Formation of Ganymede Grooved Terrain by Sequential Extensional Episodes: Implications of Galileo Observations for Regional Stratigraphy

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INTRODUCTION

Grooved terrain covers over half of Ganymede’s surface and records a period of intense surface deformation at some point in the satellite’s history. Ganymede’s neighboring satellite Callisto does not display any non-impact-related tectonic features, despite the gross similarities in size, density, and location in the Solar System of Ganymede and Callisto. Some process has occurred on Ganymede and not on Callisto to form the grooved terrain, and the determination of this process has major implications for the interior evolution of these two bodies (cf. McKinnon and Parmentier, 1986). Understanding the events that led to the formation of the grooved terrain is essential for understanding much of the unique geological history of Ganymede, and how its evolution diverged from that of its twin Callisto.

It is generally agreed based on Voyager images that most grooves are extensional tectonic structures (Shoemaker et al. 1982) and Galileo images have confirmed this general interpretation (Belton et al. 1996, Pappalardo et al. 1998). As extensional features, the orientations of the grooves are dominantly controlled by the orientations of the stresses that formed them. Different models to describe the driving mechanisms of groove formation predict different patterns of stress within Ganymede’s lithosphere, and the grooves are a surface manifestation of the strain associated with these stresses. Thus, measurements of groove orientation are essential for examining the strain history of Ganymede and constraining the driving mechanism of groove formation.

The collection of groove orientation data is relatively straightforward in swaths of grooved terrain which only display one orientation of grooves. However, many regions of grooved terrain, such as Uruk Sulcus, display complex arrays of grooves oriented in many directions (Fig. 1). In Uruk Sulcus and other regions of complex grooved terrain, polygonal areas containing sets of grooves with dominant...
orientations, or “grooved polygons,” are bounded by long, continuous sets of grooves known as “groove lanes.” Many of these grooves presumably formed at different times, during different deformational episodes, responding to different stress fields. Stratigraphic analysis of tectonic units within the grooved terrain can place these groove-forming episodes along a timeline. In this paper, we show how this information can clarify the stress orientations during any particular groove-forming episode and reveal how the stress has evolved through time.

This paper describes the sequence of extensional events that formed the grooved terrain surrounding the Galileo G1 target area in Uruk Sulcus (11° N, 169° W). To determine this sequence of events, we use high-resolution Galileo data from the solid state imaging system (SSI) to determine the stratigraphic relationships between sets of grooves. The stratigraphic observations gained from this high-resolution target area are then used to extend the analysis to surrounding areas imaged at lower resolution by the Voyager 2 spacecraft.

**Previous Models of Grooved Terrain Stratigraphy**

Golombek and Allison (1981) proposed a stratigraphic sequence based on Voyager data for the formation of the grooved terrain in Uruk Sulcus. They interpret many of the boundaries between groove sets as T terminations of faults, where the younger faults (the stems of the Ts) terminate against the structural discontinuity at the older set of faults (the crossbar of the T). This interpretation of the stratigraphic relationships between the sets of grooves leads to the following three-stage process for the formation of grooved terrain (Fig. 2a): (a) long primary grooves fracture the dark terrain, (b) secondary grooves link together primary grooves and divide the terrain into discrete, mechanically isolated polygons, (c) polygons are resurfaced by bright material and short tertiary grooves form within the polygons, terminating against the primary and secondary grooves. One may predict from this model that high-resolution images of Ganymede’s grooves should show that the grooved polygons have been volcanically resurfaced.
exhibits a moderately complex array of groove lanes, grooved polygons, and smooth bright terrain (Carr et al. 1995). This area was imaged on orbit G1 as a four-frame mosaic at 75 m/pixel, plus sections of two additional frames were returned on orbit G2 at 42 m/pixel for stereo elevation (boxes on Fig. 1; Fig. 3). These high-resolution images show that grooved terrain is pervasively fractured at small scales (from ~1 km down to the limit of resolution). The nature of these faults is primarily extensional, with morphologies suggesting horst and graben and tilt-block normal faulting. For a more detailed description of structural features and the morphology of grooved terrain at high resolution, see Pappalardo et al. (1998).

