TIDAL DEEP QUAKES IN 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. If such events exist and can be detected, they would provide strong constraints on both the subsurface and deep interior of the icy moon of Jupiter [10].

Approach: As our only observations of deep tidal quakes are from the Apollo seismometers on the Moon, we model the lunar interior and its response to Earth tides to recover the mechanical parameters of the Moon's mantle that recreate the tidally driven deep moonquakes observed by the Apollo seismometers. We then apply the same mechanical parameters to models of Europa's interior under the tides of Jupiter to study if such tidally driven deep quakes could also be likely on Europa as well, and how deep and strong they would be.

Methodology: The tidal response of the Moon is obtained with a numerical code based on [11] and validated on icy moons with the code from [12] to obtain the tidal stress in the whole interior of Europa along a full orbit. Application to this code on the liquid core Moon model of [13] is shown in Fig. 1 with good agreement between [13] and our code.

Failure in the silicate interior of Europa is modeled using the Mohr Coulomb criteria [14,15]. In this framework, material failure is reached when the shear stress τ becomes greater than the normal stress σ_n and cohesion c of the material:

$$\tau = c + \sigma_n \tan\phi$$

where ϕ is the angle of internal friction such as $\tan\phi = C_f$ with C_f being the coefficient of friction.

Reference with the Earth's Moon: The shear stress is given from the calculated tidal stress, while normal stress comes from the calculated tidal stress and from the lithostatic pressure, leaving c and ϕ as free parameters. The values of (c, ϕ) to obtain tidal deep moonquakes with similar depths as those observed by the Apollo mission is shown on Fig. 2. The special case $\phi = 0$ would represent either an ideal frictionless interior, or a local stress tensor perfectly balancing the local lithostatic pressure and hence representing a state at the edge of rupture.

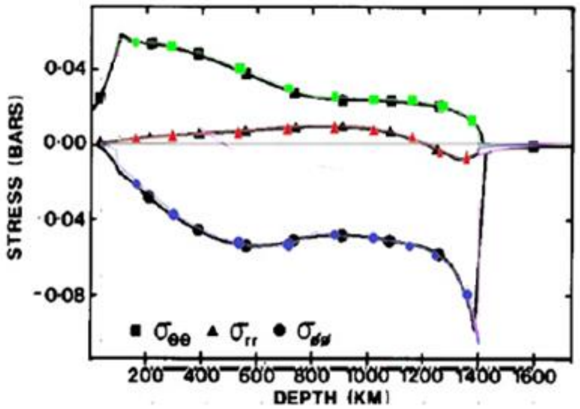

Figure 1: Tidal stress in the lunar interior. Liquid code model from [13] is used here. Black lines are results from [13] while our code is given in colored lines, with good agreements.

The values of cohesion and friction are significantly lower than standard values [14], but this may be due to the repeatability of the tidal stress, cycling every lunar month and periodically weakening existing heterogeneities and faults in the lunar interior without leaving enough time for fault healing. This phenomenon may be even stronger on Europa, as its orbits Jupiter every 3.55 days compared to the 27.3 days of the synodic lunar month.

Application to Europa: We apply the same code and failure criterion to an interior model of Europa based on [10], using an ice shell thickness of 20km and a 80-km thick subsurface ocean, a liquid core of radius 480 km, and the same parameter space for (c, ϕ) as used for the Moon in Fig. 2. The results for Europa are shown on Fig. 3. As expected from the stronger Jupiter tides, failure of Europa is more easily reached, with higher cohesion c and higher angle of internal friction ϕ compatible with failure in the mantle of Europa according to the Mohr Coulomb criterion.

