TIDAL STRESS AND DEEP MOONQUAKE OCCURRENCE. R. C. Bulow[1], C. L. Johnson[1,2], and B. G. Bills[1,3], [1]Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California San Diego, rbulow@ucsd.edu. [2]Earth and Ocean Sciences, University of British Columbia, cljohnson@ucsd.edu. [3]NASA Goddard Space Flight Center, bbills@ucsd.edu.

Overview: One defining characteristic of deep moonquakes, discovered early in the Apollo seismic experiment, is their tendency to occur with tidal periodicity, approximately 27 days apart [1]. This prompted early studies to investigate the relationship between tidal forcing and lunar seismic response [2,3,4,5,6,7]. Tidal stresses generated in an elastic 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 [8,9]).

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. We have found that nearby moonquake clusters can depend in significantly different ways on the selenographic position of the Earth and the Earth-Moon separation, potentially indicating that local structure is important to failure.

Our goal is to perform a comprehensive investigation of the role of tidal stress in moonquake occurrence. We will investigate stresses resolved on a range of plane orientations at a number of moonquake source regions. By assuming that there is *some* stress state favorable to moonquake occurrence, we explore several possible predictors of (or criteria for) failure, including shear stress, normal stress, and linear combinations of the two. We also consider stress rates, stresses that have had the mean stress tensor removed, and ambient stress. Our preliminary results suggest that moonquake occurrence is sensitive to all of these factors.

Geometry: The geometric parameters of the lunar orbit relevant to stress are the Earth-Moon distance (EMD) and the selenographic latitude and longitude of the Earth. We have observed that deep moonquakes can occur preferentially at certain values of these parameters. However, the relationships are not always consistent spatially, meaning nearby clusters might prefer opposite extrema of the same parameter, as shown in Figure 1.

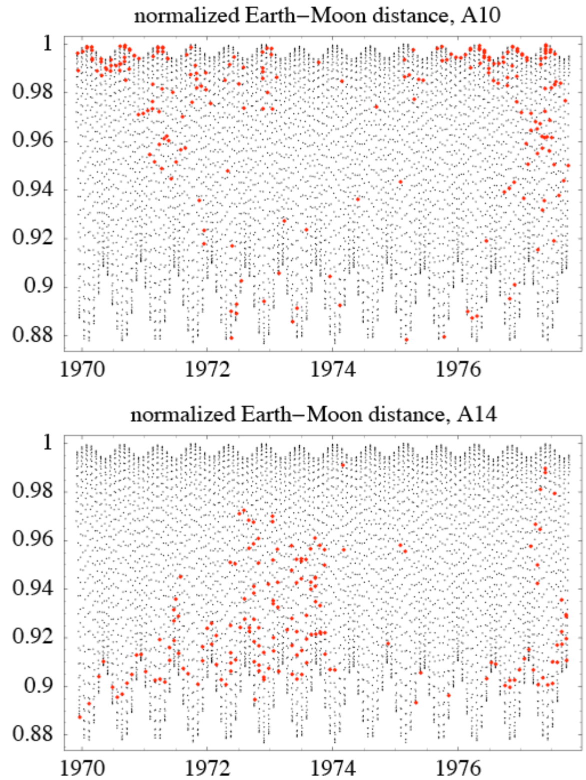

Figure 1: Fractional EMD at the times of moonquakes (red dots) over the course of the Apollo experiment for nearby clusters A10 (-35.7°N, -40.3°E) and A14 (-29.6°N, -44.4°E); locations from [10]. The angular separation between the two is ~7°, and they fall ~41° outside the ~7° box spanned by the motion of the sub-Earth point. Vertical axis is normalized such that the maximum is 1, horizontal axis is in years. Although the two clusters are close together, A10 favors maximum EMD, while A14 favors values towards the minima.

The different response of nearby deep clusters to given geometric parameters suggests that moonquake occurrence is controlled, at least in part, by local structure. Here we investigate the role of failure plane orientation.