Several boundaries between grooved polygons and groove lanes were imaged in this high-resolution mosaic (Fig. 3, triangles), two such contacts (white rectangles on Fig. 3) are shown enlarged in Fig. 4. The surface of the grooved polygon in the upper right corner of Fig. 4a is clearly older than the groove lane which runs through the lower left corner of the image, as evidenced by (a) the grooved polygon terminating in a large scarp, which also truncates a possible degraded crater about 5 km in diameter, and (b) incipient fractures along the edge of the groove lane cutting into the edge of the grooved polygon. In Fig. 4b, the ridges and troughs in the terrain to the upper right are seen in cross section where the bright scarp bounding the groove lane to the lower left truncates them at an angle; the trace of the top of the bright scarp is the trace one would expect for a normal fault dipping to the lower left as it crosses preexisting topography. This same cross-sectional profile is faintly seen along the top of the next ridge in the groove lane below the scarp, indicating that this ridge is a rotated block of the preexisting crust, consistent with the interpretation that this groove lane formed through tilt-block normal faulting (Pappalardo et al. 1998). As one proceeds into the groove lane, the faint pattern is quickly lost, though the crenulation of ridge crests in the groove lane may partly be due to the influence of preexisting topography on the back-tilted face. Similar relationships are observed at other contacts between grooved polygons and groove lanes in the Uruk Sulcus mosaic (Fig. 3, triangles). The grooved polygons are the oldest features preserved in this area of Uruk Sulcus, contrary to the predictions of the model of Golombek and Allison (1981), but in accordance with the model of Murchie et al. (1986).

Volcanic resurfacing of topographic lows is integral to the formation of the bright grooved polygons in the model of Murchie et al. However, no unequivocal volcanic features (vents, edifices, flow margins, flow textures, emplacement) are observed in this area of Uruk Sulcus (Belton et al. 1996, Pappalardo et al. 1998). There are no boundaries between units in which embayment relationships are observed. Instead, all of the boundaries appear to be tectonic, characterized by groups of faults crosscutting older terrain.

GALILEO OBSERVATIONS

The Galileo Uruk Sulcus target area was chosen to test the predictions of these stratigraphic models because it
FIG. 3. Mosaic of Galileo Uruk Sulcus images from orbits G1 (75 m/pixel) and G2 (42 m/pixel), overlaid on Voyager 2 data. White triangles show borders between grooved polygons and groove lanes (triangles are on grooved polygon side). White rectangle shows areas in Fig. 4. North is to the top.
remains an attractive candidate to explain at least some of the transformation of dark terrain to bright terrain, including observations such as (a) the existence of highly tectonized dark terrain, which retains its overall low albedo (Head et al. 1997b), (b) "caldera-like" structures observed in some areas of bright terrain (Head et al. 1998), and (c) the smooth background texture of bright terrain at high resolution upon which the oldest grooves are superposed (Pappalardo et al. 1998) vs the hummocky texture of dark terrain at high resolution (Prockter et al. 1998).

The role of the tectonic resurfacing endmember model in the evolution of grooved terrain casts new light on the overall interpretation of grooved terrain stratigraphy. The emplacement of volcanic deposits does not necessarily precede the formation of any set of grooves. The complex mosaic of grooves in Uruk Sulcus is better explained as the sequential superposition of grooves, where each new episode of groove formation overprints older areas. In this case, the groove lanes represent the latest episode of deformation, while the grooved polygons are the remnants of older deformational episodes, now isolated from each other by areas of more recent deformation (Fig. 5). It is not clear what role, if any, structural isolation plays in the evolution of grooved terrain, as it does in the models of Golombek and Allison (1981) and Murchie et al. (1986).

Deformation associated with the oldest grooved polygons often appears to continue into adjacent dark terrain without transforming the dark terrain into bright terrain, indicating that the bright terrain may not have been completely structurally isolated from the dark terrain during some stages of groove formation.

