A SIMPLE PHYSICAL MODEL FOR DEEP MOONQUAKES. R. C. Weber1, B. G. Bills2, and C. L. Johnson3,
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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:

\[ S(t) = a + bt + c \sin(f_1 t) \]  

(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 re-produce the four-corners pattern. The triangular pattern
can be reproduced by adding an additional sinusoidal term such that

\[ S(t) = a + bt + c ( \sin(f_1 t) + \sin(f_2 t) ) \]  

(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 ex-
amples shown above, the frequency of the sinusoidal
term(s) corresponds to a tidal frequency, either 27.55
days (the anomalistic month, or time between succes-
sive perigee crossings) or 27.21 days (the nodical
month, or time between successive ascending nodal
passages). In addition, for both cases the tidal fluctua-
tion (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 in-
creasing 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 varia-
tion in place of a linearly-increasing stress term is:

\[ S(t) = a + c_1 \sin(f_1 t) + c_2 \sin(f_2 t) \]  

(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 eventu-
ally begin to decrease, since we have replaced an in-
creasing 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.
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 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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**References:**