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Shallow moonquakes: How they compare with earthquakes

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Abstract—Of three types of moonquakes strong enough to be detectable at large distances—deep moonquakes, meteoroid impacts and shallow moonquakes—only shallow moonquakes are similar in nature to earthquakes. A comparison of various characteristics of moonquakes with those of earthquakes indeed shows a remarkable similarity between shallow moonquakes and intraplate earthquakes: (1) their occurrences are not controlled by tides; (2) they appear to occur in locations where there is evidence of structural weaknesses; (3) the relative abundances of small and large quakes (b-values) are similar, suggesting similar mechanisms; and (4) even the levels of activity may be close. The shallow moonquakes may be quite comparable in nature to intraplate earthquakes, and they may be of similar origin.

INTRODUCTION

The present-day moon is often regarded as a planet of extreme quiescence. The surface of the moon is nearly completely devoid of any evidence of tectonic activity during the last three billion years. The observed seismicity also appears to be very low compared with the earth (Latham *et al.*, 1972). Studies based on abundant Apollo lunar rock samples have left an impression on many of us that all significant activity in the moon occurred only during the first one and a half billion years following its creation. Yet, the measured heat-flow values are comparable to those of the earth (Langseth *et al.*, 1976), indicating that a large amount of potential tectonic energy is still stored in the lunar interior. The heat flow values certainly do not suggest that the moon is a cold, dead planet.

I have therefore re-examined various properties of moonquakes to see how they compare with earthquakes and to consider their significance in terms of the present-day tectonics of the lunar interior. This short paper presents some comparisons of moonquakes with earthquakes, and shows how I conclude that the present-day dynamics of the lunar interior may be quite comparable to the tectonics of the earth if plate boundaries are excluded.

MOONQUAKES

There are three types of moonquakes large enough to be observable at great distances. The most numerous are deep moonquakes. About two thousand of them were detected annually during the Apollo lunar seismic experiment. They occur at depths about halfway to the center of the moon. The most striking characteristic of deep moonquakes is the regularity in time of their occurrence, showing a clear correlation with the tidal periodicity of the moon. No such quakes have been identified in the earth; a reason may be that terrestrial seismographs are not sufficiently sensitive to detect them even if they exist in the earth. Deep moonquakes are very small. Despite their large numbers, the total energy released by them is quite insignificant in comparison with that of earthquakes (Lammlein *et al.*, 1974). Deep moonquakes appear to represent merely a process of storage and release of tidal energy without a significant release of tectonic energy (Nakamura, 1978; Koyama and Nakamura, 1980).

The next most abundant are moonquakes caused by impacts of meteoroids. About three hundred of them were observed yearly by the Apollo seismic network. They are obviously of external origin, and are in no way comparable to earthquakes.

The third type of moonquakes is the shallow moonquakes. They are the rarest—only four to five of them were detected yearly by the Apollo seismic network. However, they represent the most energetic sources in the moon, and account for most of the seismic energy released in the moon. They occur at depths generally shallower than about 100 km (Nakamura *et al.*, 1979), and appear to be the only moonquakes that may be related to earthquakes in their origin.

SHALLOW MOONQUAKES AND EARTHQUAKES

Tidal correlation

Shallow moonquakes occur quite randomly in time, as seen in Fig. 1. Unlike deep moonquakes, no clear correlation with the tidal cycle is observed. A strong tidal coupling would appear as periodicities of a month or seven and a half months. No such periodicities are observed for shallow moonquakes. Tidal periodicity of earthquake occurrence has been a subject of study by several investigators in the past in the hope of finding evidence for tidal triggering of earthquakes. The results, however, have been questionable at best (e.g., Knopoff, 1964). Tectonic quakes perhaps do not generally show any clear evidence of being triggered by tidal forces. In this respect, shallow moonquakes are similar to earthquakes.

