TIDAL SEISMICITY IN THE MOON AND IMPLICATIONS FOR THE SILICATE INTERIOR OF EUROPA.

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Introduction: Seismology will be a powerful tool to probe the interior of icy moons of gas giants if future missions land instruments on their surface. Europa is notably of high scientific interest with an active icy surface [1-2] above a potentially habitable subsurface ocean [3-4]. Seismicity in the icy shell of Europa is likely to be driven by diurnal tides of Jupiter [5] and could be used to probe its subsurface [6].

The Apollo seismometers on the Earth's Moon measured numerous seismic events driven by the Earth tides [7-8]. These events were located deep in the lunar mantle between 700-1000 km [9]. As Jupiter tides on Europa are stronger than Earth tides on the Moon, this raises the question of the likelihood of similar tidally driven deep seismic events in Europa. Here we model the tidal response of the Moon to quantify the likelihood of failure due to tides and study its implication for tidal quakes in the silicate interior of Europa.

Methodology: We model the lunar interior and its response to Earth tides with a numerical code based on [11] to obtain the tidal stress in the whole interior of the Moon along a full orbit. We use the Mohr Coulomb failure criterion [12] to identify the values of cohesion c and angle of internal friction ϕ in the lunar interior needed to reproduce the depth of the tidally driven deep moonquakes observed by the Apollo seismometers. The chosen mechanical parameters will then be applied to various Europa models to study the possibility of deep Europa quakes (or euroquakes) in its silicate interior.

Tidal seismicity in the Moon: We study three lunar interior models based on recent studies: the M1 model from Garcia et al. 2019 with a liquid core and a low-velocity zone above it [13], the M2 model from Garcia et al. 2019 with a liquid core and no low-velocity zone above it [13], and the model (named W model) from Weber et al. 2011 [14] with a solid inner core, liquid outer core, and partial melt above it. The resulting shear stress for the M1 model is maximal at the midpoint between perigee and apogee (curve (3) in Fig. 1), and is maximal for depths between 700 km and 1200 km, compatible with the deep moonquakes observed by the Apollo seismometers. For these moonquakes to be tidally triggered, the cohesion must be less than 10 kPa and the angle of friction less than 1e-4° (Fig. 2). As typical values for basalt are 100s of MPa and friction of about 30°, the deep moonquakes require existing weaknesses in the lunar interior to be tidally triggered.

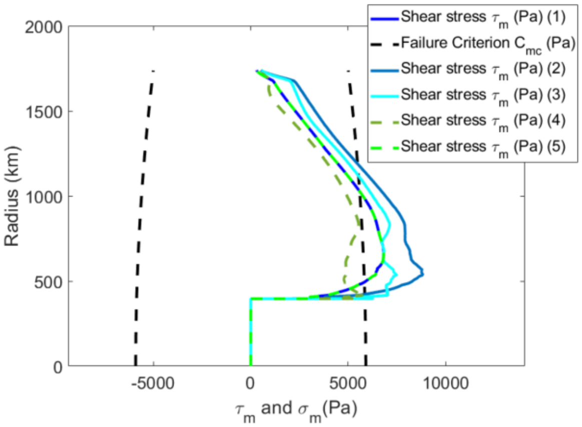

Figure 1: Shear stress in the Moon for the M1 model from [13] at the A1 epicenter, where many deep moonquakes were identified. (1) corresponds to the Moon at perigee, (5) for the Moon at apogee, and the other curves are equally sampled over the Moon's orbit.

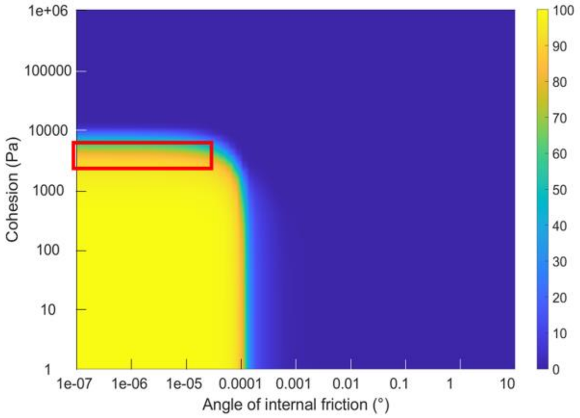

Figure 2: Failure map for the M1 model of the Moon from [13]. Yellow indicates that the whole Moon is failing, while blue indicates no failure at all. The red box indicates the necessary values of cohesion and friction in the lunar interior to replicate the deep moonquakes at the depths observed by the Apollo seismometers only.

