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Shallow moonquakes: Depth, distribution and implications as to the present state of the lunar interior

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Abstract—The observed seismic amplitudes of HFT (high-frequency teleseismic) events do not vary with distance as expected for surface sources, but are consistent with sources in the upper mantle of the moon. Thus, the upper mantle of the moon is the only zone where tectonic stresses deriving from differential thermal contraction and expansion of the lunar interior are presently high enough to cause moonquakes. The distribution of shallow moonquake epicenters suggests a possible correlation with impact basins, implying a lasting tectonic influence of impact basins long after their formation. The finite depths now assigned to these shallow moonquakes necessitate further revision to the seismic structural model of the lunar interior.

INTRODUCTION

There are three major types of natural seismic events strong enough to be observable at large distances on the moon. The most numerous, though mostly very small, are the deep moonquakes. They occur at depths approximately half way to the center of the moon. About 2000 of them were observed annually on the Apollo lunar seismograph network. Next in abundance are the meteoroid impacts. They account for about 10 percent of the detected events, or about 200 per year. The events of the third type are called HFT (high-frequency teleseismic) events because of their unusually high frequency content and great distances at which they are observed. They are rare, averaging about five per year, but they include many of the most energetic seismic events observed on the moon.

HFT events have been suspected to be shallow moonquakes, primarily because of their signal characteristics that are significantly different from those of meteoroid impacts (Nakamura, 1977). However, none of the evidence has been conclusive. The determination of depths at which the HFT events occur has been a problem ever since their discovery (Nakamura *et al.*, 1974). Relative arrival times of seismic waves from these events at the Apollo seismic stations indicate only that they originate at or near the surface of the moon. Sources at depth certainly imply moonquake mechanisms, while surface sources may be of external origin. The depth determination of HFT events, therefore, has a great significance regarding the present dynamics of the lunar interior.

In general, the times of first arrivals are insensitive to the focal depths for events outside the area of the observing network. This is the case for the HFT events, i.e., epicenters of all the detected HFT events were located outside the Apollo seismic array (see Fig. 3). The depths of HFT foci calculated from arrival times alone by Lammlein (1977) ranged from −46 to +292 km, while Goins (1978) showed that travel time residuals decreased only slightly as assumed focal depths were varied from 100 km to zero (and presumably reaching a minimum above the surface). Moreover, the surface reflected phases, such as pP and sS, which are used routinely for determining earthquake focal depths, cannot be identified in the complex wavetrain of lunar seismic signals. Many efforts to identify such phases, including the use of polarization filtered seismograms (Goins, 1978), have been fruitless. We have, therefore, looked beyond travel times to solve this problem. The critical property we have found is the variation of the observed amplitude of seismic signals with distance. This property definitely indicates that HFT events originate at finite depths, and therefore are of internal origin, i.e., moonquakes. In this paper, we first describe how we have reached this conclusion, and then we discuss its various implications upon the present dynamic state and structure of the lunar interior.

AMPLITUDE VARIATION AND DEPTH OF FOCUS

Seismic rays propagating through a medium of heterogeneous seismic velocity undergo refractions and reflections. Just as for light rays passing through a lens, refractions and reflections cause seismic energy to spread out nonuniformly, focusing in some places and defocusing in others. This nonuniform spreading of energy by heterogeneities is reflected in the variation of observed seismic amplitude with distance. The most prominent heterogeneity in the upper part of the lunar interior is the large seismic velocity contrast between the low-velocity crust and the high-velocity upper mantle at a depth of 50 to 60 km. Because of this velocity contrast, observed amplitudes of seismic waves from surface sources show a quite characteristic variation with distance. Within a distance range of about 5° to 20°, the amplitude decreases rapidly with increasing distance as seismic waves transmitted through the crust and reflected from the crust/mantle boundary contribute most of the observed seismic energy. Beyond about 20°, and extending to about 90° of distance, the observed amplitude varies only slightly with distance as seismic waves transmitted through the upper mantle dominate the detected energy. Finally, a rapid decrease of amplitude follows beyond about 90° of distance as seismic waves penetrate deeper into the lunar interior. Thus, the amplitude variation shows a characteristic flattening between distances of 20° and 90° in an otherwise monotonic decay with increasing distance. This variation is indeed observed for meteoroid impact signals (Nakamura *et al.*, 1976).

