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Tidal tectonics and lateral variations of lithospheric thickness

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1. Introduction

Most icy satellites of the outer planets show prominent tectonic features on a global scale which can be due to periodic tides, polar wander, despinning, contraction (or expansion), orbital recession and convection [1]. Among these causes, periodic tides stand out because they can explain recent tectonic activity on Europa [2] and Enceladus [3, 4] whereas other mechanisms (apart from convection) most likely occurred in the far past. Periodic tides include diurnal tides associated with an eccentric orbit (obliquity tides are usually negligible) and nonsynchronous rotation. Until now, tidal stresses have been computed under the assumption of spherical symmetry [5]. However the thickness of the lithosphere (or ice crust) is affected (1) by solar insolation, making it thinner at the equator, and (2) by internal heating, making it thinner for example at the south pole of Enceladus (where active plumes have been detected by the probe Cassini). I compute here tidal stresses assuming that the lithospheric thickness varies with latitude.

2. Method

The lithosphere of a satellite responds to tides by deforming in a shape described by spherical harmonics of degree two and of order zero and two. Given the radial deformation (dependent on the Love number h_2), I compute the stress function solving the membrane equation for a thin spherical shell of variable thickness [6]. The matrix method presented in [6] applies without change to the zonal tidal deformation. Regarding the sectoral tidal component (degree 2, order 2), this method must be slightly modified because the stress function is then represented as a sum of spherical harmonics of order two (assuming that the lithospheric thickness varies only with latitude). Thus the product of the inverse thickness and stress function appearing in the membrane equation involves products of spherical harmonics of order zero and two, which are evaluated in Mathematica with Clebsch-Gordan coefficients. In the end, there are two matrix equations for the harmonic components of the stress function, one for the zonal components and another for the sectoral components. The total stress function is the sum of the stress functions due to the two tidal components. Finally the tidal stresses are obtained by applying differential operators to the stress function.

3. Results

If a satellite undergoes nonsynchronous rotation, the orientation of the surface slowly changes in longitude with respect to the tidal axes. The associated deformation is of harmonic order two. Figure 1 shows the principal stresses at the surface due to 1° of accumulated nonsynchronous rotation. The top and bottom panels show the stress pattern for a lithosphere of constant thickness (see various examples in [2, 5]) and for a lithosphere thinner at the equator, respectively. The equatorial thinning of the lithosphere results in stresses relatively larger near the equator and smaller in the polar areas (note that the magnitude of stresses should not be compared between the panels but only within each panel). However the orientation of the principal stresses is not much affected.

Diurnal tides have harmonic components of order zero and two. Figure 2 shows the principal stresses at the surface due to diurnal tides when the mean anomaly is 120°. The top and bottom panels show the stress pattern for a lithosphere of constant thickness (see various examples in [2, 5]) and for a lithosphere thinner at the south pole, respectively. The thinning of the lithosphere results in stresses relatively larger in the southern polar area but the orientation of the principal stresses is not much affected.

4. Conclusions

The magnitude of tidal stresses is relatively enhanced in areas where the lithosphere is thinner, making it more likely that faults appear in these locations. Confirming intuitive expectations, that result would account for the location of the faults called 'tiger stripes' at the south pole of Enceladus. The orientation of the

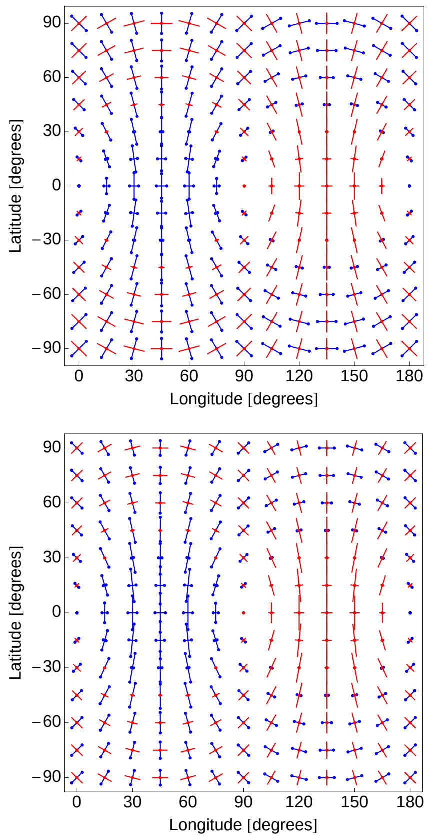

Figure 1: Principal stresses on the surface of the satellite (sub-planet point at $(0°, 0°)$) if accumulated non-synchronous rotation of $1°$. Compression is in blue, tension in red. The pattern is repeated for longitudes between $180°$ and $360°$. In the top panel, the lithospheric thickness is constant whereas it is half as thick at the equator as at the poles in the bottom panel.

faults is only slightly affected by the lateral variations in lithospheric thickness because of the assumption of isotropic elasticity. Anisotropic constitutive equations of elasticity would have a greater impact on fault orientation but it is questionable whether they would meaningfully describe a lithosphere weakened by parallel faulting.

Acknowledgements

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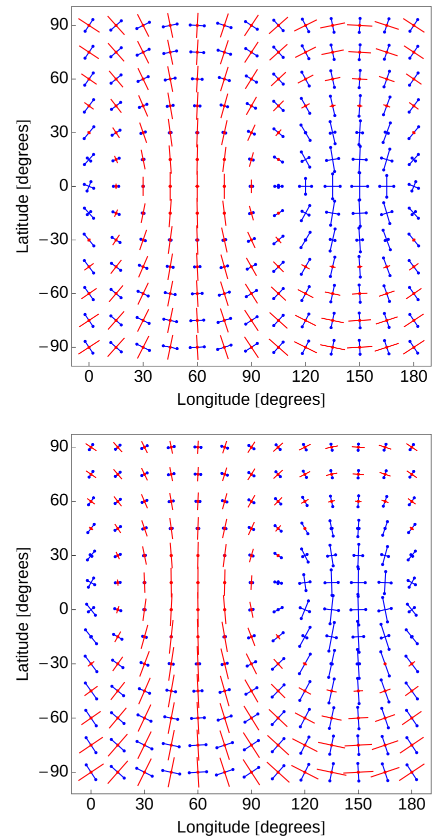

Figure 2: Principal stresses on the surface of the satellite due to diurnal tides at the point in the orbit where the mean anomaly is $120°$. In the top panel, the lithospheric thickness is constant whereas it is four times thinner at the south pole than at the north pole in the bottom panel. Other details as in Figure 1.

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