Based on crosscutting relationships and differing styles of deformation among terrain units, Senske et al. (1997) have developed a stratigraphy for the Uruk Sulcus target area (Fig. 6). The oldest grooves (Fig. 7a) trend NE–SW to N–S, and at high resolution, these grooves occur as subdued dark fractures on a relatively flat surface. This terrain is also heavily cratered, with many highly degraded craters which have been cut by the grooves. The grooves of intermediate age (Fig. 7c) trend more N–S than the older grooves and occur in a variety of morphologies. Some of these areas are smooth with fine striations, distinguished from the previous grooves by a lack of degraded craters. Other areas of this terrain exhibit horst and graben faulting and a small amount of tilt-block normal faulting (Pappalardo et al. 1998). The youngest grooves (Fig. 7e) trend NW–SE and exhibit a highly developed tilt-block morphology (Pappalardo et al. 1998). In this high-resolution sample of grooved terrain, a change through time is observed in (a) the orientation of the grooves, which implies changes in the orientation of the stresses which created them, and (b) the style of deformation, which may indicate changes in the properties of the underlying lithosphere, the strain rate, or the total strain (cf. Pappalardo and Greeley 1995).
FIG. 5. Schematic representation of grooved terrain resurfacing observed in Uruk Sulcus: (a) the original terrain is first modified by NE-trending fractures which modify preexisting craters, then is deformed by lanes of N-trending graben. In the most recent event, intense faulting trending to the NW obscures preexisting features, creating “groove lanes” and isolating older areas as “grooved polygons.” Arrows indicate inferred directions of extensional stress during each stage.

REGIONAL STRATIGRAPHY

The stratigraphic sequence determined from the high-resolution Galileo coverage can be used as an “anchor” of known stratigraphy within the Voyager data in order to expand this stratigraphic analysis to areas imaged only at lower resolution. Within the Galileo Uruk Sulcus target area, two important observations have been made which will allow extrapolation of the stratigraphy to the surrounding area. The first observation is that at T-intersections of grooves, the crossbar of the T is superposed on

FIG. 6. Stratigraphy of the Galileo Uruk Sulcus target area. White areas denote stratigraphically oldest terrain, gray areas denote the intermediate unit, and dark areas denote the youngest stratigraphic unit. The area is the same as that covered by Fig. 3; black outline denotes edges of Galileo frames. North is to the top.
which show this unit cutting across the dark terrain. The intermediate unit (coded green in Fig. 8b) also occurs as isolated polygons within Uruk Sulcus, often forming boundaries of polygons of the oldest unit and crosscut by the youngest unit. This unit continues to the north in two polygons within Nippur Sulcus and farther to the north as the primary fabric of Elam Sulci. The youngest unit (coded red in Fig. 8b) crosscuts the other two units, forming long, continuous lanes of grooves in Nippur Sulcus and Mashu Sulcus that converge and continue in a network of groove lanes in Uruk Sulcus. The area of this convergence and a possible connection of the intermediate unit in Uruk Sulcus and Nippur Sulcus is obscured by the penepalimpsest Epigean. The youngest unit also forms a network of narrow groove lanes through northern Marius Regio and prominent fractures crosscutting Philus Sulcus.

To test the accuracy of this stratigraphic extrapolation, we compared the crosscutting relationships predicted based on Voyager images in Fig. 8b to other high-resolution Galileo images in the Nippur Sulcus area obtained on orbit G2 in order to test the stratigraphic relationships inferred from the low-resolution Voyager images. Two examples of this test are shown in Fig. 10. North of Nippur Sulcus (location 1 in Fig. 8b), a polygon of subdued grooves trending ENE is dissected along its edges by more recent grooves trending NW (Fig. 10a), a relationship similar to the polygons of older grooved terrain in the Uruk Sulcus target area, and correctly predicted from the low-resolution Voyager data. Halfway between the Nippur Sulcus and Uruk Sulcus target areas (location 2 in Fig. 8b), the stratigraphy of the grooves is also correctly predicted from low-resolution data, where grooves belonging to the intermediate unit trending N are truncated by a groove lane trending NW (Fig. 10b).