If HFT events are also of surface origin, we should expect the same amplitude variation with distance. On the other hand, if HFT events originate at some finite depths, we may expect to see an amplitude variation which is different from that of surface impact signals. This is again analogous to the shifting in focusing of light rays as one moves a light source relative to a lens. We have, therefore, examined the amplitude variation of HFT signals using a regression technique described by Nakamura *et al.* (1976). A fifth-order polynomial regression curve is used to fit the observed amplitudes. The envelope amplitudes of short-period vertical (SPZ) component seismograms have been used for this analysis. On these seismograms, envelope peaks usually occur within a few minutes of the initial shear-wave arrival for HFT signals. They represent primarily the amplitudes of the most dominant shear-wave arrival. The frequency of the signals is predominantly in the 2 to 4 Hz range. The result is shown in Fig. 1. The computed curve is a composite amplitude variation curve representing all of the HFT events observed in the eight years of seismic station operation on the lunar surface. Since there is no assurance that all HFT sources are at the same depth (unless they are of external origin, in which case all HFT foci are at the surface of the moon), the curve represents the average amplitude variation for a group of events that originate within a limited depth range. It is clearly seen that this amplitude variation curve does not show the characteristic step expected for surface sources.

Figure 2 is a comparison of this amplitude variation curve with theoretical curves computed for our working lunar model LM-761 (Nakamura *et al.,* 1976)

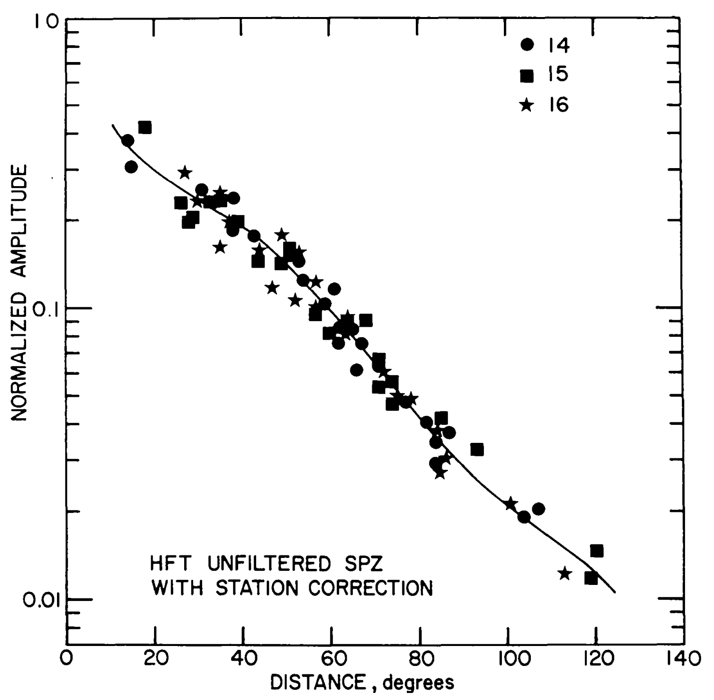

Fig. 1. Amplitude variation of HFT signals with distance. The solid line through the data is the 5th-order polynomial regression curve. Initially unknown station corrections are also determined during the least-square regression, which also normalizes the amplitudes for the differing source intensities. Data from Apollo stations 14, 15 and 16 are separately identified. Station 12 is omitted because of the failure of the short-period seismometer at this station.

for various depths of focus. The model has a 55 km thick crust. It is observed that the characteristic flattening persists as long as the seismic foci are located within the crust. The comparison, therefore, clearly indicates that HFT foci, at least a majority if not all, must be below the boundary between the crust and the mantle.

Thus, we must conclude that HFT events are moonquakes that occur mostly below the crust. Actual depths of individual HFT foci still cannot be resolved by this analysis. A few of them may have been in the crust, while travel time data restrict the depths of all HFT foci to depths less than 300 km (Nakamura, 1977) and most likely less than about 200 km.