Epicentral distribution

Though we detected only 28 shallow moonquakes, their epicenters appear to be distributed randomly on the lunar surface (Nakamura *et al.*, 1979). This is in contrast to the distribution of earthquakes, the overwhelming majority of which are concentrated within narrow seismic belts along plate boundaries. The relative

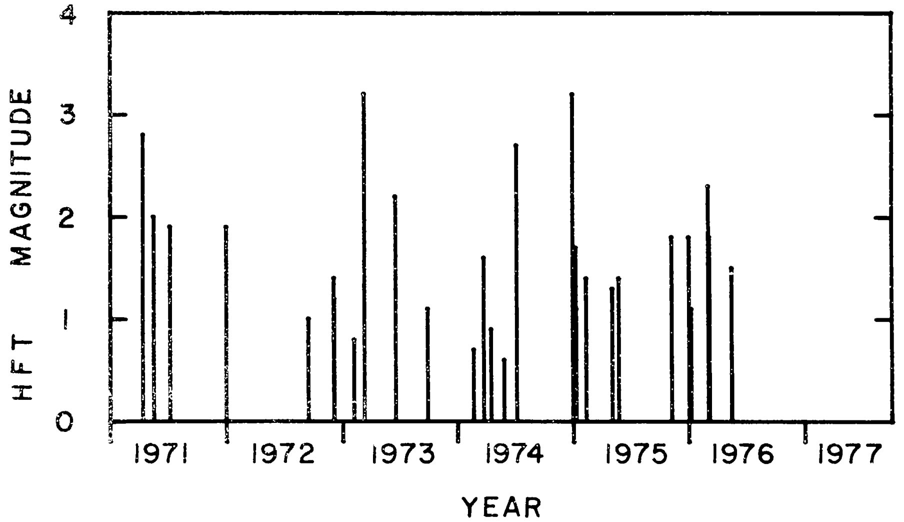

Fig. 1. Occurrence history of shallow moonquakes. HFT magnitude is defined by log (SPZ envelope amplitude in DU reduced to 60° distance). It is estimated to be approximately 1½ less than the body-wave magnitude as estimated by Goins (see text). HFT (high-frequency teleseismic) is the term previously used for this group of moonquakes. The period before the installation of Apollo 14 seismic station (February, 1971) has been excluded because shallow moonquakes could not be identified on Apollo 12 station records, which lacked a short-period component.

movements of plates are believed to be the direct cause of these earthquakes. On the other hand, there is no indication of current lunar plate movements, and little evidence of seismic belts on the moon. One might, therefore, conclude that shallow moonquakes are quite dissimilar to earthquakes.

However, there are earthquakes that occur away from plate boundaries on the earth. While not numerous, some of them can be quite large. Some similarities can be recognized between the distributions of these intraplate earthquakes and of shallow moonquakes.

Sites of intraplate seismicity can be identified as zones of pre-existing weaknesses in lithospheric plates on the earth (Sykes, 1978). Although epicenters of shallow moonquakes are not very accurately determined, their distribution seems to be correlated with the distribution of ancient impact basins (Nakamura *et al.*, 1979), which may also represent zones of weakness.

Observations of quakes associated with ancient impact structures are not confined to the moon. For example, Leblanc *et al.* (1973) report a series of St. Lawrence Valley earthquakes in the Canadian shield associated with an impact structure of middle Ordovician to late Devonian age, i.e., some 300 to 400 million years old. They suggest that these earthquakes manifest yielding of the weakened crust under the impact crater to the post-glacial strain field acting over a broader region. The lunar quakes may represent yielding to a similarly broad strain field due to some other cause such as cooling of the lunar interior.

Anomalies in electrical conductivity are found associated with impact basins on the moon (Schubert *et al.*, 1974; Sonett *et al.*, 1974; Dyal and Daily, 1979).