Implications for Europa quakes: We construct three self-consistent interior models of Europa using the PlanetProfile software [15]: the E1 model of Europa being undifferentiated with no metallic core, the E2 model with a solid core, and the E3 model with a liquid core. The shear stress in the Europa models are greater by about an order of magnitude due to the stronger Jupiter tides (Fig. 3) and are the strongest for the liquid core model. The resulting failure maps (Fig.4) show that failure from tidal stress is therefore at least 10 times

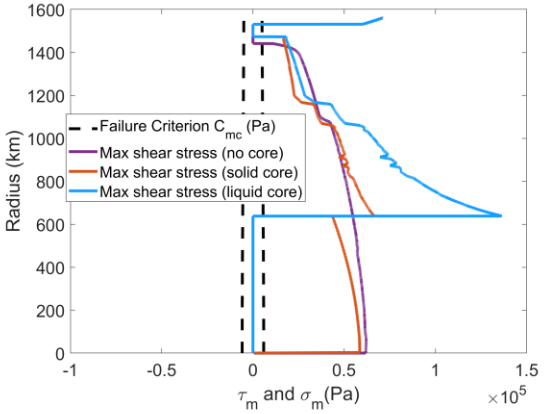

Figure 3: Maximal shear stress for different Europa models. Failure criterion is based on the same values of cohesion and friction as derived for the Moon in Fig. 1.

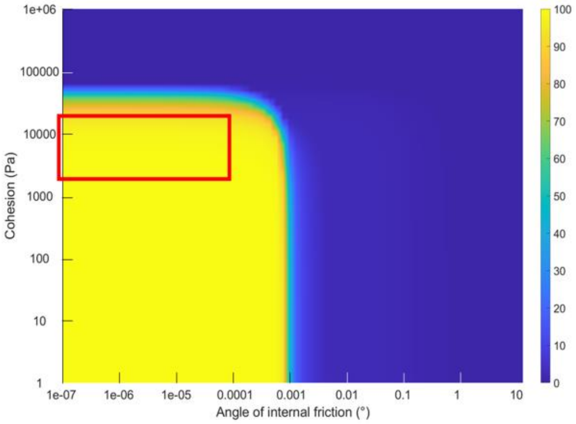

Figure 4: Failure map for the liquid core model of Europa. The red box refers to the cohesion and friction needed in the Moon to replicate the deep moonquakes observed by the Apollo seismometers. Failure in Europa can occur for values above 10 times those in the Moon.

more likely to happen inside Europa than inside the Moon, suggesting that it is likely that tidal quakes can occur in the silicate interior of Europa like in the Moon.

Seismic investigation of Europa: The amplitude and location of stress concentrations varies depending on the interior structure of Europa (Fig. 3). If Europa has a core, the most likely location for tidal quakes is at the core-mantle boundary, with stronger events suggesting a liquid core. Solid core and no metallic core models can also have failure occur at the top of the mantle, or 300 km below the seafloor. Therefore, if a future seismic mission to Europa can retrieve the strength and depth of tidal Europa quakes, it could constrain the deep interior of Europa. Since the magnitude of deep moonquakes is between 2 and 3 [16], we can also estimate the Europa quakes in the silicate interior to be at best of magnitude 4.5, which may be enough to be detected by a STS2-like seismometer landing at the surface of Europa (Fig. 5).

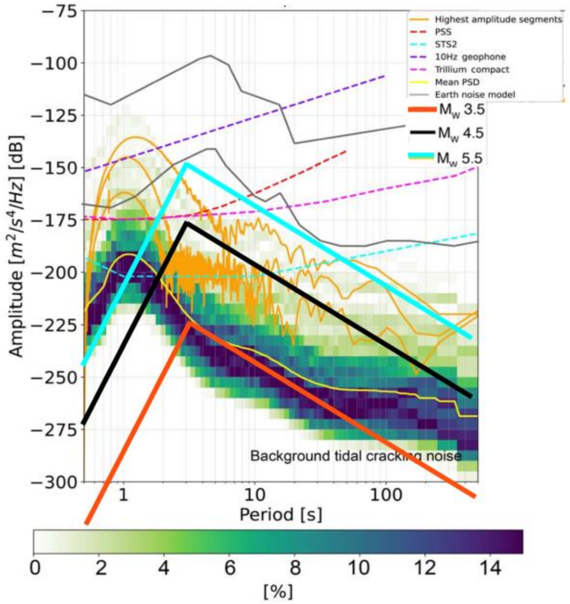

Figure 5: Estimation of background noise, icequakes signals from the ice shell of Europa, and deep Europa quakes triggered by tides in the interior of Europa compared to typical Earth seismometers, modified from [16-17]. Geophones could observe icequakes in the ice shell, but more efficient seismometers are needed for detecting the Europa quakes in the silicate interior.

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