EPICENTRAL DISTRIBUTION

Table 1 lists all of the shallow moonquakes detected during the eight years of lunar seismic observation. Epicenters and origin times have been updated from

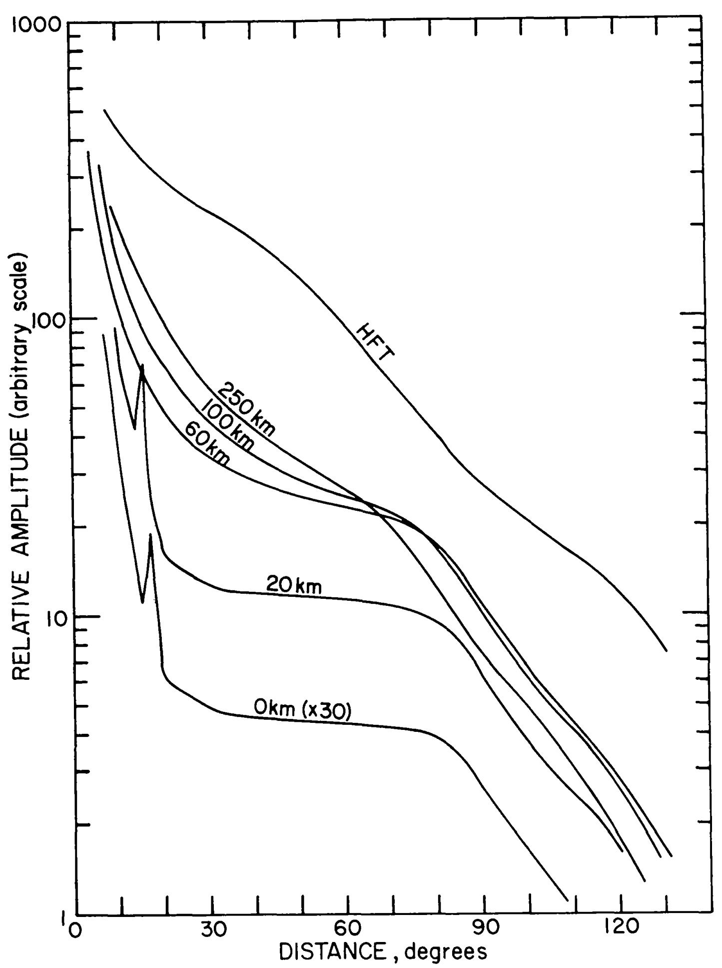

Fig. 2. Amplitude variation of HFT signals with distance (from Fig. 1) compared with theoretical amplitude variations for lunar model LM-761 for various depths of focus.

Table 1. List of detected shallow moonquakes with estimates[1].

Year	Day	Origin time	Epicenter	Magnitude[2]
1971	107 (Apr. 17)	$07^h00^m55^s$	48°N 35°E	2.8
1971	140 (May 20)	17 25 10	42°N 24°W	2.0
1971	192 (July 11)	13 24 45	—[3]	1.9
1972	002 (Jan. 2)	22 29 40	54°N 101°E	1.9
1972	261 (Sept. 17)	14 35 55	12°N 46°E	1.0
1972	341 (Dec. 6)	23 08 20	51°N 45°E	1.4
1972	344 (Dec. 9)	03 50 15	20°S 80°W	1.2
1973	039 (Feb. 8)	22 52 10	33°N 35°E	0.8
1973	072 (Mar. 13)	07 56 30	84°S 134°W	3.2
1973	171 (June 20)	20 22 00	1°S 71°W	2.2
1973	274 (Oct. 1)	03 58 00	37°S 29°W	1.1
1974	054 (Feb. 23)	21 16 50	36°N 16°W	0.7
1974	086 (Mar. 27)	09 11 00	48°S 106°W	1.6
1974	109 (Apr. 19)	13 35 15	37°S 42°E	0.9
1974	149 (May 29)	20 42 15	—[4]	0.6
1974	192 (July 11)	00 46 30	21°N 88°E	2.7
1975	003 (Jan. 3)	01 42 00	29°N 98°W	3.2
1975	012 (Jan. 12)	03 14 10	75°N 40°E	1.7
1975	013 (Jan. 13)	00 26 20	2°S 51°W	1.1
1975	044 (Feb. 13)	22 03 50	19°S 26°W	1.4
1975	127 (May 7)	06 37 05	49°S 45°W	1.3
1975	147 (May 27)	23 29 00	3°N 58°W	1.4
1975	314 (Nov. 10)	07 52 55	8°S 64°E	1.8
1976	004 (Jan. 4)	11 18 55	50°N 30°E	1.8
1976	012 (Jan. 12)	08 18 05	38°N 44°E	1.1
1976	066 (Mar. 6)	10 12 40	50°N 20°W	2.3
1976	068 (Mar. 8)	14 42 10	19°S 12°W	1.8
1976	137 (May 16)	12 32 40	77°N 10°W	1.5

