Surface stresses resulting from internal differentiation: Application to Ganymede tectonics. G. C. Collins[1], R. T. Pappalardo[1], and J. W. Head[1], [1]Dept. of Geo. Sci., Box 1846, Brown University, Providence RI 02912. Geoffrey_Collins@brown.edu.

Introduction

Grooved terrain tectonism on Ganymede records a period of intense surface deformation driven by interior processes. Many hypotheses have been proposed to explain the formation of grooved terrain [cf. 1], but morphological data, strain estimates, and stratigraphic relationships derived from Galileo data have narrowed the field [1,2,3]. Grooved terrain formation was probably dominated by global expansion, with low-order convection or changes in the figure of Ganymede organizing the strain orientations [1]. Significant amounts of global expansion may occur relatively rapidly, driven by episodes of runaway tidal heating [4] or by differentiation of a homogeneous rock-ice body into a rocky core and an icy mantle, displacing dense ice phases from the interior of the body [5,6]. The evidence from Galileo that Ganymede is strongly differentiated [7], while Callisto (which is similar in bulk properties to Ganymede but lacks grooves) is mostly undifferentiated [8] lends credence to the idea that differentiation played an important role in the formation of Ganymede grooved terrain. Here we investigate the stress fields which might result from differentiation of Ganymede, and the role these stresses may have played in the formation and distribution of grooved terrain.

Pattern of surface stress from differentiation

If global expansion caused by differentiation increased the radius of a satellite by a fixed value at every point, then the surface stresses expected from this mechanism would be isotropic, with no preferred orientation. Inhomogeneities in the lithosphere might control the expression of this isotropic stress, and thus give some orientation to the resulting strain [e.g. 9]. However, isotropic stress would only occur in the case of expanding a perfectly spherical body. Ganymede is distorted into a triaxial ellipsoid by its rotation and by the tidal pull of Jupiter. Concentration of mass toward the center of such a body will decrease the surface tidal and rotational deformations [10]. The change in tidal and rotational distortion breaks the isotropy of the global expansion stress field and may serve to organize the strain resulting from differentiation.

What is the pattern of surface deformation expected from this mechanism? The differentiation of a homogeneous body into a core and mantle decreases both the tidal and rotational distortions by a dimensionless factor *H*, which is dependent on the density of the mantle [10]. A lower density mantle (with a corresponding increase in mass concentration toward the center of the body) will decrease the value of *H*, lowering the amplitude of the tidal and rotational distortions. Orbital recession also lowers the tidal and rotational distortions of a synchronously rotating satellite. The distortions are both decreased by a factor of a^{-3}, where a is the average orbital distance of the satellite. The stress field resulting from orbital recession has been modeled by [11], by superimposing the two biaxial distortions of decreasing the tidal bulge and the rotational bulge by a constant multiplier. In the case of satellite differentiation, the tidal and rotational bulges are also decreased by a constant multiplier (*H*), so the resulting stress field is the same as that modeled by [11].

Estimates that the lithosphere of Ganymede may have been only about two kilometers thick during groove formation [e.g. 3] indicate that, for the purposes of studying deformation due to changes in figure, Ganymede would best be modeled with a thin elastic shell during this period. In the case of a thin elastic shell on Ganymede, a decrease in the amplitude of the tidal and rotational distortions should produce thrust faulting around the subjovian and antijovian points, normal faulting around the poles, and strike-slip faulting in between these areas [11]. In the case of differentiating Ganymede, where potential exists for up to several percent increase in radius [6] concurrent with the change in figure, the isotropic tensional stress caused by expansion dwarfs the stresses due to the change in figure. In this case, the entire surface should be in the normal faulting regime, but with the fault orientations controlled by slight stress differences due to the change in figure.

Due to conservation of angular momentum, a body will increase its rotation rate as mass is concentrated toward the center. Whether Ganymede increased its rotation rate during differentiation depends on the timescale of differentiation compared to the timescale of tidal locking of the satellite's rotation. The answer to this question is not clear, as the bulk of differentiation could have taken place as fast as 10^3 years [12], and the tidal locking time, while poorly constrained, could also be as fast as 10^3 years [13]. Absent any tidal locking, the differentiation of a homogeneous, centrally compressed body (C/MR^2 = ~0.39) into the Ganymede we observe today (C/MR^2 = ~0.31, [14]) would increase the rotation rate by almost 30%.

