TIDAL STRESS AND DEEP MOONQUAKES.

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Introduction: During the Apollo Moon missions, a network of four seismometers was deployed on the surface of the Moon as part of the Passive Seismic Experiment. Data were recorded continuously from 1969 to 1977 and telemetered directly to Earth for analysis. One of the first significant results from this experiment was the observation that deep moonquakes occur periodically, approximately 27 days apart. This is consistent with known tidal periods.

The presence of this periodic behavior prompted investigation into the relationship between tidal forcing and lunar seismic response. Previous studies have examined the plausibility of tidal stresses generated in an elastic Moon as a causative mechanism for moonquake activity, but conclusions differ regarding fault geometry, the structure of the lunar interior, and relevant stress tensor terms. In addition, there has been relatively little examination of any deep event source other than A1, the largest group of originally catalogued events [1].

Our objective is to perform a more comprehensive investigation of the influence of tidal stress on moonquake occurrence. We use our recent discovery of additional moonquakes [2], an improved model of the gravitational tidal potential, and a suite of internal structure models to analyze the temporal and spatial distribution of moonquakes at several deep event sources.

1. New event search: Due to the limited computing capabilities of the time, previous studies examined only those portions of the lunar seismic data where events were easily detected by eye. This method overlooked events occurring near the noise threshold, and biased event identification toward events occurring at monthly or bi-monthly intervals. Because each deep moonquake source region produces a characteristic waveform, we were able to perform an objective search through the entire continuous data set using a cross-correlation technique to identify new deep events [2]. For the nine clusters we analyzed, this resulted in an overall increase of 35% in the number of deep moonquakes identified, as described in Table 1. Augmenting the original moonquake catalog [1] with these new events produces a better data set with which to examine patterns in tidal stress at the times of moonquake occurrence.

2. Calculating tidal stress: Our goal in examining tidal stress predicted at moonquake times is to determine which aspects of the stress tensor are most diagnostic of moonquake occurrence. We began by developing an improved model of the gravitational tidal potential. Most previous deep moonquake studies use the tidal potential model of [3]. While it is convenient to use such equations, we use an alternative approach outlined below that allows a more thorough understanding of the dominant contributions to the tidal potential.

group	original	new	total	% incr.
A1	320	123	443	38
A8	224	98	322	44
A10	185	50	235	27
A18	143	71	214	50
A20	136	27	163	20
A6	132	53	185	40
A9	123	24	147	20
A14	106	57	163	54
A33	64	0	64	0
total	1433	503	1936	35

Table 1: Results of new event search for nine deep moonquake clusters. The original, new, and total number of events are listed, as well as the percent increase for each cluster.

Improved model of the tidal potential: To formulate tidal potential models, precise expressions for the positions of the primary tide-raising bodies in time are necessary. For the Moon, these are the Earth and Sun. We generate simple analytical functions in time for the positions of the Earth, Moon, and Sun by fitting time series of relevant quantities from MICA, the Multi-Year Interactive Computer Almanac [4]. MICA can generate values for the selenographic (Moon-centered) coordinates of the Earth and Sun (the sub-Earth and sub-solar latitude and longitude), as well as the Moon-Earth and Moon-Sun distances.

The spherical harmonic representation of the tidal potential in terms of the selenographic radius, co-latitude and longitude of each tide-raising source body (s,θ_s,ϕ_s) and any specified position P in the moon (r,θ,ϕ) is given by

$$\Phi[r,\theta,\phi] = -\frac{GM}{s}\sum_{n=0}^{\infty}\left(\frac{r}{s}\right)^n P_n[\cos\gamma]$$

where $\cos\gamma = \cos\theta\cos\theta_s\cos(\phi-\phi_s)+\sin\theta\sin\theta_s$ and $P_n[\cos\gamma]$ are the Legendre polynomials. The degree-2 term (n=2) is the most important for tides.

Building the stress tensor: Analytic expressions for the tidal displacement vector and the stress/strain tensors are used to calculate the response of a homogeneous elastic spherical Moon to tidal forcing [5]. As the seismic data available do not permit the determination of moonquake fault mechanisms, we explore possible predictors of, or criteria for, failure.