(1) Origin times and epicenters were estimated using Model LM-761 (Nakamura *et al.*, 1976) and assuming 100 km depth of focus. Though the epicenters are given to the nearest degree, they are not accurate to 1°, especially for smaller events.

(2) Lunar HFT magnitude defined by log (SPZ envelope amplitude in DU reduced to 60° distance). They are estimated to be approximately 1.0 less than Richter magnitude.

(3) 43°N, 47°W or 42°S, 60°W.

(4) 30° from station 16 on east side of station.

our earlier list (Nakamura, 1977) and later events have been added. In calculating the epicenters, a depth of focus of 100 km has been assumed for all events because, as stated above, we are still unable to determine the depths of individual events with reasonable certainty. Since all observed shallow moonquakes are located outside the lunar seismic network, slight variations in the focal depths do not alter the computed epicenters appreciably, as is evident when one compares the new epicenters with the previous ones. Earlier locations assumed surface foci.

The computed epicenters are plotted in Fig. 3 on a map representing the entire surface of the moon. The distribution of epicenters is not far from random, even when allowances are made for uncertainties in epicentral determinations. The lack of concentration into narrow belts like the earthquake belts on the earth disposes of a hypothesis of plate motion for explaining their mechanisms. As noted before (Nakamura, 1977), however, there are more events observed in the northeast and southwest quadrants than in other quadrants, though the statistical significance of the nonrandomness is not great owing to the small number of events. The epicenters appear to be clustered into two groups, covering slightly expanded areas of these two (northeast and southwest) quadrants.

Since lunar impact basins appear to be similarly grouped, we have drawn on the same map the circumferences of the impact basins as given by Wood and

