1. Compressed time-scale records of two of the lunar seismic events believed to be of natural origin, recorded at station 12; *Z* refers to the vertical component seisometer, *X* and *Y* to the horizontal component seismometers. The moonquake, event of 13:09 hr, 23 May 1970, originated within the zone of greatest activity (A_1 zone). For category A_1 events, the H phase is prominent on seismograms from the horizontal component seismometers. This phase is tentatively identified as the direct shear wave arrival. The event of 8:09 hr, 8 April 1970, is believed to have been a meteoroid impact (category C event).

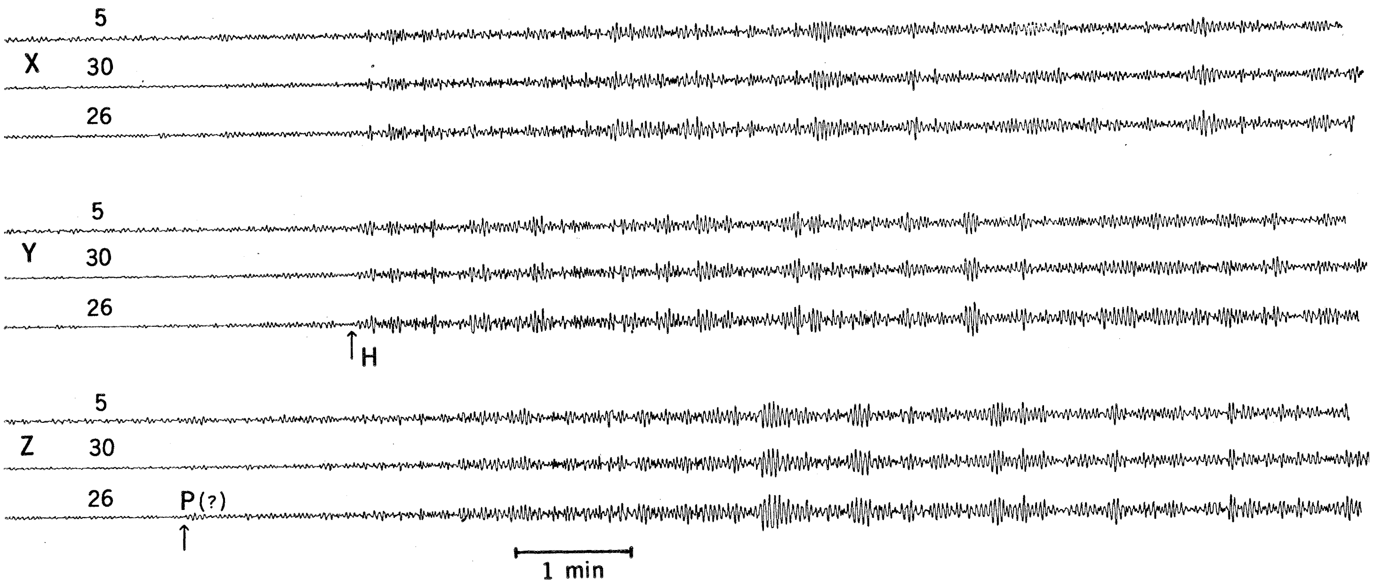

Fig. 2. Records of three of the matching seismic events detected at the Apollo 12 site on 6 January 1970 (event 5), 26 April 1970 (event 26), and 23 May 1970 (event 30). These three moonquakes originated within the zone of greatest activity (A_1 zone) detected thus far. The most prominent phases are tentatively interpreted as the direct compressional wave (P wave) and shear wave (H wave) arrivals.

variety of shapes and sizes have been recorded by the SPZ seismometer at station 14. Most of these events are attributed to venting of gases and thermoelastic "popping" within the metal structure of the lunar module (LM) descent stage located 178 m from the seismic station. However, since the SPZ seismometer is not operational at station 12, we will confine the present discussion to data from the LP seismometers.

