GLOBAL REORIENTATION AND ITS EFFECT ON TECTONIC PATTERNS ON GANYMEDE

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Abstract. The perturbation to the momental figure of Ganymede by the impact basin Gilgamesh was modelled, and it was found that the formation of the basin could have significantly reoriented the satellite. Global trends of groove orientation suggest that groove sets formed in reactivated zones of weakness, which were created by tidal despinning and furrow formation. The paleopole on which despinning occurred was shifted about 15° after the emplacement of most grooved terrain. The youngest grooves have orientations consistent with those expected for fractures caused by the reorientation.

Introduction

One of the important global forces that may affect the satellites of the outer planets is global reorientation, due to perturbation of the momental figures of the satellites by young impact basins (Smith et al., 1982). Because it is a large mass deficit, a young basin will reorient a satellite so that the basin migrates toward the body's pole. Ganymede in particular may exhibit the effects of this global process, because it both possesses impact basins and has an abundance of tectonic features that may record stresses created by global reorientation. It is the aim of this study to identify particular basins on Ganymede that may have reoriented the satellite, and to determine if there is geologic evidence that such reorientation indeed occurred.

Tectonic patterns on Ganymede

The surface of Ganymede is dominated by two material units, bright and dark terrains, and two types of tectonic features, grooves and furrows (Smith et al., 1979a,b; Casacchia and Strom, 1984). Grooves are linear troughs which cross-cut furrows and are strongly concentrated in bright terrain. They are believed to be extensional features, probably degraded grabens or tension cracks (Parmentier et al., 1982), and occur in sets of three major types: elongate parallel bands (groove lanes), polygonal areas with single groove sets (grooved polygons), and polygons with two orthogonal groove sets (reticulate polygons). Groove orientations are structurally controlled on a local scale by zones of weakness parallel and perpendicular to furrows (Murchie and Head, 1985a,b). However, on a global scale the orientations of major groove lanes follow a pattern not simply related to furrows. The groove lanes in the anti-Jovian hemisphere are dominantly oriented NW-SE while those in the sub-Jovian hemisphere are dominantly oriented SW-NE. Bianchi et al. (1985, pers. comm., oral presentation at LPSC 16) found that the majority of grooves define two systems of small circles centered on poles at approximately 55°N, 73°W and 70°N, 180°W. Because the poles are less than 50° apart, the two systems are equivalent to a single system of small circles with a pole at 70°N, 110°W, with which grooves form low angles (<25°).

Methods

Ganymede was modelled as a differentiated icesilicate spheroid, similar to that suggested by Kirk and Stevenson (1982). We assumed a silicate core of density 3.5 g cm⁻³ and radius 1826 km, and an ice mantle and lithosphere consisting of shells of ice VI, ice V, ice III and ice I. The major axes of the satellite's synchronously rotating hydrostatic ellipsoid were calculated using equations from Helfenstein and Parmentier (1983):

\[ X_1 = \frac{R(1 + 7hMR^3)}{6 m a^3} \]  
\[ X_2 = \frac{R(1 - 2hMR^3)}{6 m a^3} \]  
\[ X_3 = \frac{R(1 - 5hMR^3)}{6 m a^3} \]

where \( X_1, X_2, \) and \( X_3 \) are the major, semimajor and minor axes of the planet's ellipsoid, \( R \) is Ganymede's radius (2630 km), \( M \) is Jupiter's mass (1.899 × 10²⁰ g), \( m \) is Ganymede's mass (1.49 × 10²³ g), \( a \) is Ganymede's orbital radius (1.07 × 10¹¹ cm), and \( h \) is the Love number for a hydrostatic figure (2.5). The minor, semimajor, and major inertial moments (A, B, and C) were derived from an initial estimate based on a sphere using the relationship of Corben and Stehle (1960).

An impact basin on the planet was modelled as a cylindrical depression of a depth consistent with photogeologic evidence. The basin's moment of inertia was calculated as by Melosh (1975). The moment about an axis passing through the crater floor, \( I_3 \), is:

\[ -(4/3)\pi R^4 \rho dp (1 - \cos \theta)^2 (2 + \cos \theta)(1 + 2\cos \theta) \]  

The moment about two orthogonal axes, \( I_1 = I_2 \), is:

\[ (2/3)\pi R^4 \rho dp (1 - \cos \theta)^2 (4 + \cos \theta + \cos^2 \theta)(1 + 2\cos \theta) \]

where \( \rho \) is ejecta density, \( \theta \) is the basin radius in radians, and \( d \) is the basin depth, derived from the empirical depth-diameter relationship of Pike (1977) for fresh lunar craters.

Global reorientation was modelled numerically, by
treating cumulative reorientation as a series of incremental reorientations followed by adjustments of the tidal bulge. The decaying inertial tensor of the basin and the satellite's tensor were summed iteratively, and the new figure and principal axes were determined from the eigenvectors of the summed tensors. For the simple case where reorientation occurred by a rotation about one of the principal axes of the ellipsoid, the maximum deviatoric stress was calculated from the equation of Helfenstein and Parmentier (1985):

$$\sigma \Delta \theta = 8\mu A \Delta \theta (1+\nu)/(5+\nu)$$

where $\Delta \theta$ is the angular reorientation in radians, $A$ is the amplitude of the bulge over which the spheroid rotates ($2.3 \times 10^{-4}$), and $\mu$ and $\nu$ are the shear modulus and Poisson's ratio for ice ($3 \times 10^{10}$ dyne cm$^{-2}$ and 0.25) (Gold, 1977).