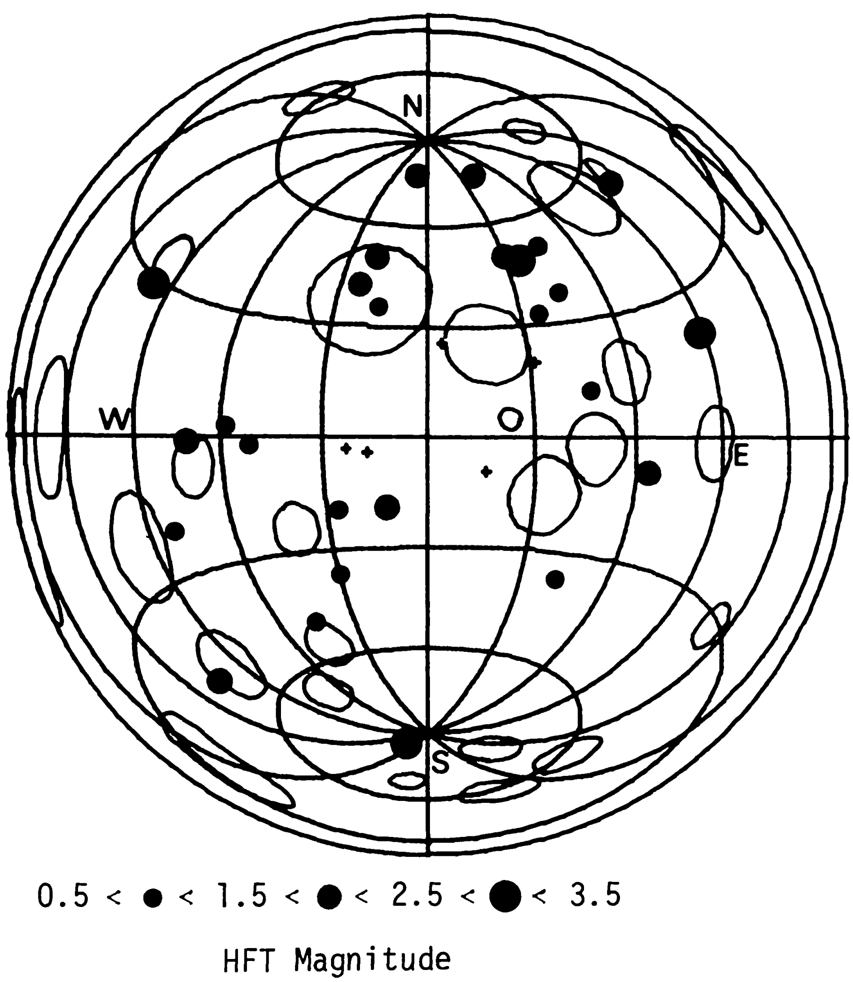

Fig. 3. Distributions of shallow moonquake epicenters and impact basins. The base map is the entire surface of the moon in an equal area projection. N and S represent north and south poles, respectively. The inner circle through NESW is the limb and the outer circle is the antipode. Small crosses represent locations of ALSEP stations. HFT magnitudes are defined in the footnote to Table 1.

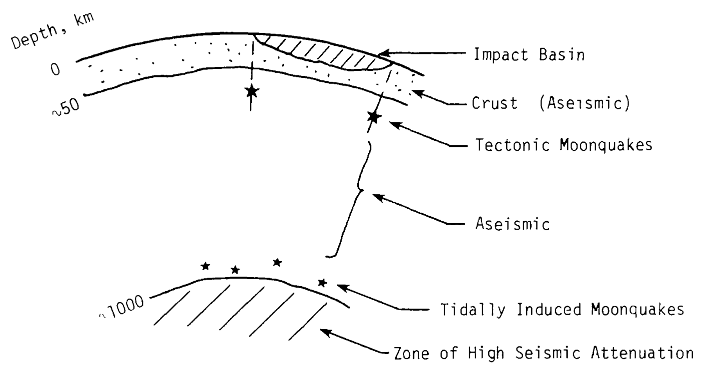

Fig. 4. Schematic diagram of the lunar interior showing foci of moonquakes.

Head (1976). Not only are the groupings similar for these two sets of data, but a close examination also reveals that several of the shallow moonquakes occur on or very close to the margins of impact basins, although the statistical significance, again, is inconclusive because of the small number of events.

The mechanisms of shallow moonquakes, therefore, might be related to the existence of impact basins. We might speculate that shallow moonquakes occur along circular fault systems around impact basins, similar to those proposed by Runcorn (1974) for explaining deep moonquakes. Deep moonquakes, however, have since been shown to have focal mechanisms different from those expected from such a model (Nakamura, 1978). If shallow moonquakes are indeed related to impact basins, then those which seem uncorrelated to known impact basins may delineate ancient impact basins or some other forms of heterogeneity not previously identified.

IMPLICATIONS

The new results on depth and distribution of shallow moonquakes have some important implications relative to the structure and dynamics of the present lunar interior. We will discuss these implications in this section.

Present dynamic state of the lunar interior

The newly determined locations of shallow moonquakes add a new constraint to the present dynamics of the lunar interior. As shown schematically in Fig. 4, moonquake foci are not distributed throughout the lunar interior. They are restricted to two well-defined depth zones, separated by an aseismic zone. Whether a given zone in the lunar interior is seismic or aseismic depends upon the existence of stress in the zone, as well as the strength of the material under the prevailing pressure and temperature.

The seismic data indicate that the crust is aseismic, i.e., no moonquakes determined to have originated in this zone have been observed. This suggests that tectonic stress in the crust at present is not sufficient to overcome the strength of rock. We can probably rule out the possibility that creep may be relieving tectonic stress in this zone because its relatively low temperature and lack of volatiles suggest very high viscosity for the crustal material. In order not to produce excessive global thermal stress in the crust, the present-day rate of change of the lunar radius due to thermal expansion and/or contraction of the lunar interior must be small.