Signals from four man-made impacts at accurately known times and distances from the seismic stations have also been recorded—the impacts of the Apollo 12 and 14 LM ascent stages and the third stage (S-IVB) of the Saturn boosters from missions 13 and 14. The impacts occurred between 67 and 172 km from the Apollo 12 and 14 seismic stations. These known impacts were necessary keys to the study of lunar seismology, because the records for them are utterly different from any obtained in observations on the earth. An analysis of the impact signals has been given by Latham *et al.* (*3*).

All natural and artificial lunar seismic signals are similar to each other, but they are strikingly different from normal terrestrial seismic recordings. Two examples are shown on compressed time scales in Fig. 1. Their most striking characteristic is their exceedingly long duration. Signals from the larger man-made impacts continue for over 4 hours. 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 are believed to be due to intense scattering and low attenuation of seismic waves in the outer shell of the moon (*2*).

Two sources of natural seismic signals are expected: moonquakes and meteoroid impacts. Learning to distinguish them by signal characteristics is a necessary first step in lunar seismology, similar to the problem of distinguishing earthquakes from explosions on Earth. The most promising criteria discovered thus far are given below.

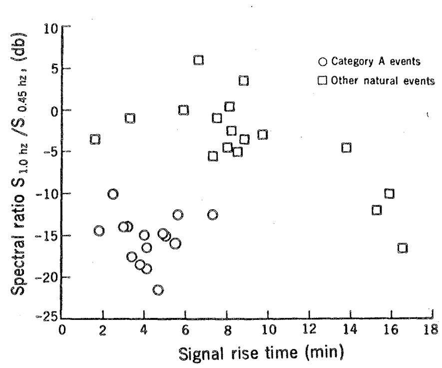

Fig. 3. Spectral ratio plotted as a function of signal rise time for natural events detected by the Apollo 12 LP seismometers. The rise time is measured from the beginning of the signal to the approximate peak of the signal envelope of the unfiltered seismogram. The ratios of the spectral amplitudes at 1.0 and 0.45 hz are not corrected for instrument response. To correct for instrument response, 16.5 db must be added to this scale. The symbols distinguishing the two categories of events were assigned by criteria other than the spectral ratio of this figure.

Wave form matching. Comparison has revealed that some of the lunar seismic signals match each other in nearly every detail for their entire duration. Ten sets of such matching signals (99 signals) have been identified out of the 272 signals recorded during the first 13 months of operation of the Apollo 12 station. These matching signals will be designated category A signals. The largest subset, A_1, contains 44 events and accounts for about 80 percent of the observed energy from matching events recorded at station 12. The A_6 subset contains seven events very similar in record character to the A_1 events. At least two A_1 events were recorded during the first month of operation of station 14. The records for three of the matching events are shown on an expanded time scale in Fig. 2. The identity of the signals for any component of ground motion is evident. The lack of similarity among the three components of motion is equally striking. A second set of signals, designated category C, has wave form characteristics similar to those of the artificial impacts, and these signals do not match each other.

Rise time. The time interval from the beginning of a seismic signal to the time of maximum signal amplitude (rise time) is generally much shorter for category A events than for category C events. For category A events, the rise time is nearly independent of frequency in narrow-band filtered playouts, whereas category C events and artificial impacts typically have frequency-dependent rise times.

Spectral characteristics. The seismic signals can be classified on the basis of spectra as low- and high-frequency signals. For example, on a graph of the ratio of the signal power at 1 hz to the signal power at 0.45 hz plotted against signal rise time (Fig. 3), the signals separate into A and C groups. Category C signals (also LM and S-IVB impact signals) are richer in higher frequencies than category A signals.

The H phase. The most prominent phases identifiable in the category A signals are designated P and H phases (Fig. 2). The P phase is the earliest detectable signal and is considered to be the direct compressional wave from the source; however, weaker signals may precede those being detected at the present time. The H phase, a stronger arrival on the seismometers sensitive to horizontal motion (LPX and LPY), begins about 100 seconds after the P phase. However, the indefinite beginning of the H phase does not permit a meaningful estimate of the difference in arrival time at the two stations. The H phase is not observed in category C signals or in artificial impact signals.

