A SIMPLE PHYSICAL MODEL FOR DEEP MOONQUAKES. R. C. Weber[1], B. G. Bills[2], and C. L. Johnson[3], [1]USGS Astrogeology Research Team (rweber@usgs.gov), [2]NASA Jet Propulsion Laboratory (bruce.bills@jpl.nasa.gov), [3]UBC Department of Earth and Ocean Sciences (cjohnson@eos.ubc.ca).

Introduction: Deep moonquakes occur between ~750 and 1000 km depth in the Moon and originate at discrete source regions referred to as numbered "clusters." Occurrence times of events from individual clusters are clearly related to tidal stress [1-8], but also exhibit departures from the temporal regularity this relationship would seem to imply.

The physical process that results in moonquakes is not yet fully understood. Even simplified models that capture some of the relevant physics require a large number of variables. However, a single, easily-accessible variable – the time interval I(n) between events – can be used to reveal behavior not readily observed using typical periodicity analyses (e.g. Fourier analyses). The delay-coordinate (DC) plot [9], a particularly revealing way to display data from a time series, is a map of successive intervals: I(n+1) plotted vs. I(n). We use a DC approach to characterize the dynamics of moonquake occurrence (Figure 1a).

Koyama [10] first applied the DC technique to deep moonquake times, and noted that moonquake-like DC plots can be reproduced by combining sequences of synthetic events that occur with variable probability at tidal periods. Though this model gives a good description of what happens, it has little physical content, thus providing only little insight into why moonquakes occur. We investigate a more mechanistic model.

In this study, we present a series of simple models of deep moonquake occurrence, with consideration of both tidal forcing and stress relaxation during events. We first examine the behavior of inter-event times in a delay-coordinate context, and then examine the output, in that context, of a sequence of simple models of tidal forcing and stress relief. We find that the stress relieved by moonquakes has a non-negligible influence on their occurrence times.

Our model: In our model, we assume there is a background stress (S), which is composed of three components: one that is constant, one that accumulates linearly with time, and one that is periodic in time:

$$S(t) = a + bt + c\sin(f_1 t) \qquad (1)$$

Whenever the background stress level reaches a fixed threshold value (v), failure occurs, relieving a fixed fraction (q) of the accumulated stress. Thus the stress at and just after each slip event is constant, but the intervals of time separating slip events are variable, since the phase of the sinusoidal oscillation at which slip occurs will vary from one event to the next. The first slip event occurs when the stress first reaches the threshold level. Subsequent slip events occur whenever the initial stress, minus the slip-induced reductions, reaches the threshold value again. In such a manner we can construct a series of slip times. Using the values a = 0, b = 0.07, c = 9.36, and f_1 = 0.228 (2π/27.55 days) in Equation 1, with v = 2.375, and q = 0.6, we can reproduce the four-corners pattern. The triangular pattern can be reproduced by adding an additional sinusoidal term such that

$$S(t) = a + bt + c\,(\sin(f_1 t)+\sin(f_2 t)) \qquad (2)$$

with all parameters remaining the same except for the additional sinusoid, with f_2 = 0.231 (2π/27.21 days). Some examples are shown in Figure 1b.

Sources of the linear stress term: In the two examples shown above, the frequency of the sinusoidal term(s) corresponds to a tidal frequency, either 27.55 days (the anomalistic month, or time between successive perigee crossings) or 27.21 days (the nodical month, or time between successive ascending nodal passages). In addition, for both cases the tidal fluctuation (sinusoid term) is approximately 130 times larger than the linearly increasing term. Given that the tidal stresses in the deep moonquake region vary by ~1 bar per month [3], the linearly increasing stress terms in our models should therefore increase by ~7.7 mbar per month. Possible dynamic processes in the lunar interior (such as thermal convection or contraction) are likely too slowly-varying to account for such a linearly increasing term. It may be possible that some of the longer-period variations in the lunar orbit (and hence the tidal stress) act as the linear term over short time scales. These variations include the precession of the argument of periapse (5.997 years), the apsidal period (8.85 years), and the nodal period (18.6 years). A stress function that includes a long-period sinusoidal variation in place of a linearly-increasing stress term is:

$$S(t) = a + c_1\sin(f_1 t) + c_2\sin(f_2 t) \qquad (3)$$

If we replace the linear term in Equation 3 with an 18.6-year sinusoid and use the anomalistic period as the monthly sinusoidal variation, we can produce DC plots (not shown) that resemble moonquake DC plots. However, we note that this stress function will eventually begin to decrease, since we have replaced an increasing linear term with one that is sinusoidally varying. Because our model allows only progressive slip, the stress function will eventually decrease to the point where the slip threshold is no longer reached, and events cease. We know this is likely not the case for deep moonquakes, which appear to occur continuously (see e.g. Figure 4 of [2]), although some clusters do appear to have periods of quiescence.