Grid search for failure plane: Traditionally, deep moonquakes have been assumed to involve shear failure, due to the large S/P arrival amplitude ratios observed on seismograms [11]. We make the more general assumption that we can find a linear combination of stresses (shear and normal) that is approximately constant at the times of moonquakes, and compute the best-fitting failure plane orientation for which this criterion is satisfied. The procedure is as follows:

(1) Compute the tidal stress tensors at quake 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 plane orientation (dip γ and strike α), and compute the shear and normal stresses τ_S and τ_N on that plane. (3) Compute the stress coefficients w_S and w_N necessary to minimize $C - w_S\tau_S + w_N\tau_N$ 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. (5) Using the resulting coefficients, we compute the best-fitting linear combination of stresses, both at quake times and at the uniform time intervals, and take the variance. The measure of goodness of fit is the variance ratio, which removes bias associated with the uneven sampling of moonquakes. (6) Repeat the procedure on a 10° grid of plane orientations until an absolute minimum variance ratio is achieved.

The results for five spatially close moonquake clusters are presented in Table 1.

	min. var.	γ	α	w_S	w_N	w_{Sr}	w_{Nr}
A1	0.43	50°	270°	2.47	-4.70	—	—
A8	0.56	40°	110°	-0.41	2.66	—	—
A10	0.55	60°	240°	-0.96	-5.43	—	—
A14	0.33	50°	250°	2.60	-4.30	—	—
A204	0.16	60°	110°	2.12	2.15	—	—
$A1^*$	0.33	30°	200°	3.67	-0.34	-1.23	9.23
$A1^+$	0.32	70°	40°	21.14	-6.39	—	—

Table 1: Minimum variance ratio and resulting plane orientation and stress coefficients for 5 spatially close moonquake clusters (average angular separation 17.5°). The dip (γ) is the angle with respect to local horizontal and the strike (α) is measured clockwise from east.

As expected, spatially close clusters have best-fit plane orientations that can be quite different from cluster to cluster. However, they also have varying stress coefficients. The ratio of these coefficients w_N / w_S is similar to the friction coefficient μ_f (relevant to the Coulomb stress), which our model does not allow to vary laterally. While it is possible that the Moon's physical parameters are laterally inhomogeneous, there are other factors that can affect the grid-search results. Before introducing 3-D structure to the physical model, we explore the sensitivity of moonquakes to: (a) stress rates, (b) stress with the mean stress level removed, and (c) the presence of ambient stress.

Stress rates: At some sources, moonquakes appear to occur preferentially at maxima or minima in stress. This can seemingly violate causality for some situations in which the stress peaks occur at higher subsequent values each month [7], since there is no way for a moonquake to know to "wait" for a maximum in stress once a critical threshold has been passed. This suggests that in some cases moonquakes are sensitive to stress rates. For A1, inclusion of the rates of shear and normal stress in the plane search (such that $w_S\tau_S + w_N\tau_N + w_{Sr}\dot{\tau}_S + w_{Nr}\dot{\tau}_N \cong 1$) improves the fit (see Table 1, $A1^*$). Note that the best-fitting shear-to-normal weight ratio increases, which is in agreement with the conventional understanding that moonquakes represent shear failure.

De-meaned stress: Some previous studies posit that the long-term tidal stresses in the Moon are likely to have been relieved [5]. Thus it can be argued that we should consider time-varying stresses that have had the mean stress tensor removed [7]. For A1, consideration of de-meaned stress can also improve the results of the grid search (see Table 1, $A1^+$). In this case, the best-fitting shear-to-normal weight ratio also increases, although to a lesser extent than the case in which stress rates were considered.

Ambient stress: Several earlier studies of the relationship between tidal stress and moonquake occurrence conclude that tidal stresses alone cannot adequately describe moonquakes, since the magnitude of the stresses is small and likely not large enough to cause failure at the depth of deep moonquakes [6]. They conclude that the tidal stresses act as a trigger for the release of energy due to a separate, ambient stress (thermal or tectonic). We modify our grid-search algorithm to solve for the terms of an unknown ambient stress tensor, and explore how the addition of ambient stress effects the fit.

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