Discussion: Depending on the values of these two parameters, the location of the quakes in the interior of Europa also changes. As shown in Fig. 4, assuming a frictionless interior with no effect of the lithostatic

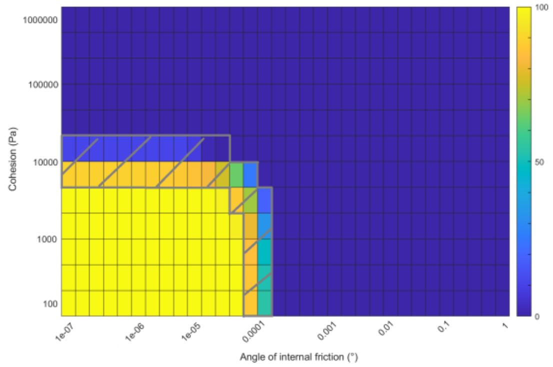

Figure 2: Values of cohesion c and ϕ where tidal moonquakes occur in the lunar interior. Lunar model used is from [16]. Dark blue cases indicate that failure is not occurring at all, while yellow indicates failure is reached in the lunar mantle. The gray area and outline delimitate the values for which only deep moonquakes occur in the Moon (as opposed to shallower events).

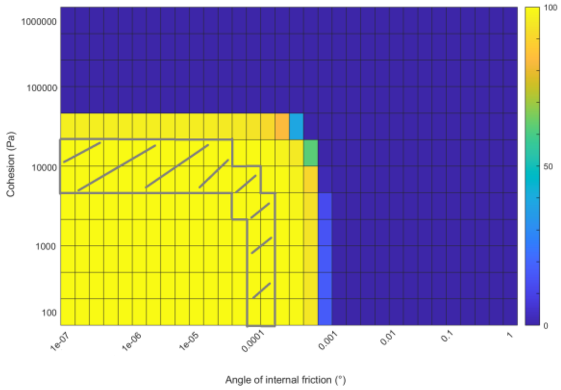

Figure 3: Values of cohesion c and ϕ where tidal moonquakes occur in the interior of Europa. Europa model used is inspired from [10]. Dark blue cases indicate that failure is not occurring at all, while yellow indicates failure is reached in the lunar mantle. Gray area and outline is for the Moon from Fig. 2.

pressure (as often done when studying tidal moonquakes, as in [7-8]) leads to rupture being more likely at the core-mantle boundary before being possible in the whole silicate interior. However, if the lithostatic pressure is taken into account, failure starts in the silicate interior at the ocean – mantle boundary, and no events at the core – mantle boundary are likely for (c, ϕ) values compatible with the deep moonquakes on the Earth's Moon. Accurate determination of the depth of Europa quakes would therefore constrain the appropriate model for the mechanical state of the silicate interior of Europa.

Only eccentricity-driven diurnal tides are taken into account for this stress calculation. While obliquity tides and non-synchronous rotation have a strong impact on ocean worlds [17], this has little impact of our work focused on the underlying solid silicate mantle. Following studies will focus on linking stress amplitude to fault orientation, event magnitude and expected source spectrum. This could also be applied to the faults observed at the surface of Europa, or to the interior of other icy worlds like Enceladus or Titan.

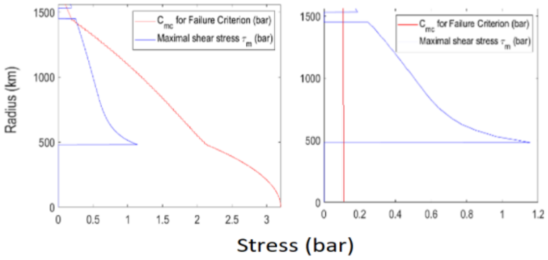

Figure 4: Mohr Coulomb failure criterion (red) and shear stress amplitude (blue) in function of radius in the interior of Europa. Europa model used in inspired from [10]. Left model is taking lithostatic pressure into account, albeit with a very weak value for ϕ. Right case is a mechanical model with no lithostatic pressure (akin to using a coefficient of friction $\phi = 0$). Cohesion is 10 kPa for both cases. Failure can occur either at the ocean – mantle boundary, or in the whole silicate interior starting at the core – mantle boundary.

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