Such anomalies represent differing physical properties between impact basins and surrounding areas, and may suggest the presence of different thermal conductivity and temperature regimes. It is reasonable to expect that concentrations of tectonic stresses in such heterogeneous regions would cause moonquakes to occur there. The association of intraplate seismicity with anomalous distribution of electrical conductivity is also observed on the earth (e.g., Lilley, 1975).

b-value

One way to characterize a given population of earthquakes is to compare the relative abundance of large and small earthquakes. This relationship is normally plotted as a magnitude-frequency diagram. Figure 2 shows this relationship for the shallow moonquakes. The relative abundance is usually expressed by the slope of such a curve, called its "b-value." The b-value of shallow moonquakes, as determined by the maximum likelihood estimate of Aki (1965), is 0.55. (Events smaller than HFT magnitude 1.0 have been excluded from this determination because it is likely that many small events were not detected.) In comparison, deep moonquakes give b-values generally in excess of 1.5 (Lammlein *et al.*, 1974), while most earthquakes give values close to 1.0 (Matuzawa, 1964). The low b-value for the shallow moonquakes means that large moonquakes are proportionately more abundant than in normal earthquakes.

Interestingly, low b-values of 0.5 to 0.6 are also found for earthquakes occurring in continental interiors (Matuzawa, 1964; Lammlein *et al.*, 1971). Although the physical significance of b-values is not well understood, the common and signif-

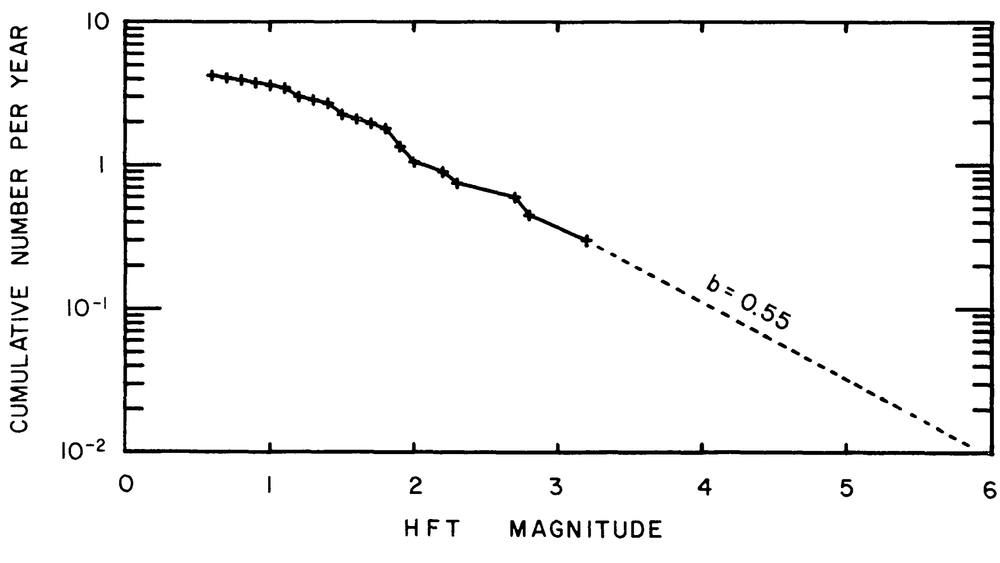

Fig. 2. Cumulative frequency-magnitude distribution of detected shallow moonquakes. The ordinate of each point represents the number of events N observed per year to have magnitude M equal to or greater than the value represented by the abscissa. The b-value is defined by $-d(\log N)/dm$, i.e., the slope of the distribution curve. The dashed line is an extrapolation of the slope representing $b = 0.55$.

icantly lower than normal b-values for shallow moonquakes and intraplate earthquakes suggest a possibility of similar processes that cause these two groups of quakes.

Energy release

The level of shallow moonquake activity, i.e., the average amount of seismic energy released by all shallow moonquakes, is not easy to estimate because of the short duration of observation, as will be explained below. Values such as 2×10^{17} ergs/year given by Goins *et al.* (1980), I believe, are a gross underestimation because of this.

Let us consider a population of quakes, with a set of observed quakes representing a sample from the population. If large quakes are proportionately abundant, as in the case of shallow moonquakes, most of the energy released by the entire population is attributable to the largest quake in the population. The difficulty in estimation arises when the size of the sample (observations) is so small that one cannot reasonably estimate the magnitude of the largest quake in the population. Then, the energy release estimated from the largest observed quakes is quite likely to be well below the true rate of energy release over a long term.