Three timescales are important in determining the duration and amount of global reorientation. The damping time of Ganymede's libration about its new orientation was calculated using the equations of Melosh (1975) and is less than 2 yrs, insignificant on the timescale of reorientation. The time in years for relaxation of the tidal bulge is given by Greenberg and Weidenschilling (1984) as:

$$\tau \text{ bulge} \approx \eta/\rho g \Delta R$$

where $\eta$ is mantle viscosity ($10^{14}$P) (Poirier al., 1981; Parmentier and Head, 1981; Zuber and Parmentier, 1984), $\rho$ is the average density of the body, 1.93 g cm$^{-3}$, $\Delta R$ is the change in radius of the hydrostatic ellipsoid due to reorientation, and $g$ is Ganymede's gravity, 160 cm s$^{-2}$. The time for isostatic adjustment of the crater by viscous relaxation was given by Parmentier and Head (1981) as:

$$\tau \text{ crater} = 50 \eta_{\text{eff}}/\rho g D$$

where $\eta_{\text{eff}}$ is the effective mantle viscosity, and $D$ is the crater diameter in km. If the time for relaxation of the tidal bulge is much shorter than the lifetime of the basin, the satellite will undergo continuous reorientation until the basin reaches isostasy.

Results

The calculated values for Ganymede's principal moments are $A = 2.71614 \times 10^{-4}$ g cm$^{-2}$, $B = 2.70000 \times 10^{-4}$ g cm$^{-2}$, and $C = 2.72130 \times 10^{-4}$ g cm$^{-2}$. Gilgamesh (62øS, 123øW), which formed during later stages of grooved terrain emplacement (Shoemaker et al., 1982), was found to be the only basin large enough to have caused significant global reorientation. It was modelled as a 9-km topographic depression occurring only within the middle 600-km diameter basin ring. The area between the middle basin ring and the 900-km diameter outer ring is largely refilled with ejecta. Principal moments were
geologic features follow from this hypothesis: a thickening of the lithosphere due to the low surface temperature around the paleopoles may be evident (cf. Shoemaker et al. 1982), areal patterns of groove orientation consistent with relict despining fractures may be present, and a preferred orientation of younger groove sets consistent with stresses caused by global reorientation may occur.

Shoemaker et al. (1982) suggested that thicker lithosphere would have developed on Ganymede in polar regions due to lower surface temperature. If this is also true of the paleopolar regions, we might expect less tectonic deformation of their thicker lithosphere. Lucchitta (1980) noted that the two largest expanses of nearly continuous dark terrain are Galileo Regio and a large antipodal dark area. Both of these areas define large parts of the paleopolar region.

Melosh (1977) calculated that tidal despining of a body with a constant volume would result in conjugate fractures bisected by lines of latitude equatorward of 48° paleolatitude, and fractures parallel to lines of paleolatitude poleward of 48°. If global expansion was occurring at the time of despining, the zone of fracturing parallel to lines of latitude would extend to more equatorial regions. As is illustrated in Figure 1, groove lanes are dominantly parallel or at low angles to paleolatitude lines. These orientations are consistent with the lanes having developed in reactivated formation of furrow systems, (4) formation of Gilgamesh, at lower right, and (5) global reorientation and accompanying groove lane formation. The perspective of the drawings is a global view of the anti-Jovian hemisphere, centered at 180°W longitude.

The relative times required for relaxation of the tidal bulge and for isostatic adjustment of Gilgamesh are consistent with the idea of a geologically short period of continuous reorientation of the satellite. The time for relaxation of the bulge is about 200 yrs; the time for isostatic adjustment of the basin is about 100,000 yrs. Cumulative reorientation would equal about 15°, and would be nearly equivalent to a rotation of the satellite on the major axis of its ellipsoid. The predicted location for the paleopole is near 75°N, 95°W. The close coincidence of the predicted paleopole with the composite pole of global groove orientations suggests that groove orientations are related to a fracture system centered on the paleopole. Such a system of fractures a low angles to lines of paleolatitude is predicted by Melosh (1977) to have been formed early in the planet's history by tidal despining.

To explain the observed regional and global control of groove orientations in terms of global reorientation, we propose that groove sets developed preferentially where fractures due to tidal despining were at low angles to one of the orthogonal zones of weakness parallel and perpendicular to furrows. During the later stages of grooved terrain formation, Gilgamesh was formed and reoriented the satellite. Resulting stresses may have affected groove formation and resulted in a preferred orientation. Three predictions about global

found to equal $I_1 = I_2 = 0.4 \times 10^{-37}$ g cm$^2$ and $I_3 = 0.6 \times 10^{-35}$ g cm$^2$.

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associated with despining and furrows were at low angles (stage 3). During the later stages of grooved terrain development the impact basin Gilgamesh was formed (stage 4), and caused global reorientation of about 15°. Associated stresses caused the youngest groove lanes to form with a preferred orientation (stage 5).

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