PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Phil. Trans. R. Soc. Lond. A 1977 **285**, 485-487
doi: 10.1098/rsta.1977.0092

Phil. Trans. R. Soc. Lond. A. **285**, 485–487 (1977) [485]
Printed in Great Britain

Transient lunar phenomena, deep moonquakes, and high-frequency teleseismic events: possible connections

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The positions of the epicentres of the recently discovered, high-frequency teleseismic (h.f.t.), shallow moonquakes have been compared with those of the surface phenomena known as lunar transient phenomena (l.t.p.). About 300 sites for the latter and about 17 shallow moonquake epicentres have been recorded. Most of the epicentres are within 5° of at least one l.t.p. site and the depths are given by Nakamura *et al.* (1974) as up to 265 km. The present paper considers some of the implications of the correlations between the two classes of sites and between the l.t.p. and the epicentres of the deep moonquakes at levels of about 800–1000 km below the surface. It appears likely that channels produced by the outrush of gases from the interior of the Moon are associated with the sites of the h.f.t. and of the l.t.p. that are almost vertically above them, and that release of gases through poorly consolidated soils at an early stage of the Moon's history may have led to the formation of at least some of the craters on the Moon.

Reports of short-lived changes on the Moon abound in the literature. These describe obscurations, anomalous colours (usually red), and increase in brightness in areas of about 5 km in diameter and lasting from a few seconds to several hours; exceptionally, large areas such as the whole of a mare have been said to have been involved and an occasional event may repeat on consecutive or closely following nights. Visual observations, which are the majority, have been criticized by some on the grounds of personal bias, possible unreliability, and the lack of a permanent record. However, 20 permanent records of such phenomena are known to me (Middlehurst 1967) and for these, the properties deduced from the statistics of the larger number of visual records are even more sharply defined. These are: periodicities related to tidal stresses on the Moon; and the non-random distribution of the l.t.p. sites which seemingly avoid the southeast highland area and are found mainly on the borders of the maria, at the larger ray craters, and in or close to black-floored craters and craters with peaks. The intelligence and scientific integrity of the majority of the early lunar observers (eighteenth–early twentieth centuries) such as W. Herschel, J. Schröter, all the Astronomers Royal of the nineteenth century, Kater, Smyth, E. E. Barnard, and many others, also suggests that their reports are not greatly biased.

Similar tidally related properties were found in 1970 by Meissner *et al.* (1971) to be shown by the deep moonquakes that were eventually recorded by the four lunar seismographs stationed at the Apollo 12, 14, 15, and 16 sites; the deep moonquakes also seemingly avoided the southeast highlands and were preferentially associated with several of the maria. In addition, at least one of the great-circle belts associated by Latham *et al.* (1973) with the distribution of the deep-moonquake epicentres is very close to a great-circle defined by ray craters from Tycho to Aristarchus, all of which have been reported as l.t.p. sites (Middlehurst 1973). More recently, the finding of 17 h.f.t. shallow moonquake sites has brought further, quite striking correlations with l.t.p. sites in some new areas away from the large maria. The class of high-frequency shallow moonquakes is being studied by Nakamura *et al.* (1971 and unpublished), to whom I am much indebted for recent data on the positions of the epicentres. See also the paper by Lammlein *et al.* (this volume).