Certain thermal history models of the moon indicate concentration of compressional stress in the upper crust (A. B. Binder, pers. comm., 1979). This leads to an expectation that moonquakes may exist in the upper crust. There is a possibility that extremely shallow moonquakes, if they occur within the surface scattering zone, cannot be distinguished from meteoroid impacts. However, until such moonquakes are identified, we must assume that no moonquakes originate in the crust.

Rare, but relatively energetic, moonquakes occur in the upper mantle, probably within the depth range of 50 to 200 km. In contrast to deep moonquakes, they are not clearly correlated with the tidal cycle of the moon, though a slight suggestion of possible correlation has been observed (Nakamura, 1977). Thus they appear to represent the only truly tectonic moonquakes. The global tectonic stresses, caused by differential thermal contraction and expansion of the lunar interior, and possibly by convection below the zone, in the present evolutionary stage of the moon, must be sufficiently high to cause moonquakes in this depth range. A thermal history model by Binder and Lange (pers. comm., 1979) indeed show a peak in tensional stress in the upper mantle.

The apparent localization of epicenters around impact basins may be due to local stresses caused by structural heterogeneity as well as thermal heterogeneity in the area. Schubert *et al.* (1974) and Sonett *et al.* (1974) have reported on a strong anisotropy of Apollo 15 lunar surface magnetometer signals, which they interpret as possibly resulting from the influence of either or both of the Imbrium and Serenitatis basins. They suggest either diminished or enhanced electrical conductivity in the mare basin regions. A similar conductivity anomaly is also reported for Mare Serenitatis by Dyal *et al.* (1979) using Lunokhod 2 magnetometer data. It is reasonable to assume that structural disturbances, geochemical differentiation and redistribution of radiogenic heat sources associated with impact phenomena may have significantly altered the local thermal regime, with a resulting influence on the tectonics of the region lasting long after the impact event. While mechanical considerations of impact basin formation, such as those of Solomon and Head (1979) and Melosh (1978, 1979), explain structural deformations immediately following the basin formation, an addition of the long-lasting thermal heterogeneities coupled with the global thermal stress should explain tectonics of impact basins through present time.

The zone between the depths of 200 and 800 km is generally aseismic. This suggests that the present-day thermal stress is low in this zone, or possibly that high-temperature, aseismic creep is relieving the accumulated stress, though the relatively high seismic Q of this zone may argue against a high-temperature effect.

Near the bottom of the middle mantle, mostly at depths of 800 to 1000 km, are the foci of deep moonquakes. Both their time of occurrence and mechanism are fully controlled by the tidal stress variations (Lammlein *et al.,* 1977; Nakamura, 1978). Though numerous, they are so small that the total amount of energy released by all of the deep moonquakes can easily be supplied by tidal dissipation in the moon. Thus, a tectonic origin is unlikely for these moonquakes, and no accumulation of thermal stress is indicated in this depth range at present. Deep moonquakes concentrated at this level may be related to a sharp gradient of mechanical properties there.

The zone below about 1000 km depth is seismically quiet. High attenuation of shear waves passing through this zone (Nakamura *et al.,* 1973) suggests that at least its upper portion may be partially molten. Tectonic stress cannot accumulate in this zone because it is quickly relieved by the presumably low viscosity of the material.

Structural implications

All previous structural models of the lunar interior dealing with the lunar mantle based on Apollo seismic data have assumed either surface or extremely shallow (about 1 km) foci for shallow moonquakes. This has caused a systematic error of varying degrees in determining structural parameters depending upon how the shallow moonquake data are used in conjunction with meteoroid impact data. Our previous model (Nakamura *et al.,* 1976) was highly influenced by the data from two large, shallow moonquakes for deriving mantle structure because of the lack of major meteoroid impact events to cover appropriate distance ranges at that time. A later model by Goins *et al.* (1978) is expected to be somewhat less affected by this bias because more impact events had been added to the data set in the meantime, but it still is not free of this systematic error.

