JSDAP Summary of Research:
Origin, structure, and evolution of grooved terrain on Ganymede and comparison to Europa

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"Ridge and trough terrain" (RTT) is a generic term for sets of subparallel ridges and troughs observed on several icy outer planet satellites. Ganymede's grooved terrain is the best studied example of ridge and trough terrain. However, the >500 m resolution of Voyager images limited the conclusions that could be drawn regarding its detailed morphology and deformational style, as well as the relationship of bright grooved terrain to dark terrain on Ganymede. The goal of this study was to utilize Galileo high resolution images to examine and categorize the detailed local-scale morphology of ridge and trough terrains on Ganymede, in order to determine the morphological variety and deformational styles of the terrain, and its evolutionary sequence. This included comparison of the ridges and troughs that occur within dark terrain to those within bright terrain. This study addressed implications for the satellite's local-scale stress history, its lithospheric character, and its broader-scale geological history. Conclusions from the Ganymede were applied to gain insight into the origin of ridge and trough terrains on Europa. Following are the abstracts of the 7 papers and list of 1 popular press article and 13 abstracts which resulted from this study. No subject inventions are associated with this work.

Associated Papers

1. Head, J. W., R. T. Pappalardo, and R. J. Sullivan, Europa: Morphological characteristics of ridges and triple bands from Galileo data (E4 and E6) and assessment of a linear diapirism model. *J. Geophys. Res., 104*, 24,223-24,236, 1999.

Galileo solid-state imaging (SSI) images of Europa provide high-resolution data on the morphological characteristics of ridges and permit the development of nomenclatural schemes for their description and classification. Key observations are that ridges (1) are remarkably consistent in their along-strike linearity, width, and height, (2) form long linear features in which preexisting structures can sometimes be traced up the outer slopes of the ridges and in other cases appear to be buried, (3) contain narrow apical zones of small-scale, ridge-parallel faulting, (4) are sometimes flanked by narrow troughs and ridge-parallel fractures, and (5) often display associated color variations. On the basis of the characteristics and associated features of ridges, we find that a process in which initial fracturing (most plausibly related to tidal deformation) of a brittle layer overlying a buoyant ductile substrate leading to linear diapiric upwelling provides a consistent explanation for the observed features. In this process the upwelling linear diapir causes flexure (bending and faulting) of the region marginal to the fracture, the deformation and uplift of adjacent plains material and its preexisting structures to form the apical part of the ridge, the exposure of the inner walls of the crack, and the mass wasting of the inner and outer walls of the ridge to modify, but often not completely destroy, the preexisting structure of the adjacent plains. Specifically, this mechanism can account for many characteristics of the ridges, including their linearity, their consistent and regular

morphology over their great lateral extent, their positive topography, the presence of preexisting structure on the outer ridges (caused by upbowing of background ridged plains), the formation of marginal troughs las diapiric rim synclines), the detailed nature of their outer and inner slopes (caused largely by faulting and mass-wasting processes), and their sequential formation with multiple orientations (related to tidal deformation processes). Linear diapirism also provides a possible explanation for color and albedo characteristics, related to thermal effects of the upwelling warm ice (e.g., inducing volatile migration and grain-size variations). As the vast majority of deformation is vertical in this scenario, this mechanism minimizes the necessity for complementary compressional deformation required by some other models.

2. Nimmo, F., R. T. Pappalardo, and B. Giese, Elastic thickness and heat flux estimates on Ganymede. *Geophys. Res.. Lett.*, 10.1029/2001GL013976, 2002.

We identify sites of apparent flexural uplift at rift zone boundaries on Ganymede using Galileo stereo-derived topography. The estimated effective elastic thickness te is 0.9–1.7 km for a nominal Young's modulus of 1 GPa. Using a viscoelastic model of the ice crust we find that the temperature defining the base of the elastic layer is <185 K for likely strain rates. The inferred local heat flux during deformation is less than 245 mW m^{-2}, and probably close to 100 mW m^{-2}. The stresses required to cause fault motion are around 1 MPa. Both the high heat flux and the high stresses are consistent with estimates of these quantities during an episode of transient tidal heating in Ganymede's past.

3. Patel, J. G., R. T. Pappalardo, J. W. Head, G. C. Collins, H. Hiesinger, and J. Sun, Topographic wavelengths of Ganymede groove lanes from Fourier analysis of Galileo images, *J. Geophys. Res., 104*, 24057-24074, 1999.