Time of occurrence. With few exceptions, the category A events occur at monthly intervals near the time of perigee, with a secondary peak in activity near apogee. The occurrence of category C events does not appear to be correlated with the orbital cycle.

The relative seismic energy detected by station 12 during the first 13 months of operation is plotted against time in Fig. 4. The bar graph in Fig. 4 represents the sums of the squares of the maximum trace amplitudes of the vertical component for signals in consecutive, nonoverlapping 2-day intervals. Category A activity peaks at monthly intervals near the time of perigee. About 85 percent of the seismic energy detected from category A events occurs in an interval from 4 days before to 3 days after perigee. Several A_1 events usually occur during each active period, and the first in each period is usually the largest.

In addition to the monthly cycle, longer-term variations in moonquake activity are apparent. As shown in Fig. 4, both the total monthly energy release due to A events and the time of occurrence, relative to perigee, of the first A event detected each month appear to vary systematically with time and with one another. Maximum energy is released during months when activity begins latest. Except for phase differences, these variations are similar to the long-term gravity variations, which are plotted in Fig. 4 for comparison. The period of these variations is about 213 days, which is in very good agreement with the theoretical 7-month gravity cycle. The phase relations between seismic activity and various gravity components require detailed examination with respect to internal viscosity and other factors.

Long-duration signals that are identical must traverse identical wave guides. This can occur in a complex, heterogeneous medium only if the events have a common point of origin. Meteoroids can be eliminated as a source because of their presumably random impact locations. It is also improbable that they would occur only in association with apogee and perigee. The tidal correlation of category A events suggests that they are moonquakes triggered by tidal strains. Ten subsets of category A events suggest at least ten distinct foci for the repeating moonquakes detected by the Apollo 12 and 14 seismic instruments. In contrast, the similarities between the LM and S-IVB impact signals and the category C signals suggest that the latter are generated by meteoroid impacts.

An important objective of the Apollo seismic experiment is locating the zone in which moonquakes originate. Similarities among the signals of several of the groups of matching events indicate that some of the ten moonquake foci mentioned above may be close to one another. The A_1 focus, however, accounts for about 80 percent of the