The effect of a change in rotation rate on surface stress patterns during differentiation will be twofold. First, if the satellite were rotating at a nonsynchronous rate, there would be stresses due to shifts of the tidal axis across the surface [15]. Second, the decrease in rotational distortion due to concentration of mass in the satellite's center would be offset by an increase in rotational distortion due to a faster spin rate. This would serve to decrease the influence of the pole-centered biaxial distortion component of the stress field in the model of [11], moving the stress trajectories toward a pattern radially symmetrical around the tidal axis [cf. 16], and perhaps beyond this, into concurrent shortening of the tidal and rotational axes. The relative strengths of the tidal and rotational deformations could change through time, changing the pattern of surface stress through time. The stress pattern would change as the tidal axis is constantly shortening during differentiation, while the spin axis of the satellite shortens as it is first spun up, and then lengthens as the satellite becomes tidally locked.

The heat produced by differentiation will probably produce a liquid water ocean in Ganymede's interior [6], decoupling the surface ice from the rest of the body. Thus, even if the tidal locking timescale is faster than the differentiation timescale, and Ganymede as a whole does not increase its spin rate, the floating ice shell is likely to rotate nonsynchronously [17], since it is unlikely to preserve any large mass asymmetries. The decoupling of the ice shell would add the nonsynchronous rotation stresses [15] to the other stresses due to differentiation.

Magnitude of surface stress from differentiation

The magnitude of the surface stresses expected from differentiation depends on: 1) the degree of differentiation, which controls the size of the tidal and rotational bulges, 2) the amount of radius expansion during differentiation, 3) the elastic properties of the lithosphere, and 4) the timescale of the buildup of these stresses compared to the time over which these stresses would relax by viscous flow. For even a modest amount of radial expansion (1%) and a shear modulus for ice of ~10 GPa, the magnitude of surface stress due to expansion are ~100 MPa to 1 GPa [cf. 11], compared to approximate lithospheric strength at this time of 2-3 MPa [1]. This isotropic tensional stress is a few orders of magnitude larger than the stress due to changes in Ganymede's figure (~1 MPa [cf. 10,11]). Thus, to determine if brittle failure will occur or is stress will instead relax viscously, the important factor to investigate is the radial expansion through time versus the Maxwell time of the lithosphere. The bulk of Ganymede's differentiation may have taken place within $>10^3$ years [12], and the bulk of the radial expansion may have taken place during the first half of the differentiation [6]. Based on crater relaxation, the Maxwell time of the lithosphere may be $\sim10^8$ years [18], so it appears that the stresses due to differentiation may have built up much faster than they could be viscously accommodated, leading to brittle faulting of the lithosphere.

Discussion

The differentiation of Ganymede would have affected the surface by radial expansion and by changes in the tidal and rotational distortion of the body, which are to a first order similar to the changes expected for a body in orbital recession. Two questions remain: would evidence of differentiation remain on the surface, and are the predicted stresses consistent with the formation and observed trends of grooved terrain?

Differentiation may have taken place very early in Ganymede's history, and the heat pulse associated with the primary differentiation of Ganymede may have been too large for any surface features to remain preserved, thus erasing any tectonic record of this process [6]. However, the timing of differentiation and heating on Ganymede may have to be reevaluated in light of Callisto's evolutionary path, and the possibility that Ganymede presently has a molten iron core [7]. If the surface record of differentiation was erased, then perhaps grooved terrain may either preserve a record of secondary differentiation [6], or a record of tidal stresses, heating, and global expansion due to passage through an orbital resonance [4].

Because it is possible that a record of differentiation could be preserved on the surface today, we are working to compare the predictions of the differentiation model against our observations of grooved terrain. Observations of grooved terrain on Ganymede suggest that: 1) the amount of extensional strain represented by grooved terrain is locally high [3,19], and no unambiguous compressional features have been found to accommodate this extension, 2) grooves appear to have formed in episodes, with regionally coherent orientations within each episode [1], and 3) the orientation of grooves appears to have changed through time, implying that the regionally coherent stress orientations have changed through time [1,20]. The global expansion that occurs with differentiation provides locally high extensional strain without the need for balancing compression elsewhere. The changes in figure that occur with differentiation can provide shifting, regionally coherent stress patterns which may organize the strain caused by global expansion. In the case of slow differentiation with respect to the tidal locking time, the shifting stress pattern could be caused by nonsynchronous rotation of a floating ice shell. In the case of fast differentiation with respect to the tidal locking time, the shifting stress pattern could be due to a combination of nonsynchronous rotation and a time lag between the decreases in the tidal and rotational distortions. Further work is in progress to examine the progression of the fast differentiation stresses through time, and to compare these predictions to groove orientations on Ganymede.

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