Shear stress generally promotes fault slip, and compressive normal stress inhibits slip. We attempt to determine what combination of these stresses is best used as an indicator for lunar seismicity. For a stress tensor $\overline{T}$ and a hypothetical failure plane with orientation defined by its perpendicular unit vector $\hat{n}$, the normal (σ) and shear (τ) stresses are formulated as:

$$\sigma = \hat{n} \cdot (\hat{n} \cdot \overline{T}) \qquad \tau = \left| \hat{n} \cdot \overline{T} - \hat{n}\sigma \right|$$

Normal stress resolved onto a locally horizontal plane at the A33 source is shown in Figure 1.

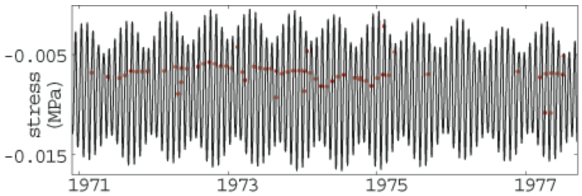

Figure 1: Normal stress (MPa) at depth on a horizontal plane at the A33 source vs. time in years. Red dots indicate stress at times of A33 moonquakes.

Results such as those shown in Figure 1 allow us to determine which stress state is favorable to moonquake occurrence. In the case of A33, moonquakes seem to occur at a fairly constant value of normal stress. However, rather different patterns of shear and normal stresses emerge when examining other clusters. Local structure in stress patterns at moonquake times is evident for individual clusters, but we have not yet found a single tidal stress indicator that consistently predicts moonquakes at all sources.

3. Exploring stress results: Our observations of correlation between moonquake occurrence times and stresses estimated for a homogeneous elastic Moon are encouraging, but still not definitive. Several tests have indicated that a more complex Moon model may yield better results. For example, at some locations, moonquakes correlate better with velocity than with position of the Earth. Figure 2 illustrates an example of this in which the sub-Earth latitude rate is compared with moonquake times. This suggests that moonquakes may respond to stress rate in addition to or in combination with the stresses themselves, or that the Moon would be better modeled visco-elastically.

The degree-3 (n=3) term in the spherical harmonic potential may also be important. The n=3 term due to the Earth is larger than the n=2 term for the Sun, and including it may improve correlation of stress with moonquake times.

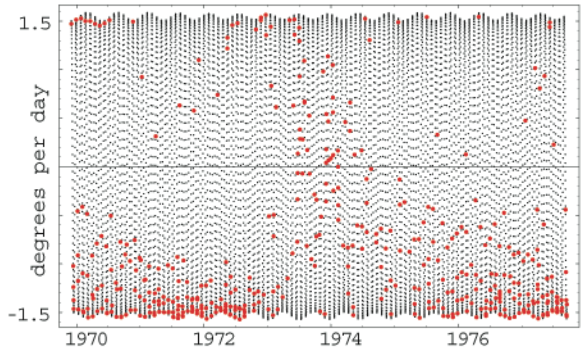

Figure 2: Selenographic Earth latitude rate (degrees per day) vs. time in years. Red dots indicate rate at times of A1 moonquakes.

In addition, examination of layered internal structure models will provide a spatial constraint, though less well resolved than the temporal characteristics. Tidal stress is depth dependent, and modeling the stress environment for a variety of layered internal structure models may allow us to learn something about the gross structure of the Moon through examination of moonquake occurrence.

4. The Moon's response to stress: After making the aforementioned observations, we will attempt to determine whether stress behavior falls into a consistent pattern that helps explain how the Moon actually responds to tidal stress. Initial investigations of various failure criteria (normal, shear, and Coulomb stress), along with a variable failure plane orientation are inconclusive, with each deep moonquake cluster apparently responding to different contributions to the local stress. Further work will determine whether this conclusion holds, or whether there is a single failure criterion more indicative of seismicity observed on the Moon.

References: [1] Nakamura, Y., G. V. Latham, H. J. Dorman, and J. E. Harris (1981), UTIG Technical Report No. 18. [2] Bulow, R. C., C. L. Johnson, and P. M. Shearer (2005), J. Geophys. Res., 110, E10003, doi:10.1029/2005JE002414. [3] Harrison, J. C., Journal of Geophysical Research Vol. 68 No. 14, 1963. [4] MICA is a software system available from the U.S. Naval Observatory providing astronomical data for a wide variety of celestial objects. It utilizes the JPL DE405 ephemerides for position calculations. [5] Alterman, Z., H. Jarosch, and C. L. Pekeris (1959), Proc. Royal Soc. London, Series A Vol. 252, No. 1268, p. 80-95.