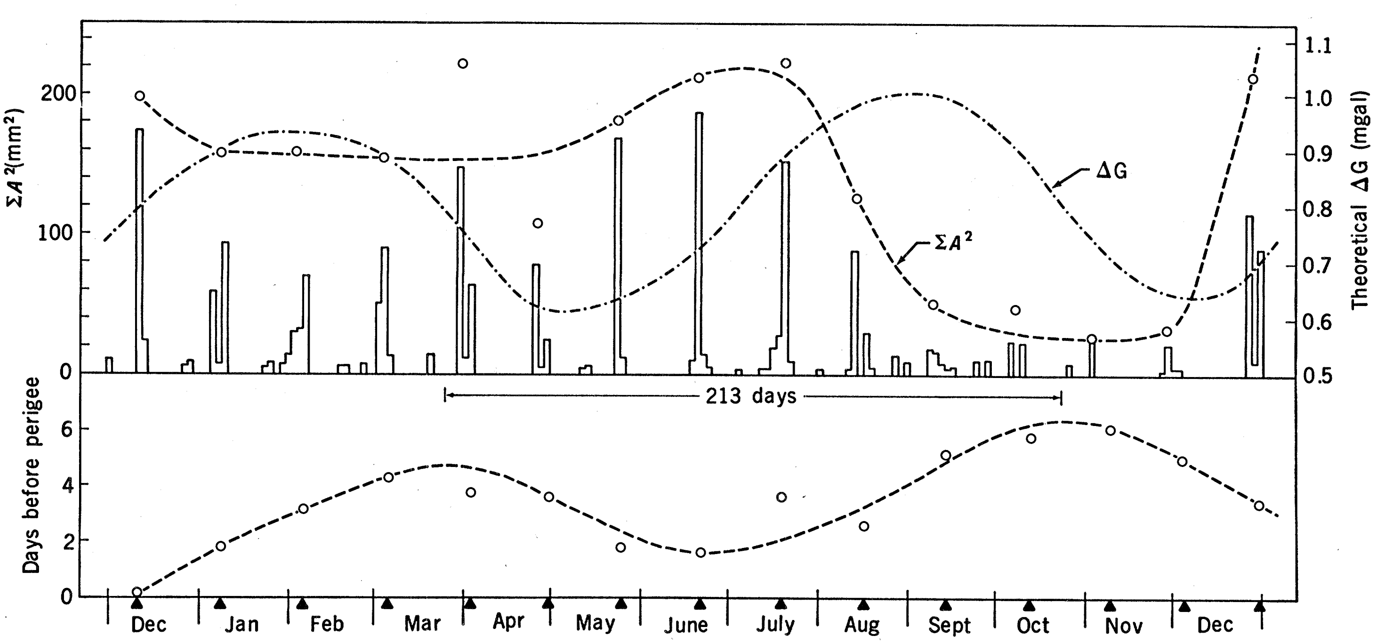

Fig. 4 Relative seismic energy from the LPZ component of the Apollo 12 seisometer as a function of time. A for an event is the maximum peak-to-peak amplitude (in millimeters) of the LPZ component. The height of each bar is the sum of A^2 for all events during a 2-day interval. For this instrument, 0.8 mm is 1 digital unit. The curve marked ΣA^2 is the total seismic energy observed at each perigee. ΔG is the theoretical earth-generated change in vertical gravitational acceleration at the Apollo 12 seismic station, calculated for a rigid spherical moon. The lower curve indicates the interval between perigee and the time of occurrence of the first category A_1 event observed each month. Times of perigee are indicated by solid triangles.

moonquake energy recorded at the Apollo 12 site. At least two A_1 moonquakes were recorded by the Apollo 12 and 14 instruments during the first perigee period following activation of the Apollo 14 station. The first detectable signals from these events arrived at the Apollo 12 site only 1.8 seconds earlier than at the Apollo 14 site. Thus, the A_1 zone is nearly equidistant from the two Apollo sites (slightly closer to the Apollo 12 site). With the uncertainty in the onset of H, the time interval between P and H phases is between 91 and 98 seconds at the Apollo 12 site and 102 and 107 seconds at the Apollo 14 site. We take the average interval as 100 seconds, and, interpreting the H phase as the direct shear (S) wave arrival, we obtain a ray path 600 to 700 km long between the Apollo 12 and 14 sites and the A_1 focus. This is the distance at which a 100-second interval occurs between the P and S travel times from man-made impact signals (*4*).

Several observations support the possibility that moonquakes originate at an appreciable depth within the moon: (i) by comparison with the man-made impact signals, the signals from moonquakes have rise times shorter than the minimum value expected from a surface source; (ii) the beginnings of the P and H phases in moonquake signals are relatively impulsive; (iii) the interval between the P and H phases is less complicated than the early parts of signals from known impacts; and