In qualitative terms, the removal of this bias will affect the lunar structural models in the following direction: (1) The seismic velocities in the upper mantle will be reduced somewhat from our previous values. This is because for a given apparent velocity the actual velocity will be lower for a source at depth than for a surface source. (2) The boundary between the upper and middle mantles, where the shear-wave velocity starts decreasing rapidly with increasing depth, will be lowered. This is because sources at depths allow the seismic rays to penetrate deeper into the lunar interior than those from assumed surface sources before being affected by the reduced shear-wave velocity below the boundary. (3) The lower seismic velocities in the upper mantle indirectly contribute to a reduction in the computed thickness of the crust.

We have started to revise the lunar structural model based on the newly determined depths of shallow moonquakes. The results will be published elsewhere in the near future.

CONCLUSIONS

HFT events are moonquakes that occur mostly, if not exclusively, in the upper mantle of the moon. Their epicentral distribution appears to be related to the distribution of impact basins, although the statistical significance of the correlation is inconclusive because of the small number of detected events.

The moon is thus tectonically active, but the seismic activity is limited at present to the upper mantle of the moon. This implies that the upper mantle of the moon is the only zone in the lunar interior where present tectonic stresses deriving from differential thermal contraction and expansion are sufficiently high to cause sudden mechanical failure. The apparent correlation of shallow moonquake epicenters and the distribution of impact basins suggests that the tectonic influence, both mechanical and thermal, of impact basin formation persists long after the event.

The newly estimated finite depths of shallow moonquakes necessitate further revisions to the seismic structural model of the lunar interior. The needed revisions include a decrease in the velocity of the upper mantle, an increase in the depth to the transition between the upper and the middle mantles, and a reduction in crustal thickness.

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REFERENCES

Dyal P., Vanyan L. L., and Daily W. D. (1979) Mare Serenitatis conductivity anomaly detected by Apollo 16 and Lunokhod 2 magnetometers (abstract). In *Lunar and Planetary Science X,* p. 335–337. Lunar and Planetary Institute, Houston.

Goins N. R. (1978) Lunar seismology: The internal structure of the moon. Ph.D. thesis, MIT, Cambridge.

Goins N. R., Toksöz M. N., and Dainty A. M. (1978) Seismic structure of the lunar mantle: An overview. *Proc. Lunar Planet. Sci. Conf. 9th,* p. 3575–3588.

Lammlein D. R. (1977) Lunar seismicity and tectonics. *Phys. Earth Planet. Inter.* **14,** 224–273.

Melosh H. J. (1978) The tectonics of mascon loading. *Proc. Lunar Planet. Sci. Conf. 9th,* p. 3513–3525.

Melosh H. J. (1979) The thickness of the ancient lunar lithosphere. (abstract). In *Lunar and Planetary Science X,* p. 828–830. Lunar and Planetary Institute, Houston.

Nakamura Y. (1977) HFT events: Shallow moonquakes? *Phys. Earth Planet. Inter.* **14,** 217–223.

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

Nakamura Y., Dorman J., Duennebier F., Ewing M., Lammlein D., and Latham G. (1974) High-frequency lunar teleseismic events. *Proc. Lunar Sci. Conf. 5th,* p. 2883–2890.

Nakamura Y., Duennebier F. K., Latham G. V. and Dorman H. J. (1976) Structure of the lunar mantle. *J. Geophys. Res.* **81,** 4818–4824.

Nakamura Y., Lammlein D., Latham G., Ewing M., Dorman J., Press F., and Toksöz N. (1973) New seismic data on the state of the deep lunar interior. *Science* **181,** 49–51.

Runcorn S. K. (1974) On the origin of mascons and moonquakes. *Proc. Lunar Sci. Conf. 5th,* p. 3115–3126.

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.

Solomon S. C. and Head J. W. (1979) Characteristics and evolution of the lunar lithosphere from the deformation of mascon mare basins (abstract). In *Lunar and Planetary Science X,* p. 1140–1142. Lunar and Planetary Institute, Houston.

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.

Wood C. A. and Head J. W. (1976) Comparison of impact basins on Mercury, Mars and the Moon. *Proc. Lunar Sci. Conf. 7th,* p. 3629–3651.