SHALLOW LUNAR SEISMIC ACTIVITY AND THE CURRENT STRESS STATE OF THE MOON

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Introduction

A vast, global network of more than 3000 lobate thrust fault scarps has been revealed in high resolution Lunar Reconnaissance Orbiter Camera (LROC) images [1, 2]. The fault scarps are very young, <50 Ma, based on their small scale and crisp appearance, crosscutting relations with small-diameter impact craters, and rates of inflation of associated small, shallow graben and may be actively forming today [Fig. 1][1-3].

The population of young thrust fault scarps provides a window into the recent stress state of the Moon and offers insight into the origin of global lunar stresses. The distribution of orientations of the fault scarps is non-random, inconsistent with isotropic stresses from late-stage global contraction as the sole source of stress. Modeling shows that tidal stresses contribute significantly to the current stress state of the lunar crust [1]. Tidal stresses (orbital recession and diurnal tides) superimposed on stresses from global contraction result in non-isotropic compressional stress and may produce thrust faults consistent with lobate scarp orientations. At any particular point on the lunar surface, the most compressive stress will be reached at a certain time in the diurnal cycle. Co-seismic slip on currently active thrust faults is expected to be triggered when peak stresses are reached. Analysis of the timing of the 28 shallow moonquakes recorded by the Apollo seismic network (Fig. 2) shows that 19 indeed occur when the Moon is closer to apogee, while only 9 shallow events occur when the Moon is closer to perigee [7]. Here we report efforts to refine the model for the current stress state of the Moon by investigating the contribution of polar wander. Progress on relocating the eventual locations of the shallow moonquakes using an algorithm designed for sparse networks [12] is also reported.

Current Stress State and Polar Wander

Radial contraction from interior cooling is the dominant source of stress, contributing 22% but <10 MPa based on the currently mapped population of lobate scarps [1, 2]. Superimposed on compressional stresses from contraction are two components of tidal stress, orbital recession stress σ and diurnal stress σ. Tidal stresses are dominated by σ, that may reach 20 to 40 kPa [1]. Stress due to orbital recession do not change with orbital position, thus it is with the addition of diurnal stresses that peak stresses are reached. At apogee, diurnal and recession stresses are most compressive near the tidal axis, while at perigee they are most compressive 90° away from the tidal axis. Thus, the occurrence of shallow seismic events generated by co-seismic slip on the thrust faults may be triggered when the Moon is near apogee or perigee [1].

An additional component of stress that may significantly contribute to the current lunar stress state is polar wander. The Moon has been attributed to a change in the Moon’s moments of inertia due to a low-density thermal anomaly beneath Procellarum [8]. The change in the location of the poles is consistent with the observed remnant polar hydrogen deposits [8]. Modeling shows that stresses from ~3° of polar wander dσ result in thrust faults with preferred orientations that are in general agreement with orientations of the mapped faults (Fig. 4). Although the contribution of diurnal tidal stresses to σ is small (≤5 kPa), the addition of σ results in peak stress when the Moon is near apogee or perigee, consistent with the occurrence of most shallow seismic events [7].

Moonquake Relocation

Using the LOGSMITH relocation algorithm [12] adapted for using inaccurate data from very sparse seismic networks, the result for each event is not a single location, but a cloud of candidate locations that are not falsifiable (regions where theoretical arrival times fall within arrival time windows for all stations) by any arrival time or back azimuth data (Fig. 5). Of the 28 total shallow moonquakes, 13 have confirmed locations - the location cloud contains the nominal epicentral location, 7 candidates for relocations - the location either moved, or a second location is acceptable (binary cloud), and 8 events are not well constrained - location cloud is fragmented. Acceptable locations occur at depths up to 300 km, and beyond which the search was terminated. However, the location cloud is also generated for all surface locations. Of the 20 relocated moonquakes with confirmed or binary clouds, 15 have solutions at the surface. (See Table 1.)

Visual comparison of the location clouds with mapped lobate scarps indicates that 9 ≤ 10 Scarps or scarps clusters are within close spatial proximity to shallow moonquake locations (Fig. 5). These are prime candidates in the search for evidence of recent activity on the young fault scarps. A statistical analysis shows that...