It has been noted that grooves are often parallel to the local furrow trends in the dark terrain, forming the zones of weakness in the Murcie et al. (1986) model. While grooves are sometimes parallel to furrow trends and may exploit furrows as zones of weakness, this behavior is not exclusive to any of these groove units. Both the oldest and youngest units are observed parallel to furrow trends in different areas, when the furrows happen to be parallel to the trend of the grooves. Groove formation does not appear to be strongly affected by the presence or absence of parallel furrows. For instance, the youngest grooves in Fig. 8b are parallel to and may exploit the Galileo Regio furrows, but they are generally normal to the furrows of Marius Regio. Similarly, the oldest grooves are generally normal to the Galileo Regio furrows, but seem to exploit the Marius Regio furrow trends. Thus, while grooves may locally exploit furrows as zones of weakness, this does not appear to be the primary control on groove orientations across the region and through time.

When the grooves in this mapped region are separated
FIG. 8. (a) Voyager mosaic of study area, covering ~1.6 million km$^2$. (b) Same area shown in (a) color coded to show sequence of groove formation. Color code denotes three stratigraphic units; blue is the oldest unit, green is the intermediate unit, and red is the youngest unit. Yellow box in lower right corner is Galileo Uruk Sulcus target area, locations 1 and 2 refer to areas in Fig. 10 used to check the accuracy of this stratigraphic interpretation. (c) Rose diagrams showing histograms of the orientations of grooves within each of the stratigraphic units. Arrows show inferred orientation of least compressive stress.
into stratigraphic units and the orientations of the grooves within each unit are measured, we find that the orientations are remarkably consistent within each unit. Figure 8c shows rose diagrams of the groove orientations within each unit. The oldest grooves trend NE–SW, the intermediate grooves trend N–S, and the youngest grooves trend NW–SE. Murchie and Head (1989) also noted the same general progression in groove trends through time in their geologic map of the Phitus Sulcus quadrangle, which overlaps with the northern portion of our study area. Bianchi et al. (1986)
unit seen in stereo in the Uruk Sulcus target area exhibits over 50% extensional strain. However, it is not known if this is representative of all of the youngest grooves in the area; did all of the area coded in red in Fig. 8b undergo ~50% extension or is the high-resolution target area an anomaly? This strain estimate is not applicable to other stratigraphic units within the grooved terrain, which often appear in high resolution to have undergone lower strain.

Also mapped the orientations of grooves in this area, but did not observe this trend because they did not separate the grooves into stratigraphic units.

Most of the grooves imaged at high resolution by Galileo exhibit extensional strain, though some may have a small strike-slip component (Pappalardo et al. 1998). Potential strike-slip faults with larger offsets have been reported based on Voyager imagery (Lucchitta 1980, Murchie and Head 1988), but our mapping effort has not been able to address this question. Assuming that the grooves seen in Voyager images of this area are primarily extensional structures, as is the case in the Galileo images of this area, the inferred direction of extension during each groove-forming episode is perpendicular to the trend of the grooves (Fig. 8c, arrows). The consistency of groove orientations implies that the least compressive stress direction was remarkably consistent across this large region during each of the groove-forming episodes. The orientation of least compressive stress has changed in this region through time, from NW–SE, to E–W, and finally to NE–SW.