The latest estimate (Neal Goins, pers. comm., 1979) assigns a body-wave magnitude of 4.8 to the largest observed shallow moonquake. If this were the largest ever expected, the average energy release rate would be about 2×10^{17} ergs/year for the entire moon. However, there is no reason to believe that we have observed, in the short duration of our observation, the largest shallow moonquakes, which are expected to occur much less frequently than once every eight years. The magnitude-frequency relation of Fig. 2, in fact, shows no indication of the line deviating from the linear trend at large magnitude. This means that larger shallow moonquakes are indeed expected in a longer period of observation.

Thus, it is quite reasonable to expect that the magnitude-frequency relation of Fig. 2 can be extrapolated further to larger magnitude, following the dashed line of Fig. 2. How much extrapolation is justifiable cannot be determined from the presently available data. However, if we extrapolate this relation to HFT magnitudes of 4.0, 5.0 and 6.0 (equivalent to body-wave magnitudes of roughly 5½ to 7½), for example, we obtain estimated energy release rates of 10^{18}, 3×10^{19} and 10^{21} ergs/year, respectively, for the entire moon. Shallow moonquakes of such magnitudes are expected only once in every 9, 32 and 115 years, respectively.

These estimated long-term energy release rates are still very small fractions of the average annual energy release by all the earthquakes, which is estimated to be 10^{24} to 10^{25} ergs/year (Stacy, 1977). Of this amount, intraplate earthquakes account for about 0.2% (Gutenberg and Richter, 1949); i.e., about 10^{22} ergs/year.

To compare these values with the above estimates for the moon may not be a simple matter. Besides the simple difference in size of these two planets, the process of how planetary bodies of different sizes envolve need be considered, which is beyond the scope of this paper. As a rough comparison, if one takes into account only the volume ratio of 49.2 to 1 and surface ratio of 13.5 to 1 between the earth and the moon, the energy release rate of intraplate earthquakes is roughly equivalent to 10^{20} to 10^{21} ergs/year for either volume or surface equivalent to the moon. This is quite comparable to the above estimates for the shallow moonquakes.

This comparison, of course, is valid only under the assumption that the magnitude-frequency relation of Fig. 2 can be extrapolated to larger magnitude. To obtain an energy release rate comparable to intraplate earthquakes, one needs to extrapolate the shallow moonquake frequency curve to HFT magnitude of 5½ to 6, or equivalent body-wave magnitude of 7 to 7½. The expected frequency of occurrence of such moonquakes is once in 50 to 100 years. Such intervals are also comparable to those of rare, large intraplate earthquakes.

The largest expected shallow moonquakes may have magnitudes even greater than those used in the above examples. Since the lunar lithosphere is thicker than the terrestrial lithosphere, the former may be able to accumulate larger stress than the latter. As a consequence, much larger amounts of energy may be stored in the lunar lithosphere than in the terrestrial lithosphere for infrequent release by rare, large moonquakes.

CONCLUDING REMARKS

The above comparisons of moonquakes with earthquakes thus show that shallow moonquakes are quite similar in many respects to intraplate earthquakes. To summarize the comparisons: (1) their occurrences are apparently not tidally controlled; (2) their locations in relation to structural weaknesses and other geological features are similar; (3) the b-values are about the same, suggesting similar nature of source mechanisms; and (4) even the estimated long-term energy release rates are about the same.

These similarities certainly are not solid evidence that shallow moonquakes are caused in exactly the same way as intraplate earthquakes. Rather, they may be viewed only as circumstantial evidence. However, there are enough similarities that we can reasonably accept shallow moonquakes as the lunar equivalent of intraplate earthquakes.

There are some important implications of this observation. First, for the moon: Even though shallow moonquakes appear to be associated with ancient impact basins (Nakamura *et al.*, 1979), the estimated amount of energy released by them is far greater than expected from simple isostatic adjustments of original disturbances caused by impacts. The energy of shallow moonquakes, therefore, must be supplied by other, contemporary tectonic sources.

