GEOGRAPHIC VARIATIONS IN THE TIDAL CONTROL OF DEEP MOONQUAKE NESTS AND SPECULATION ABOUT THEIR MECHANICAL ORIGIN.

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Introduction: Understanding variations in the tidal response of deep moonquake (DMQ) nests may help us understand the origin of deep moonquakes. We have grouped nests of deep moonquakes into categories depending on how strongly their occurrence is influenced by the anomalistic or draconic month and the phase of this dependence. For well-located nests having 20 or more individual events, we show that epicenters of some categories are geographically separated from one another on the Moon.

Data and Methods: We selected the data for this study from Nakamura's [1] compilation of DMQ. For this study we evaluated only nests having 20 or more DMQ and a known nest location with uncertainty of 10° or less in latitude and longitude. After applying these selection criteria there remained 53 of the 316 nests (17%) in Nakamura's compilation, and 3279 of the 6549 DMQ (50%).

Statistical procedure. To objectively categorize the remaining 53 nests, we used Rayleigh's test [2, 3] at 0.01 day intervals for periods ranging from 13 days to 33 days and determined the maximum value $D_{R\text{-}max}$ of the Rayleigh statistic. We categorized nests as 'strongly periodic' if the ratio of $D_{R\text{-}max}$ and the expected value exceeded 6.5, and 'weakly periodic' if the ratio was less than 6.5. We further categorized nests as 'predominantly draconic', 'predominantly anomalistic', or 'other' depending on whether the $D_{R\text{-}max}$ occurred at periods within 0.10 days of 27.21 days, 27.55 days, or some other value.

We further subdivided strongly periodic nests into two phase categories. For strongly anomalistic nests one subdivision comprised anomalistic phase angles of 170°-350°, which corresponds roughly to intervals when the Moon approaches perigee; the complementary subdivision when the Moon approaches apogee. For strongly draconic nests one subdivision corresponds to intervals when the subearth point is north of the lunar equator; the complementary subdivision when the subearth point is south of the equator.

Geographic regions. The amount of ellipsoidal deformation caused by tides changes during the tidal cycle. Moreover, as the Moon's mean orbital radius increases slowly at several cm/yr; over time this causes a secular decrease in both the ellipsoidal deformation produced by Earth tides and the equatorial bulge produced by lunar rotation. All of these processes induce regions of positive and negative strain within the Moon, and these regions are separated by nodal surfaces where the strain vanishes (Fig. 1). It is plausible that as the Moon's orbit changes, its changing shape produces strain and/or faulting at the base of its lithosphere, and that DMQ nests in regions of positive and negative strain respond differently to tidal forcing; i. e., that DMQ properties change across nodes in the strain pattern.

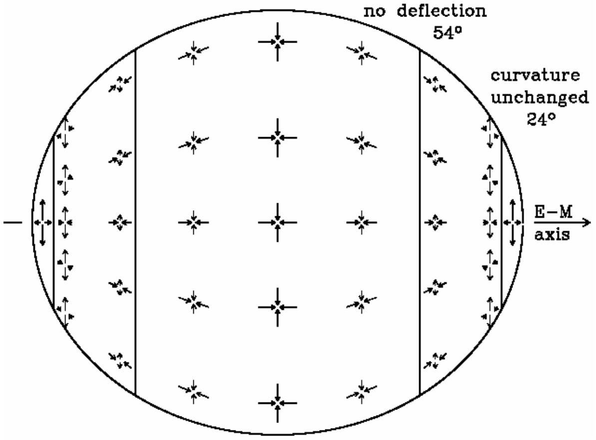

Fig. 1. There exist strain nodes in the pattern of tidal deformation. At distances of 24° from the subearth point the Moon's curvature is unchanged; at distances of 54° there is no surface deflection.

For models of lunar structure where the density ρ depends only on the distance r from the Moon's center, both the tidal and rotational potentials are separable into the product of two terms, one depending only on the distance r from the Moon's center and the other depending only on the angular distance γ_E from the subearth point (for the tidal potential) or on the the colatitude θ (for the rotational potential). Furthermore, to highest order, different distributions of density $\rho(r)$ affect only the radial term. This means that nodes in the pattern of tidal strain or rotational deformation on the Moon's surface will correspond to nodes at depths where DMQ occur. For example, the vertical component of tidal deformation is proportional to $3\cos^2 \gamma_E - 1$ and thus one such node occurs when γ_E is 24°. Thus in this study we look for variations in tidal behavior correlated with the distances where these nodes occur.

Results: Of the 53 selected nests, 15 were strongly anomalistic, 10 were strongly draconic, and 27 were weakly periodic. The Raylegh test identified only one nest (A20) that was strongly periodic having $D_{R\text{-}max}$

occurring at a period other than the anomalistic or draconic month.