The magnitude and consistency of extensional strain within each of these stratigraphic units is not well constrained. Strain may be estimated for grooves at high resolution based on structural interpretation and detailed measurements of the ridges and troughs. For instance, Collins et al. (1998a) estimated that the portion of the youngest unit seen in stereo in the Uruk Sulcus target area exhibits over 50% extensional strain. However, it is not known if this is representative of all of the youngest grooves in the area; did all of the area coded in red in Fig. 8b undergo ~50% extension or is the high-resolution target area an anomaly? This strain estimate is not applicable to other stratigraphic units within the grooved terrain, which often appear in high resolution to have undergone lower strain.
deformation by fracturing and graben formation (Pappalardo et al. 1998). Some areas of dark terrain also appear to have been highly strained (e.g., Head et al. 1997b). If there is no compressional strain on the surface of Ganymede, Squyres (1980) set a limit to the average amount of extensional strain which could occur within grooved terrain due to global expansion to 15%, and similarly McKinnon (1981) set a limit of 4% average extensional strain in the grooved terrain due to the intact nature of Galileo Regio. If the high amount of extensional strain estimated in high-resolution target areas is representative of grooved terrain as a whole, then either the limits on global extensional strain are underestimates, or compressional strain is taking place somewhere on the surface of Ganymede and has gone unrecognized. Compressional strain may be unrecognized because it may be accommodated by (a) ductile creep very close to the surface, (b) subduction of silicate-rich dark terrain crust into a cleaner ice mantle, (c) structures not recognized as being compressional in origin, or (d) tectonism on a scale too small to resolve with current imaging data.

POSSIBLE GROOVED TERRAIN DRIVING MECHANISMS

The observations made so far can be used to test the predictions of possible driving mechanisms for grooved terrain formation. Based on the region of Ganymede described in this paper, we find that the grooves may be divided into a small number of coherent stratigraphic units. The grooves within each of these units share common orientations over a large area. The orientation and morphology of the grooves is different in each of the stratigraphic units and thus changed through time, implying that the stress orientations and the conditions in which the grooves formed has changed through time. Another important observation is that while many unambiguous extensional features have been identified in high-resolution Galileo images, no unambiguous compressional features have been identified to date.

These observations can be compared to the general predictions of proposed hypotheses for the generation of the extensional forces responsible for the formation of grooved terrain. Four classes of hypotheses are summarized below: (1) coupling of stresses from mantle convection to the lithosphere, (2) volume changes within bright terrain cryovolcanic deposits, (3) stresses arising from tidal and rotational changes in Ganymede’s figure, and (4) extensional strain at the surface from volume changes in the interior of Ganymede. Predictions may be made from these models for the orientation and magnitude of stress generated and the conditions in which the grooves formed. These predictions are then checked against our observations for consistency and are summarized in Table I. Future global mapping, strain determination, and further constraints on the conditions in which grooves formed will serve to narrow the field to a few specific hypotheses, but given the preliminary nature of this study with respect to making global conclusions, we shall only favor or disfavor these broad classes of hypotheses based on observations of the region described in this paper.

Solid State Convection

One hypothesis for the formation of the grooved terrain is that it could be due to extension of the brittle surface layer over upwellings of warm ice. If the ice crust of Ganymede overlays a liquid water layer, solid state convection should begin before it reaches a thickness of 30 km (Reynolds and Cassen 1979). Extension should be concentrated over the upwellings with grooves oriented perpendicular to the direction of mantle flow, as they are driven by shear traction between the mantle and lithosphere (Squyres and Croft 1986). Extension caused solely by this process would have to be compensated by compression elsewhere. Compressional features have not been unambiguously observed on Ganymede.

Squyres and Croft (1986) estimated that the stresses coupled to the surface would be on the order of 0.1 MPa, which they concluded is too low to fracture the whole lithosphere. Collins et al. (1998a) estimated that the lithosphere during the youngest episode of groove formation was ~2 km thick. Depending on the cohesion of the ice in the lithosphere, this thickness yields a lithospheric strength of 2–3 MPa in this area of Ganymede during this time period. Diapirs generated during the final freezing of a ganymedian ocean in the “heat pulse” model of Kirk and Stevenson (1987) may produce enough stress to fracture the lithosphere. Calculations by McKinnon (1998) show that whole-mantle convection on Ganymede may also generate enough stress to fracture the lithosphere, but layered convection would be too weak to form the grooves. Whole-mantle convection early in Ganymede’s history would have been characterized by a high Rayleigh number, perhaps in the hard turbulence regime (McKinnon 1998). In this case, thermal plumes may have dominated the organization of the grooves.