Galileo images have shown that grooved terrain on Ganymede consists of pervasive ridges and grooves at a variety of spatial scales, which complicates visual interpretation. We use Fourier analysis to separate complex surface deformation into its component dominant wavelengths (closely correlated to topographic wavelengths) to determine spatial relationships within and among grooved terrain units. We analyze groove lanes in four Galileo target sites (Uruk Sulcus, Byblus Sulcus, Tiamat Sulcus, and Nicholson Regio), spanning a range of resolutions and lighting geometries, and we find multiple dominant wavelengths in each. Fourier analysis of the complexly deformed Uruk Sulcus shows both similarities and differences in wavelength distribution among its tectono-stratigraphic subunits (a range of 0.5 to 6 km, with a concentration at 1.2 km); favorable comparison is made to a stereo-derived topographic model. Of the dominant wavelengths displayed by Byblus Sulcus (similar to 1, 3.3, and 10 km), the longest wavelength is revealed by profiles across both high- and low- resolution images with very different lighting geometries. Tiamat Sulcus displays different dominant wavelengths north (5 to 10 km) and south (3 to 5 km) of the orthogonally trending Kishar Sulcus. Groove lanes in Nicholson Regio are significantly different from the other sites because they are isolated within dark terrain. Fourier analysis of these dark terrain groove lanes shows dominant wavelengths (similar to 2.1, 3.2, and 8.0 km) that are similar to those in lanes of more typical grooved terrain. This suggests that the tectonic style and lithospheric characteristics in this portion of Ganymede's dark terrain were similar to those in bright grooved terrain at the time of deformation. Our results support the hypothesis that longer topographic wavelengths in Ganymede's groove lanes formed by means of extensional necking of the lithosphere, while multiple shorter wavelengths formed by normal faulting of the brittle lithosphere, in both bright and dark terrains. The similar wavelengths of deformation seen in several groove lanes in both bright and dark terrain suggest similarity in lithospheric thickness, composition, and mechanical structure at these disparate sites. A global process (such as differentiation) could be responsible for creating a similar planet-wide strain and thermal regime during the time of grooved terrain formation.

4. Prockter, L.M. and R.T. Pappalardo. Folds on Europa: Implications for crustal cycling and accommodation of extension. *Science*, *289*, 941-943, 2000.

Regional-scale undulations with associated small-scale secondary structures are inferred to be folds on Jupiter's moon Europa. Formation is consistent with stresses from tidal deformation, potentially triggering compressional instability of a region of locally high thermal gradient. Folds may compensate for extension elsewhere on Europa and then relax away over time.

5. Prockter, L.M., P. Figueredo, R.T. Pappalardo, J.W. Head III, and G.C. Collins. Geology and mapping of dark terrain on Ganymede and implications for grooved terrain formation. *J. Geophys. Res.*, *105*, 22,519-22,540, 2000.

Geological mapping of regional and high-resolution Galileo images reveals a variety of units and structures within Ganymede's dark terrain. We have made a detailed study of areas within Galileo, Marius, and Nicholson Regiones in order to investigate the style of tectonic deformation experienced by dark terrain adjacent to swaths of grooved terrain. Dark terrain appears to become fractured as a precursor to grooved terrain formation; in places, dark fractured swaths are recognized which have similar characteristics to brighter grooved terrain swaths. Tectonic deformation may be, but is not always, focused through preexisting weaknesses caused by impact craters and furrows, A prominent groove lane, Anshar Sulcus, is inferred to have formed by the process of hanging wall rollover, accompanied by a small amount of right-lateral horizontal shear offset resulting from NE-SW extension.

6. Prockter, L. M., R. T. Pappalardo, and J. W. Head, Strike-slip duplexing on Jupiter's icy moon Europa. *J. Geophys. Res.*, *105*, 9483-9488, 2000.

Agenor Linea is a similar to 1500 km long, similar to 20-30 km wide geologically young zone of deformation on Jupiter's icy moon, Europa. On the basis of recent Galileo high-resolution images, we interpret Agenor Linea as a strike-slip zone formed in three stages by a combination of lithospheric separation, extension, and dextral horizontal shear. Agenor Linea exhibits excellent examples of strike-slip duplexes in an icy lithosphere, unobscured by vegetation and unaltered by erosion.

7. Prockter, L. M., J. W. Head III, R. T. Pappalardo, J. G. Patel, R. J. Sullivan, A. E. Clifton, B. Giese, R. Wagner, and G. Neukum, Morphology of Europan bands at high resolution: A mid-ocean ridge-type rift mechanism. *J. Geophys. Res.*, 10.1029/2000JE001458, 2002.