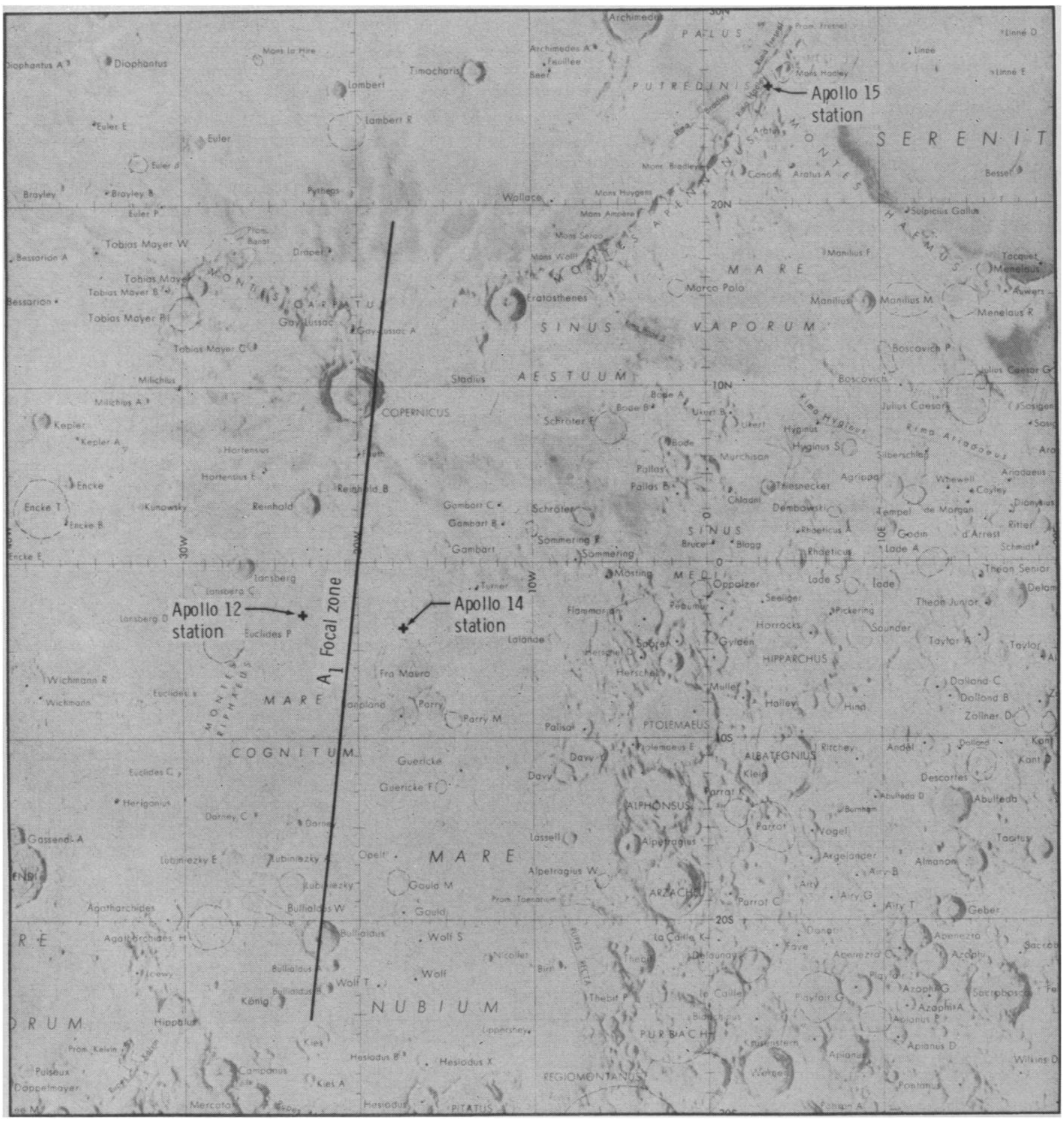

Fig. 5. Map showing locations of seismic stations 12 and 14. The dark line covers the zone (A_1 zone) of possible epicentral locations for the most active source of moonquakes detected thus far.

(iv) the P wave amplitudes are larger, relative to the maximum amplitudes in the wave train, for the moonquake signals, than for impacts. Corresponding characteristics are recognized in seismograms from deep earthquakes. One hypothesis that would explain these observations is that the source zones for moonquakes are located below the near-surface zone in which intense scattering of seismic waves takes place. Maximum depths of approximately 900 km are possible. Thus, based on present data, the focus for the most active source of moonquakes (A_1 zone) may be located as shown in Fig. 5. The operation of a third seismic station concurrently with stations 12 and 14 will make possible a more exact location of the A_1 focus. The successful installation of the Apollo 15 station, approximately 1100 km northeast of stations 12 and 14, has just been accomplished.

The source of strain energy released as moonquakes is not known, but if significant depth of focus for the moonquakes is verified by future data, it will have profound implications concerning the dynamics of the lunar interior.

Each focal zone must have dimensions of the order of 1 wavelength (10 to 20 km) or less and be fixed in location to about the same dimensions for periods of at least 1 year. If moonquake foci were separated by as much as 1 wavelength, larger differences would be observed among the signals recorded at station 12.