The geographic locations of strongly anomalistic nests separated into two distinct groups depending on the phase of the anomalistic month when DMQ occur (Fig. 2, two upper diagrams). Nests that are active when the tidal potential is decreasing (Moon moving from perigee towards apogee) are all situated where the distance γ_E from the subearth point is less than 24°; nests active when the tidal potential is increasing (Moon moves from apogee torwards perigee) are all situated where γ_E exceeds 24°.

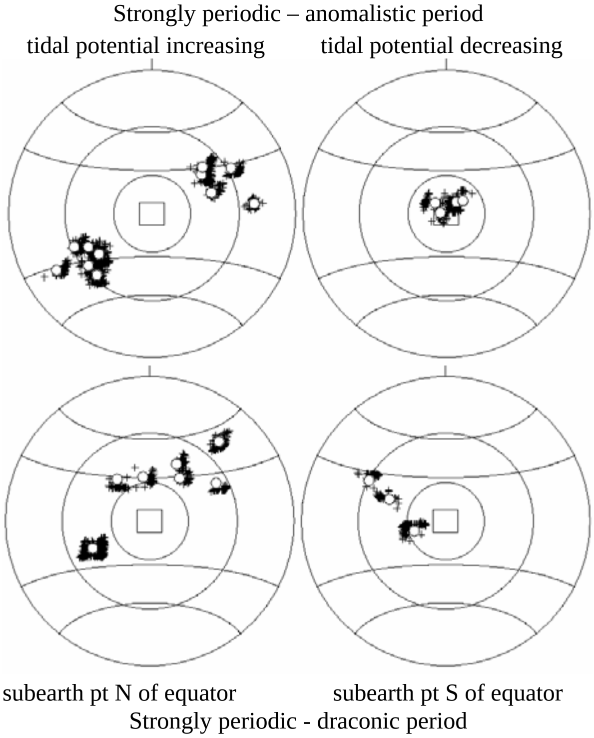

Fig. 2. Maps of Moon's front side indicating locations of strongly periodic categories of DMQ. Open circles are nest location; + symbols are locations of individual DMQ relative to subearth point. Solid lines are nodes in strain caused by tidal and rotational deformation. Map pro-jection used: distance from center of plot is proportional to angular distance from 0°N 0°E.

Similarly, strongly draconic nests occur in two geographic phase groups (Fig. 2, two lower diagrams), both at subearth distances γ_E exceeding 20°. When the subearth point is south of the lunar equator only nests W and NW of the lunar center are active; when the subearth point is north of the lunar center only nests NE, N, and SW of the lunar center are active.

We found no similar geographic pattern in the distribution of weakly periodic nests. However, there were almost no DMQ within 40° of the north and south lunar poles, or within ±25° of the lunar equator at distances γ_E of 60°-90° from the subearth point.

Discussion: The principal result of this study is that DMQ nests active at different phases and periods occur at distinct geographic locations on the Moon. The boundaries separating these locations coincide approximately with some nodal lines in the strain pattern attributable to tidal deformation and the equatorial bulge caused by the Moon's rotation.

Mechanical origin of DMQ: We have shown that some features of DMQ occurrence correlate with strain patterns attributable to the evolution of the Moon's orbit. However, the fact that they occur both when the Moon moves towards and away from perigee suggests they aren't caused solely by new growth on faults produced as the Moon's shape changes in response to its slow retreat from the Earth.

A more promising explanation is that DMQ are produced by dehydration embrittlement that enhances the growth of fuild-filled megacracks or high-aspect-ratio voids that may occur at the base of the lunar lithosphere and change volume cyclically in response to tidal forcing. This is consistent with several observations: (1) Recent analysis [4] indicates that the temperature-pressure conditions where DMQ occur are equivalent to those at depths of 100-150 km within the Earth. (2) On Earth, these are the depths were magmagenesis occurs and where dehydration embrittlement is responsible for intermediate-depth earthquakes [5]. (3) On Earth, seismicity that exhibits a correlation with tides has been observed near volcanoes where zones of trapped liquid occur. (4) DMQ nests are quite localized spatially, with dimensions of at most ~1-2 km and possibly much less [6]. (5) Failure in confined fluid-filled megacracks can occur at both local maxima and minima in the tidal stress cycle.

References: [1] Nakamura Y. (2003) *PEPI, 139*, 197-205. [2] Rayleigh L. (1919) *Phil. Mag., 37*, 321-347. [3] Fisher N. L. et al. (1987) *Statistical Analysis of Spherical Data*, Cambridge Univ. Press. [4] Gagnepain-Beyneix J. et al. (2006) *PEPI, 159*, 140-166. [5] Frohlich C. (2006) *Deep Earthquakes*, Cambridge Univ. Press. [6] Nakamura Y. (2007) *LPS XXXVIII*, Abstract #1160.