Second, for the earth: Recently, there has been increased interest in interpreting intraplate seismicity in terms of plate tectonics (e.g., Sykes, 1978). To the contrary, shallow moonquakes have shown us that it is possible for a significant number of tectonic quakes to occur without apparent plate movement. The lunar data thus suggest that the plate tectonic interpretation of intraplate seismicity may not be a valid one.

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REFERENCES

Aki K. (1965) Maximum likelihood estimate of b in the formula log $N = a - bM$ and its confidence limits. *Bull. Earthquake Res. Inst. Univ. Tokyo* **43,** 237–239.

Dyal P. and Daily W. D. (1979) Electrical conductivity anomalies associated with circular lunar maria. *Proc. Lunar Planet. Sci. Conf. 10th,* p. 2291–2297.

Goins N. R., Dainty A. M., and Toksöz M. N. (1980) Seismic energy release of the moon (abstract). In *Lunar and Planetary Science XI,* p. 336–338. Lunar and Planetary Institute, Houston.

Gutenberg B. and Richter C. F. (1949) *Seismicity of the Earth.* Princeton Univ., Princeton, New Jersey. 273 pp.

Koyama J. and Nakamura Y. (1980) Focal mechanism of deep moonquakes. *Proc. Lunar Planet. Sci. Conf. 11th.* This volume.

Knopoff L. (1964) Earth tides as a triggering mechanism for earthquakes. *Bull. Seismol. Soc. Amer.* **54,** 1865–1870.

Lammlein D. R., Latham G. V., Dorman J., Nakamura Y., and Ewing M. (1974) Lunar seismicity, structure, and tectonics. *Rev. Geophys. Space Phys.* **12,** 1–21.

Lammlein D. R., Sbar M. L., and Dorman J. (1971) A microearthquake reconnaissance of southeastern Missouri and western Tennessee. *Bull. Seismol. Soc. Amer.* **61,** 1705–1716.

Langseth M. G., Keihm S. J., and Peters K. (1976) Revised lunar heat-flow values. *Proc. Lunar Sci. Conf. 7th,* p. 3143–3171.

Latham G., Ewing M., Dorman J., Lammlein D., Press F., Toksöz N., Sutton G., Duennebier F., and Nakamura Y. (1972) Moonquakes and lunar tectonism results from Apollo passive seismic experiment. *Proc. Lunar Sci. Conf. 3rd,* p. 2519–2526.

Leblanc G., Stevens A. E., and Wetmiller R. J. (1973) A microearthquake survey of the St. Lawrence Valley near La Malbaie, Quebec. *Can. J. Earth Sci.* **10,** 42–53.

Lilley F. E. M. (1975) Electrical conductivity anomalies and continental seismicity in Australia. *Nature* **257,** 381–382.

Matuzawa T. (1964) *Study of Earthquakes.* Uno Shoten, Tokyo. 213 pp.

Nakamura Y. (1978) A_1 moonquakes: Source distribution and mechanism. *Proc. Lunar Planet. Sci. Conf. 9th,* p. 3589–3607.

Nakamura Y., Latham G. V., Dorman H. J., Ibrahim A. K., Koyama J., and Horvath P. (1979) Shallow moonquakes: Depth, distribution and implications as to the present state of the lunar interior. *Proc. Lunar Planet. Sci. Conf. 10th,* p. 2299–2309.

Schubert G., Smith B. F., Sonett C. P., Colburn D. S., and Schwartz K. (1974) Polarized magnetic field fluctuations at the Apollo 15 site: Possible regional influence on lunar induction. *Science* **183,** 1194–1197.

Sonett C. P., Smith B. F., Schubert G., Colburn D. S., and Schwartz K. (1974) Polarized electromagnetic response of the moon. *Proc. Lunar Sci. Conf. 5th,* p. 3073–3089.

Stacey F. D. (1977) *Physics of the Earth.* 2nd ed. Wiley, N.Y. 414 pp.

Sykes L. R. (1978) Intraplate seismicity, reactivation of preexisting zones of weakness, alkaline magnetism, and other tectonism post-dating continental fragmentation. *Rev. Geophys. Space Phys.* **16,** 621–688.