The consistency of groove trends within stratigraphic units across this 1.6 million square kilometer area indicates that the grooves are not organized above spheroidal diapirs or finger-like upwelling plumes, as one would expect these to form radial or concentric sets of grooves. Convection organized along linear upwellings or in hemisphere-scale plumes could explain the consistency of groove orientations in this area, as the mantle flow would be generally uniform in direction across the region. In such a model, the consistent change in groove orientations through time
TABLE I
Summary of Possible Constraints on the Nature of Grooved Terrain Formation from Stratigraphy and Mapping, Compared to Predictions of Hypothesized Driving Mechanisms

<table>
<thead>
<tr>
<th>Driving mechanism</th>
<th>Convection:</th>
<th>Convection:</th>
<th>Cryovolcanic</th>
<th>Shell deformation</th>
<th>Global expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observation/inference</td>
<td>diapirs/plumes</td>
<td>low-order planform</td>
<td>volume change</td>
<td></td>
</tr>
<tr>
<td>Regionally coherent stress orientation</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>High strain possible</td>
<td>O</td>
<td>X</td>
<td>O</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Compressional strain may not globally balance extensional strain</td>
<td>O</td>
<td>X</td>
<td>O</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Changing stress orientation through time</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Cryovolcanic resurfacing may not be associated with groove formation</td>
<td>O</td>
<td>X</td>
<td>O</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Enough stress generated to fracture</td>
<td>X</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Note. X, the driving mechanism may fit within the constraint. O, unusual circumstances would be necessary for the model to fit the constraint. Blank space, the model does not fit the constraint.

*a* Lithospheric inhomogeneities may control expression of strain, but cannot solely explain multiple orientations.

*b* Nonsynchronous rotation predicts change through time, for other cases combinations of models or *ad hoc* scenarios may be necessary.

*c* Kirk and Stevenson (1987) modeled resurfacing by solid-state flows of clean ice from diapirs, but cryovolcanic and/or solid-state resurfacing is not necessarily associated with convection.

d*Dependent on time scale of mechanism.

e*The entire lithosphere is not fractured in this model.

would need to be explained by large, coherent shifts in the planform of convection.

**Volume Change of Volcanic Deposits**

If the material making up the bright terrain is emplaced as flows of liquid water filling low areas, the surfaces of these flows may fracture as their interiors cool. Thermal contraction of a warm, frozen cryovolcanic deposit could produce cracks in the surface, exhibiting small amounts of strain (Squyres and Croft 1986). Expansion of a confined layer of liquid water as it freezes underneath the crust of a cryovolcanic flow could also cause fractures to form, which may be exploited to create grooves (Allison and Clifford 1987). Cryovolcanic deposits of “exotic” compositions, such as quenched MgSO4 brine, may also expand as they equilibrate (Hogenboom et al. 1997). These processes would produce very little strain (up to a few percent) and do not require compression in the surrounding terrain.

The nature of the grooves at high resolution is contrary to that expected from this class of models. The normal faults which form the grooves are observed to modify pre-existing terrain rather than being confined to the surface of a new flow, and there is no evidence at high resolution for the emplacement of separate groove sets as separate cryovolcanic flows. The amount of extensional strain measured from high-resolution stereo data of the most recent set of grooves in the Uruk Sulcus target area is about 50% (Collins et al. 1998a), which is much more strain than these models would be able to produce. Additionally, the expected stress orientations from volume change of a flow would be highly dependent on the local geometry of the flow, contrary to the regionally consistent groove orientations within the stratigraphic units.

**Shell Deformation**

Satellites are distorted from perfect spheres into triaxial ellipsoids by a combination of rotational flattening and a tidal bulge created by the gravitational attraction of the primary planet. Changes in the satellite’s rotation or tidal interactions can change the shape of the body, inducing global stress patterns. The patterns produced by changes in the amplitude of the tidal bulge or by shifting of the bulge across the surface have been investigated by Helfenstein and Parmentier (1983, 1985) and Melosh (1980a). Stresses caused by changes in the spin rate have been investigated by Melosh (1977), and those caused by a reorientation of the spin axis have been investigated by Melosh (1980b) and Murchie and Head (1986).