Data that bear on the focal mechanism for moonquakes are the polarities of the seismic signals and the cumulative distribution of moonquake amplitudes. With a few exceptions, the polarities of signals in 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 possible, of course, that detectable movements in one direction are compensated for 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 a problem for further study. Several possible sources are (i) slight expansion of the moon due to internal radiogenic heating or slight contraction on cooling; (ii) gradual settling of the lunar body from an ellipsoidal form to a more nearly spherical form as the moon gradually recedes from the earth

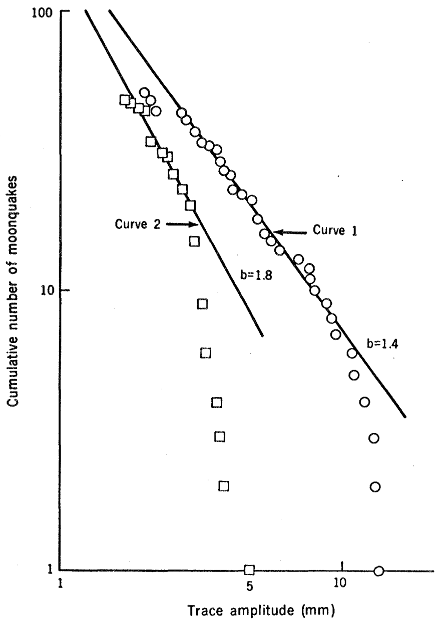

Fig. 6. Cumulative curves for all category A events recorded at the Apollo 12 station. Each point on a curve indicates the number, N, of events with amplitude equal to or greater than A. Curve 1 contains data for category A_1 and A_6 events only. Curve 2 contains data for category A events excluding categories A_1 and A_6; 1-mm trace amplitude $= 0.625 \times 10^{-8}$ cm ground motion amplitude.

(*6*); (iii) localized strains due to uncompensated masses; (iv) localized strains introduced by readjustment of the lunar material following large impacts; or (v) localized thermal stresses.

The largest natural events yet recorded are C events, while moonquakes have amplitudes varying from barely perceptible to about ten times larger. The cumulative number of moonquakes plotted against maximum signal amplitudes are shown in Fig. 6 for two groupings of events: (curve 1) category A_1 and A_6 events and (curve 2) all other moonquakes. At higher amplitudes, the slopes of both distributions become steeper, apparently defining a limit to the size of moonquakes which can occur at the respective foci.

For earthquake data, the cumulative amplitude curves often have a nearly linear slope known as the b value. The b values for tectonic earthquakes are normally close to 1. The b values of the moonquake data in Fig. 6 are considerably higher than this even in their upper portions. Higher b values are typical of one class of earthquakes—those associated with volcanic activity. Volcanic earthquakes 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 (*7*), and with cracking due to thermal stresses induced by heating and cooling of samples (*8*). High b values are also measured when two surfaces are rubbed together under high contact pressure (*9*). Thus, while no definite conclusion regarding the focal mechanism of moonquakes can be based on b value data alone, comparison with laboratory data and seismic measurements for earthquakes suggests that moonquakes may be generated by (i) thermal stresses, possibly of volcanic origin; (ii) tectonic stresses at low stress levels; or (iii) dislocation along preexisting fractures. The correlation between maximum moonquake activity and perigee demonstrates that tidal stresses must play an important role in the release of seismic energy within the moon.

Low stress levels, whether of thermal or mechanical origin, are inferred from the low rate of occurrence and relatively small magnitudes of moonquakes. The largest moonquakes detected have Richter magnitudes of 1 to 2, depending on the method of calculation. Earthquakes of this size would be barely perceptible even to persons standing near the epicenter. Possible focal depths as great as 900 km may favor the thermal stress hypothesis, but there is considerable evidence that melting temperatures may not be reached at any depth in the moon. Relatively low internal temperatures are indicated by the existence of mascons and by the nonequilibrium figure of the moon, which imply considerable internal strength. Also, results from the Apollo surface magnetometer experiment (*10*) indicate that temperatures in the deep lunar interior are below the in situ melting point.

These suggestions are of the most tentative nature, but they serve as hypotheses against which future data will be tested.