The distribution of the epicentres of the h.f.t. is quite different from that of the deep moonquakes. Most of the h.f.t. epicentres are near the limb and few are in or near maria. However, the h.f.t. also show tidal periodicities and when l.t.p. and h.f.t. sites are plotted together on the same diagram, it is immediately obvious that close pairing of the sites in the two classes (within 5° in 12 cases and within 10° in the others) exists. The calculated depths of the h.f.t. range up to 265 km, the majority being at about 25 km depth. Although there are similarities between the types of sites for the deep moonquakes and the surface phenomena, the great depths of the moonquakes make a direct one-to-one correspondence between them over such long distances unlikely, and indeed, such correspondences are not found. Upward channels caused by stoping under favourable conditions are known to exist on the Earth for vertical distances of up to 100 km but no data are yet possible for locating such channels to depths comparable to those of the moonquakes. The much closer correlation of the h.f.t. sites with the l.t.p. sites, that has been found, suggests that such channels may also exist on the Moon and that at least some of the associated craters may have been produced by fluidization/erosion (see also Middlehurst 1973, 1974) which may be the chief mechanism for the formation of chimney-like volcanic pipes on Earth. Examples of such pipes are kimberlite and carbonatite pipes in Africa, Siberia and the Colorado Plateau in the United States of America, and the tuffsite pipes of Swabia in Germany. Such pipes are known to penetrate to depths of 100 km and are situated over dykes and fissures. The formation of a pipe above a fissure could begin at a point where the fissure widens and where it is likely to extend upwards. Gas, if it is present at all (and it cannot be entirely ruled out at an early stage of the Moon's history, e.g. 4 Ga ago), will collect at such points and will penetrate upwards and outwards, extending any cracks along lines of least resistance. Once a substantial outflow of gas is established to the surface, any irregularities will be subjected to local stresses, thermal and mechanical, that will tend to remove them through increased local abrasion. Thus, no matter how irregular the original channel, the gas flow will tend to shape it into a circular-section, cylindrical pipe. Many of the rocks in the pipe will also suffer considerable abrasion during the period spent in the pipe and will eventually, if the abrasion continues long enough, become rounded. It can be noted here that in several l.t.p. sites, e.g. Schröter's Valley and the crater Vitello, large numbers of rounded rocks have been observed in Orbiter and other lunar photographs and that some of them have apparently travelled for some distance over the surface and even uphill. Ejection from within the Moon could provide a reasonable explanation for this phenomenon.

Kimberlite pipes contain mixtures of material of shallow and deep origin that usually show signs of previously violent agitation with considerable abrasion and rounding-off of rocks in just such a way as has been described above. It is thought that the material of deep origin, e.g. eclogite, has been brought up in a violent outrush of gas, probably a mixture of steam (because water-alteration products are found in the pipes) and carbon dioxide with smaller quantities of other gases. Water and water-containing rocks are conspicuously absent in the lunar samples (but see O'Hara's paper, this conference); gases, except in the most minute quantities, are also generally absent although short-lived local atmospheres of very low density, e.g. of radon near Aristarchus (Gorenstein & Bjorkholm 1973) have been recorded. Armalcolite, a high-titanium rock of probable deep origin, first identified on the Moon, has also been found on the Earth in a kimberlite pipe (see Proceedings of the International Kimberlite Conference 1973).

Mills (1969, 1971) and others (e.g. Woolsey, McCallum & Schumm 1973) have shown that craters similar to many types found on the Moon can be produced on a small scale in the laboratory by passing gas through a fine gravel or soil at various speeds. At a certain rate of flow, the bed of fine-grained particles expands and the individual grains become contained in bubbles of gas and ultimately, as the rate of gas flow increases, are transported upward, more or less as a fluid. A large proportion of the rock fragments in tuffisite and kimberlite pipes are characteristically rounded. In the course of time, any rocks abraded in the upward passage will be worn down to the most symmetrical shape, i.e. a sphere. If the temperature is high enough, at least some of the smaller particles will turn to glass. On the Moon, spherical rocks and glass particles are known.

Neither impact nor volcanism produces sufficient variety of crater forms to account for the diversity of lunar craters without some additional mechanism of formation. In addition, as, with few exceptions, terrestrial volcanic cones (even fresh ones) are asymmetric and are secondary to the rifts that give rise to volcanism, it is almost certain that any lunar volcanism that has occurred must have had properties distinctly different from those of the terrestrial varieties.

The existence of the deep moonquakes and of the h.f.t., together with the reports of the l.t.p., demonstrates that there is still some present activity on the Moon, though at a level of intensity that would in most cases be impossible to detect on the Earth. It appears to me likely that connecting channels may exist between the h.f.t. and l.t.p. sites and possibly, also, between the deep-seated moonquake zones and the surface. It would be of great interest if a renewed watch, if possible with instruments available that are capable of recording details of short-lived changes on the Moon, could again be undertaken. Then correlations could be attempted with records of h.f.t. activity. So far, although recent changes have been recorded in the craters Manilius, Atlas, Pluto, Chevalier A, Proclus and Hercules (Moore 1971) all of which are close to h.f.t. epicentres, the records are too early to be correlated directly with the known dates of h.f.t. activity. When records are available for 1971 onwards, it will be interesting to see if any correlation exists.

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