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Tidal stress and deep moonquake occurrence

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One characteristic of deep moonquakes, discovered early in the Apollo seismic experiment, is their tendency to occur with tidal periodicity, $\sim$27 days apart. This prompted early studies to investigate the relationship between tidal forcing and lunar seismic response. Tidal stresses generated in the Moon have been linked to moonquake occurrence, but conclusions differ regarding fault geometry and relevant stress tensor terms. In addition, relatively few deep moonquake source regions have been investigated, with a majority of the literature focusing on the A1 source (the largest in terms of total number of events – 443). We can eliminate some complexity from the problem by examining its geometry. Variations in the position of the Earth with respect to moonquake source locations control the gravitational tidal potential, upon which stress depends. The geometric parameters of the lunar orbit relevant to stress (and stress rates) are the Earth-Moon distance and the selenographic latitude and longitude of the Earth (and the rates of change of these parameters). We have observed that deep moonquakes can occur preferentially at certain values of these six parameters. However, these relationships are not always consistent spatially, meaning moonquake occurrence at nearby clusters can depend in different ways on the position of the Earth. This suggests that moonquake occurrence could be controlled by local structure. One way to incorporate local structure into a failure model is to investigate the role of tidal stress resolved on fault planes at various moonquake source regions.

Our goal is to perform a comprehensive investigation of the role of tidal stress in moonquake occurrence, by investigating stresses resolved on a range of plane orientations at the times of moonquakes from a number of different source regions. Traditionally, deep moonquakes have been assumed to involve shear failure, due to the large S/P arrival amplitude ratios observed on seismograms. While A1 moonquakes were found to coincide with shear stress peaks over short intervals, no correlation was found which extended throughout the entire Apollo experiment. We therefore make the more general assumption that we can find a linear combination of stresses that is approximately constant at the times of moonquakes, and compute the best-fitting failure plane orientation for which this criterion is satisfied. We explore several possible criteria for failure, including shear stress, normal stress, shear stress rate, normal stress rate, and linear combinations of both stresses and stress rates. The procedure is as follows: (1) At a given deep source location, compute the tidal stress tensors at moonquake times and at uniform (one-day) time steps. The latter allows us to map the general stress state at any location over the course of the experiment. (2) Select a local plane orientation (dip γ and strike α), and compute the shear and normal stresses ts and tn on that plane. (3) Compute the stress coefficients ws and wn necessary to minimize C – (ws ts + wn tn) in a least-squares sense. Any constant can be chosen since the resulting linear combination can be changed with a scale factor. We use C = 1 bar. (4) Using the resulting coefficients, compute the variance of the best-fitting linear combination of stresses, both at quake times and at the uniform time intervals. The measure of goodness of fit is the variance ratio, which removes bias associated with the uneven sampling of moonquakes. (5) Repeat the procedure on a 10-degree grid of plane orientations until an absolute minimum variance ratio is achieved.

At some sources, moonquakes appear to occur preferentially at monthly stress peaks, over intervals during which the magnitudes of the stress peaks themselves are increasing from month to month. This behavior contradicts the hypothesis that moonquakes occur when the tidal stress reaches a threshold level. An alternative interpretation is that in some cases moonquakes are sensitive to stress rates. For many clusters, a grid search for the best-fitting linear combination of the rates of shear and normal stress (such that wsr dts + wnr dtn $\sim$ 1, where d indicates a time derivative) improves the fit, meaning a lower variance ratio is obtained. Still lower variance ratios can be achieved using linear combinations of both stresses and rates (such that ws ts + wn tn + wsr dts + wnr dtn $\sim$ 1). For some deep moonquake clusters, tidal stresses (and stress rates) resolved on a plane provide a good criteria for failure, and we are able to identify a plane orientation that produces an approximately constant (low variance) linear combination of stresses (and/or rates) at moonquake times. At other clusters, we sometimes observe that even the maximum variance ratio is quite low, meaning the best-fitting linear combination of stresses does not depend heavily on plane orientation. This suggests a mechanism other than tidal stress-driven shear failure might be appropriate to some deep clusters.

The depth at which deep moonquakes occur (between 850-1000 km depth, where temperatures range from 1000 to 1500 degrees C and ductile behavior is expected) suggests that for some clusters, other avenues of investigation that don’t invoke only shear-stress-driven failure on a plane might better describe moonquakes. A plausible analogy is provided by deep earthquakes, for which phase changes and dehydration embrittlement are thought to promote failure in a regime where brittle shear failure would otherwise not be expected. However, the extent to which these analogies apply to deep moonquakes has not yet been fully explored. A future lunar seismic network should be sensitive enough to detect the directions of first motion associated with deep moonquakes, allowing fault mechanisms to be determined. This would greatly aid our understating of the role of tidal stress in deep moonquake occurrence.