The consistent orientation of tidal stresses over large regions of the satellite makes these models attractive candidates for explaining the consistent orientations of grooves in this region, though the nonsynchronous rotation model of Helfenstein and Parmentier (1985) is the only model which necessarily predicts changes in stress orientation through time. However, these models may not be able to produce the potentially large amount of extensional strain exhibited in the grooved terrain. Also, the extensional strain observed in grooved terrain would need to be balanced by compression somewhere else, which is not yet observed.
Global Expansion

Positive volume changes in the interior of Ganymede could provide the extensional strain on the surface necessary to drive the formation of grooved terrain. Differentiation, formation of a subsurface ocean, and heating of the interior are all possible mechanisms for global expansion.

Differentiation of the satellite from a homogeneous mixture would concentrate silicates in the core and displace dense ice phases toward the exterior, where they are altered to less dense ice phases, thereby expanding the radius of the globe and thus its surface area. Squyres (1980) calculated that this mechanism could produce an increase in surface area on Ganymede up to 6.5%, assuming that Ganymede differentiated into a silicate core, a liquid water ocean, and a 100-km thick ice I crust. Mueller and McKinnon (1988) modeled differentiation to a rocky core, a possible mixed ice-rock lower mantle, and an ice upper mantle, and calculated up to a 4.5–6.4% increase in surface area on Ganymede, depending on the rock composition. If the rather large global extensional strain from these models was concentrated into the area covered by grooves, it could explain the potentially large amount of extensional strain represented by grooved terrain as a whole without the need for this extension to be compensated for by compression elsewhere.

Evidence for differentiation as an important event in Ganymede’s history comes from measurements of the moment of inertia and magnetosphere of Ganymede. Initial Galileo results indicate that Ganymede is highly differentiated and probably has a molten iron core (Schubert et al. 1996). Differentiation is likely to release a large amount of heat, possibly melting to near the surface, which would remove any surficial evidence of this process, so it is uncertain whether this episode of differentiation is responsible for forming the grooves. It is interesting to note, however, that Galileo gravity results indicate that Callisto may be essentially undifferentiated or differentiated to a very small degree (Anderson et al. 1997, McKinnon 1997). This alone may argue for groove formation to be linked to the differentiation of Ganymede.

Global expansion may also occur subsequent to the differentiation of Ganymede, driven by episodes of “runaway” tidal heating which may have led to subsurface ocean formation (Showman et al. 1997). Expansion due to melting of dense ice phases overcomes contraction from melting of ice I to water, producing an increase in surface area of 0.3–1.3% over $10^3$–$10^6$ years, thereby producing up to hundreds of bars of stress at the surface (Showman et al. 1997), though the surface will fail by extensional faulting before these high stresses are achieved. Freezing the upper layer of a subsurface ocean into an ice I mantle is unlikely to produce extension, as the freezing of denser phases at the bottom of the ocean would balance out the volume change and probably cause net compression (Squyres 1980).

Heating of Ganymede by radionuclides is another potential source of global expansion. The total increase in surface area of the satellite by this mechanism is only about 0.3–0.5% (Zuber and Parmentier 1984). If Ganymede started as a cold differentiated body, the stresses on the upper 1–2 km of the lithosphere may reach up to tens of MPa (depending on the effective viscosity of the surface), and the buildup of stress is spread out over billions of years. If Ganymede started as a cold, undifferentiated body, as Callisto may be (Anderson et al. 1997), then the lithosphere could build up to hundreds of bars of stress (to be relieved by extensional faulting) over the first half-billion years of Ganymede’s history (Zuber and Parmentier 1984). The relatively low strain and strain rate associated with expansion by heating are not consistent with the potentially high strain in grooved terrain and the estimated formation time scale for the most recent grooves in Uruk Sulcus on the order of a million years (Collins et al. 1998a).