We utilize imaging data from the Galileo spacecraft to investigate band formation on one of Jupiter's moons, Europa. Bands are polygonal features first observed in Voyager data close to Europa's anti-Jovian point and represent areas where preexisting terrain has been pulled apart, allowing new material to move up into the gap. We examine the detailed morphology of several bands imaged at different resolutions and lighting geometries. We identify several distinct morphological characteristics, including central troughs, hummocky textures, and ridge and trough terrains, some of which are common among the bands studied. In many cases, bands have initiated along segments of one or more preexisting double ridges, ubiquitous within Europa's ridged plains. Distinctive morphological features and high standing topography imply that the bands formed from compositionally or thermally buoyant ice, rather than liquid water. Comparisons between Europan band morphologies and features found on terrestrial mid-ocean ridges reveal several similarities, including axial troughs, subcircular hummocks, normal faults, and indications of symmetrical spreading. We conclude that terrestrial mid-ocean ridge rifting is a good analogy for Europan band formation. If a terrestrial seafloor-spreading model is applicable to Europan bands, we speculate that band morphologies might be related to the relative rate of spreading of each band. Bands may have contributed significantly to the resurfacing of Europa. Europan bands we examine predate (but do not postdate) lenticulae and related features, implying that the style of resurfacing on Europa has changed over recent geological time in these regions.

Popular Press Articles

Pappalardo, R.T. Ganymede and Callisto, in *The New Solar System, 4th ed.* (J.K. Beatty, C.C. Peterson, and A.L. Chaikin, eds.). Cambridge, Mass.: Sky Publishing Corp., pp. 263-275, 1999.

Abstracts

Collins, G. C., R. T. Pappalardo, and J. W. Head III, Surface stresses resulting from internal differentiation Application to Ganymede tectonics. *Lunar Planet. Sci. Conf., XXX*, abstract #1695, Lunar and Planetary Institute, Houston (CD-ROM), 1999.

Collins, G. C., R. T. Pappalardo, and J. W. Head III, Differentiation and the formation of grooved terrain on Ganymede. *Eos, 80*, S206, 1999.

Collins, G. C., J. W. Head, R. T. Pappalardo, B. Nixon, B. Giese, R. Wagner, and the Galileo SSI Team, The formation of Arbela Sulcus and other smooth linear features on Ganymede: Possible crustal spreading and shear. *Lunar Planet. Sci. Conf., XXXII*, abstract #1498, Lunar and Planetary Institute, Houston (CD-ROM), 2001.

Collins, G. C., R. T. Pappalardo, and J. W. Head, Grooved terrain formation on Ganymede. Jupiter Conference, Boulder, CO, 2001.

Nimmo, F., Pappalardo, R. T. and B. Giese, Elastic thickness and heat flux estimates on Ganymede. Eos, 82, F688, 2001.

Pappalardo, R. T., F. Nimmo, and B. Giese, Elastic thickness and heat flux estimates on Ganymede, *Bull. Am. Astron. Soc., 33*, 1107, 2001.

Pappalardo, R. T. and G. C. Collins, Extensionally strained craters on Ganymede. *Lunar Planet. Sci. Conf., XXX*, abstract #1773, Lunar and Planetary Institute, Houston (CD-ROM), 1999.

Pappalardo, R. T. and G. C. Collins, Extensionally strained craters on Ganymede, *Eos, 80*, S205, 1999.

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Patel, J. G., R. T. Pappalardo, L. M. Prockter, G. C. Collins, James W. Head III, and the Galileo SSI Team, Morphology of ridge and trough terrain on Europa: Fourier Analysis and Comparison to Ganymede. *Eos, 80*, S210, 1999.

Prockter, L. M., R. T. Pappalardo, R. Sullivan, J. W. Head, J. G. Patel, B. Giese, R. Wagner, G. Neukum, and R. Greeley, Morphology and evolution of Europan bands: Investigation of a seafloor spreading analog. *Lunar Planet. Sci. Conf., XXX*, abstract #1900, Lunar and Planetary Institute, Houston (CD-ROM), 1999.

Prockter, L. M., J. W. Head, R. T. Pappalardo, G. C. Collins, J. E. Klemaszewski, P. E. Geissler, and the Galileo SSI Team, Geological mapping of central Agenor Linea, Europa. *Lunar Planet. Sci. Conf., XXX*, abstract #1299, Lunar and Planetary Institute, Houston (CD-ROM), 1999.