As discussed above, it appears certain that seismic energy release related to lunar tides does occur within the moon. However, the number and magnitudes of these events are small compared to the seismic activity that would be recorded by an equivalent seismic station on Earth. The estimated seismic energy released by the largest moonquakes ranges from 10^9 to 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 can be compared with about 5×10^{24} ergs per year for total seismic energy release within the earth. The uncertainty is due primarily to the difficulty of estimating the ranges of natural events. However, 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 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. The outer shell of the moon appears to be cold, rigid, and tectonically stable compared to the earth, except for the minor disruptive influence correlated with lunar tides.

Since this report was written, a third seismic station has been installed near Hadley Rille as part of the Apollo 15 mission. Two moonquakes from the most active source (A_1 zone) were recorded by the three stations of the Apollo seismic network during the first two perigee periods following activation of the new station. The epicenter has been tentatively located at 21°S, 28°W, 600 km SSW of stations 12 and 14. The depth of the focus is about 800 km—deeper than any known earthquake. Unlike the earth, the moon must be sufficiently rigid at this depth to sustain appreciable shear stress. The remaining foci have not yet been located.

In addition to the repeating moonquakes, moonquake "swarms" have been discovered. During periods of swarm activity, events occur as frequently as one event every 2 hours over intervals lasting several days. The source of these swarms is unknown at present. The occurrence of swarms does not appear to be related to lunar tides, although present data are not sufficient to rule out this possibility.

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11. We thank M. Langseth and J. Chute for reviewing the manuscript and offering suggestions. Supported by NASA under contracts NAS9-5957 and NAS9-5632. Computer facilities were provided by the NASA Goddard Space Flight Center, Institute for Space Studies, New York. Lamont-Doherty Geological Observatory Contribution 1698. Hawaii Institute of Geophysics Contribution 408.

9 August 1971

Mercury in a Greenland Ice Sheet: Evidence of Recent Input by Man

Abstract. *The increased mercury content in a Greenland ice sheet over the last several decades suggests the dissemination of this element about the earth's atmosphere through the activities of man. The mercury content in the atmosphere appears to result primarily from the degassing of the earth's crust. Increased flux may come about as a result of the enhancement of this degassing process through the actions of man.*

Has the flux of mercury from the continents to the atmosphere been influenced measurably by the activities of man? Such processes as the combustion of fossil fuels, the roasting of ores, or the production of chemicals with mercury catalysts could, in principle, compete with other natural phenomena to cause the injection of mercury into the air. The purpose of this investigation was to probe this possibility.

Permanent snowfields record the introduction of matter into the atmosphere. These ices contain in essentially unchanged condition both the water and the accumulated solids that precipitated from the air as a function of time. Thus, it is possible to draw inferences regarding the chemical composition of the atmosphere as it existed centuries and even millennia ago through the analysis of this material, particularly since the various strata are susceptible to reliable dating by a variety of techniques including ^{210}Pb and fission product geochronologies, the isotopic analysis of oxygen, and firn stratigraphy.

Dated glacial samples from Greenland (and a single sample from Antarctica), which had been previously analyzed for their lead (*1*), sulfate (*2*), and selenium (*3*) concentrations, formed the basis of this work. The Greenland samples were from the Camp Century area (77°10′N, 61°07′W) and from a virgin site 80 km east by southeast of this location. The ices were collected by Patterson under extremely careful conditions (*1*). The older samples of the Greenland ice sheet were recovered from the walls of an inclined shaft at Camp Century, and the samples of more recent ages were taken from the walls of open trenches at the virgin site. The single Antarctic sample was recovered from an inclined shaft at the New Byrd Station (80°01′S, 119°31′W). The samples were melted and stored in sealed polyethylene containers in 1966 immediately after removal from the glaciers (*1*).

The mercury content of the glacial ice was determined by thermal neutron activation analysis. Thirteen samples whose total volumes ranged from 200 to 400 ml were analyzed. The water from each sample was introduced directly from the original polyethylene containers into the requisite number of 15-ml polyethylene vials, each of which contained 1 ml of concentrated nitric acid. The vials had been previously im-