To a first order, the strain produced by global expansion would be expected to be isotropic, with no preferred stress orientations, though inhomogeneities may control the initial failure of the lithosphere. However, the regionally coherent, shifting patterns of groove orientations may argue against inhomogeneities having more than a local effect. Instead, stress from mechanisms such as convection or shell deformation may combine with the strain from global expansion to produce the patterns of grooves we observe on the surface of Ganymede. Indeed, the mechanisms which produce global expansion may also change or trigger the other mechanisms. Since the global expansion mechanisms discussed above all produce increased interior temperatures, there may be an association with transient convective patterns. Concentration of mass in the center of Ganymede will lead to a decrease in the amplitude of the tidal and rotational bulges (Dermott 1979). Possibly counteracting this, differentiation of Ganymede may increase the spin rate (due to conservation of angular momentum) enlarging the rotational bulge if the time scale of differentiation is faster than the time scale of tidal locking. The initial trigger for the differentiation of Ganymede may have been tidal heating (Malhotra 1991), implying that strain from global expansion and stresses from changes in the figure of the satellite may have been intimately linked.

Conclusion

The stratigraphy of grooved terrain at high resolution is inconsistent with the Golombek and Allison (1981) model in which groove lanes isolate the dark terrain into polygons, some of which are then volcanically resurfaced and tectonized to form grooved polygons. At high resolution, these grooved polygons are observed to be the oldest features, not the youngest. This is generally consistent with the Murchie et al. (1986) model in which volcanically resur-
faced grooved polygons are cut by reactivation of the groove lanes.

The lack of evidence for volcanic embayment and the possibility of tectonic resurfacing (Head et al. 1997a) lead us to support a third model in which the grooved terrain is formed through sequential extensional episodes, forming a mosaic of superposed groove sets. The grooved polygons are remnants of terrain modified by older extensional episodes, isolated from each other by more recent grooved polygons and by groove lanes which are the result of the most recent episode of extension. Cryovolcanism is not a necessary component of this stratigraphic model, but it may have occurred at some time before or perhaps during groove formation (Head et al. 1998) to transform dark terrain into bright terrain. This stratigraphy, mapped over an area of approximately 1.6 million square kilometers from northwestern Uruk Sulcus to Philus Sulci, suggests that (a) groove orientations are consistent across large areas within each stratigraphic interval, implying that the least compressive stress direction was consistent over this area and rotated through time, and (b) the style of deformation has changed through time, indicating changes in the properties of the underlying lithosphere, the strain rate, or the total strain. These general conclusions may be true for other areas, but the specific changes in style, orientation, and the timing of groove forming events may differ (cf. Collins et al. 1998b).

The coherent groove orientations within each stratigraphic unit, the large amounts of strain represented in some areas of grooved terrain, and the crosscutting relationships of the grooves appear to rule out the hypothesis that these grooves are solely the result of volume change within cryovolcanic deposits. Formation of grooves as an expression of diapirism or small mantle convection cell is unlikely, as these mechanisms would probably create grooves radial or concentric to the localized upwellings, contrary to the coherent linear groove orientations observed over this large region. Convection of lower order planform may produce the even, unidirectional mantle flow necessary in this region to produce the coherent orientations of grooves, but a specific model has yet to be proposed in which low-order convective activity on Ganymede would couple enough stress to fracture the lithosphere. Shell deformation models produce the coherent regional stress patterns, but may not produce enough strain to form the grooves. The observations of the regional character of grooved terrain in this study may be consistent with groove formation by a combination of global expansion and either low-order convection or shell deformation, producing coherent, shifting stress patterns on a large scale and large amounts of strain concentrated into narrow zones. This implies that Callisto may not have formed grooved terrain because of its mostly undifferentiated state and/or the lack of significant tidal stresses. The Voyager data, combined with Galileo gap fill images of Ganymede obtained on orbits E6 and C9 now provide a near-global data set of groove orientations, which can be used to test the validity of these preliminary conclusions and to reveal the global nature of the grooved terrain in order to better distinguish among these driving mechanism hypotheses.

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