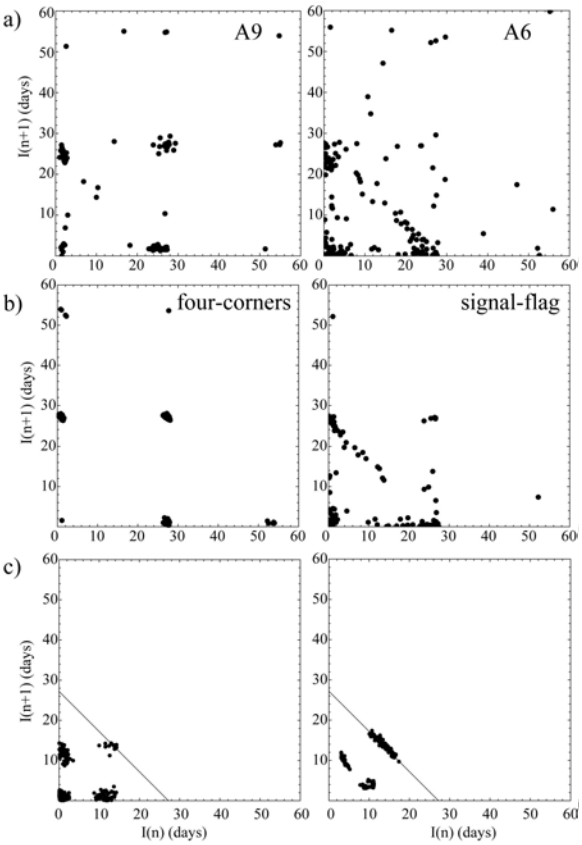

Figure 1: a) Delay coordinate plots of moonquake times from the A9 and A6 clusters. Nearly all clusters exhibit one of these two types of periodic behaviors, which we term "four-corners" (A9) and "triangular" (A6). b) Delay coordinate plots of synthetic event times computed using Equations 1 (left) and 2 (right). To reproduce the "noisy" look of the real moonquake DC plots shown in Figure 1, we have assumed that the threshold (v) at which slip occurs has a random element normally distributed over the interval 0 to 0.3 days. c) Delay coordinate plots of synthetic event times computed using the revised slip model, and the stress function shown in Figure 2e. (left) Model in which the fraction of stress relieved varies randomly between zero and some value. This plot resembles the four-corners pattern, but events occur twice as frequently as real deep moonquakes. (right) Model in which the random amount of stress relieved is restricted to a specific range of values. This plot somewhat resembles the triangular pattern.

Revising the slip model: Although the three stress accumulation equations we have tested with our slip model thus far result in moonquake-like DC plots, all of them suffer from the same problem: they do not approximate the real tidal stresses resulting from the periodicities present in the lunar orbit (Figures 2a-d). Periodic (constant-mean) stress functions are not compatible with our current slip model, since they do not permit increasing slip. We therefore revised our slip model to use a stress function that is a zero-mean sinusoid consisting of two closely-spaced tidal frequencies (Figure 2e). In this revised model, a fraction of the

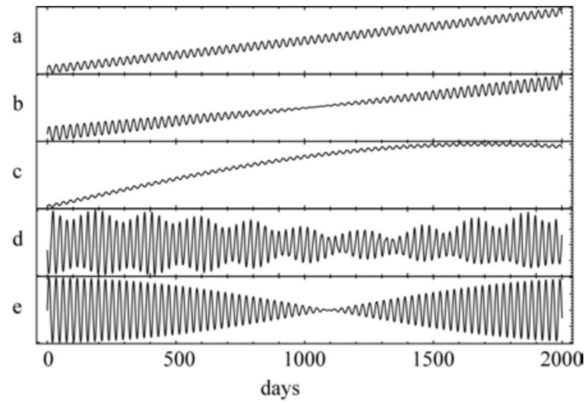

Figure 2: Stress accumulation functions. a) Linear plus monthly sinusoid. b) Linear plus two monthly sinusoids. c) Long-period sinusoid plus monthly sinusoid. d) Real tidal stress tensor term σ_{rr} computed at the A1 source location. e) Two closely-spaced monthly sinusoids. The beat period between the two sinusoids approximates the real long-term variations seen in d).

stress function is relieved whenever either a positive or negative threshold value is reached.

If the positive threshold is reached when the stress function is increasing, slip occurs and decreases the stress function. This is similar to the previous slip model. However, if the negative threshold is reached when the stress function is decreasing, slip occurs and increases the stress function. Such slip-reversal has been suggested as a possible explanation for the observed opposite-polarity A1 deep moonquakes [3].

Preliminary experimentation with this model yields promising results (Figure 1c), but further modifications are necessary to adequately match real deep moonquake DC plots. Also, the slip-reversal model may possibly account for the periods of quiescence observed at some clusters.

Implications: If the revised slip model can be used to successfully produce moonquake-like delay coordinate plots, we have good reason to believe that the same will be true when testing real tidal stress functions unique to each cluster location. This work has the potential to provide a much-sought mechanism to explain deep moonquake occurrence.

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