STRESS AMPLIFICATION BY WEAK INCLUSIONS AND THE SOURCE OF DEEP MOONQUAKES. R. A. Strelitz, Lunar and Planetary Institute, 3303 NASA Road 1, Houston, Texas 77058.

The occurrence of deep moonquakes shows an unmistakable periodicity at tidal frequencies (1). Even more remarkable is the phase coherence of this seismic release and the concommitant nearly perfect correlation between the tidal phase curve and the quakes. This connection nearly requires any explanation for the moonquakes to include a tidal forcing function. However, there is more to the situation, because the stresses generated by the tides for realistic lunar models do not exceed $10^{-4}$ of the ambient stress, an amount too small to initiate fracture in solid rock.

Some workers have appealed to the existence of a weak core to amplify the tidal stresses (2), bumps on a core mantle boundary (3), or preexisting fault planes (4) to explain the existence of moonquakes and their connection to the weak tidal forces. Any appeal to large scale radial features such as a weak core or shell with reduced rigidity imply that the moonquakes should all be at approximately the same depth. This is demonstrably untrue for any reasonable laterally homogeneous moon model. Furthermore, these explanations do not consider the second striking feature of the deep moonquakes: their localization in space. The evidence for this confinement of activity to nests is the remarkable similarity of the seismic records for nest receiver pairs.

These last two observations imply that the seismic activity takes place at regions in the lunar interior that serve to concentrate the tidal stress to a degree significantly greater than in those quiescent spots. One can perhaps rule out slip along preexisting faults by noting the high ambient stress.

A possible explanation for moonquakes is, in essence, an amalgam of the above theories: that moonquakes are triggered by tidal stresses near the boundaries of irregularly shaped and distributed inclusions inside the moon.

Calculations of the stress amplification factor for an elliptical inclusion of show a strong dependence both on the aspect ratio (departure from sphericity) and rigidity contrast (5). To maximize the amplification, the inclusion should be as long and narrow as possible and be as weak as possible. The latter assumption is made because it is far easier to weaken a rock from standard values than it is to conceive of a number of hardened inclusions. Also, the observed absence of volatiles in the Moon and its preserved fossil bulges require a very high viscosity for the bulk of the Moon's mantle. The lack of volatiles would tend to eliminate grain boundary creep and other means of accommodating strain.

Rocks may be weakened in two ways: by having the homologous temperature ($T/T_m$ - the melt temperature) approach values near those of the partial melt regime, or by having the material hydrated or otherwise altered by an adulterating agent.

The first hypothesis sets some constraints on the degree of irregularity of the inclusion because of the thermal consequences of the surface to volume ratio. In short, there is a trade-off

between the longevity of the inclusion as the aspect ratio approaches 1 (a spherical shape for which surface to volume is minimized) and the degree of stress amplification due to the irregularity of the inclusion. In addition, it is important to recognize that a thermal contact would be relatively smooth and thus tend to dampen any of the amplification. However, if the inclusion contains long lived thermal sources, it could generate enough heat to maintain its integrity and existence until the present. All models of the nature of the inclusion assume that they have not been emplaced recently, geologically speaking; this does not preclude the hypothesis that what is being observed constitutes the last remanent of what was once a much more active moon.

A second possible model is that the inclusion is compositional in nature with increased volatile content to weaken the material. The absence of observed volatiles on the surface should not be in conflict with the possibility; even the most optimistic estimate of the depth of excavation by impacts would leave the region of active moonquakes unsampled. There is no bar to the existence of hydrated phases at these depths which correspond to a depth of about 100 km on earth, a region where some hydrates are stable and also a region where the velocity models have significant structure indicating compositional or mineralogical variations (6). There is also the possibility that these inclusions correspond to the chemical plumes (7), although in the case at hand, what is observed is not a steady state flow or advection but an aborted plume, or the fossil result of inhomogeneous accretion (8).

Finally, one is left with the question of the lifetime of these anomalies. Given their small size, if one accepts the source volume estimate by Nakamura (4) then there must come a point at which brittle fracture is no longer possible barring a perfect healing of the crack caused by the fracture. The details of the rheology of fault gouge are uncertain, but it does not seem plausible that the local heating generated by the rupture will not eventually diminish the stress amplification. Here again there is a trade-off between persistence of the fractures phenomena and the aspect ratio of the crack.

In conclusion, just as the existence of deep moonquakes has been instrumental in delineating the bulk properties of the lunar interior, the fact that they are localized both in space and on the tidal phase curve should be just as relevant to the study of the evolution of the lunar interior.

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