Grooved Terrain on Ganymede: First Results from Galileo High-Resolution Imaging

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High-resolution Galileo imaging has provided important insight into the origin and evolution of grooved terrain on Ganymede. The Uruk Sulcus target site was the first imaged at high resolution, and considerations of resolution, viewing geometry, low image compression, and complementary stereo imaging make this region extremely informative. Contrast variations in these low-incidence angle images are extreme and give the visual impression of topographic shading. However, photometric analysis shows that the scene must owe its character to albedo variations. A close correlation of albedo variations to topography is demonstrated by limited stereo coverage, allowing extrapolation of the observed brightness and topographic relationships to the rest of the imaged area. Distinct geological units are apparent across the region, and ridges and grooves are ubiquitous within these units. The stratigraphically lowest and most heavily cratered units (“lineated grooved terrain”) generally show morphologies indicative of horst-and-graben-style normal faulting. The stratigraphically highest groove lanes (“parallel ridged terrain”) exhibit ridges of roughly triangular cross section, suggesting that tilt-block-style normal faulting has shaped them. These extensional-tectonic models are supported by crosscutting relationships at the margins of groove lanes. Thus, a change in tectonic style with time is
suggested in the Uruk Sulcus region, varying from horst and graben faulting for the oldest grooved terrain units to tilt block normal faulting for the latest units. The morphologies and geometries of some stratigraphically high units indicate that a strike-slip component of deformation has played an important role in shaping this region of grooved terrain. The most recent tectonic episode is interpreted as right-lateral transtension, with its tectonic pattern of two contemporaneous structural orientations superimposed on older units of grooved terrain. There is little direct evidence for cryovolcanic resurfacing in the Uruk Sulcus region; instead tectonism appears to be the dominant geological process that has shaped the terrain. A broad wavelength of deformation is indicated, corresponding to the Voyager-observed topography, and may be the result of ductile necking of the lithosphere, while a finer scale of deformation probably reflects faulting of the brittle near surface. The results here form a basis against which other Galileo grooved terrain observations can be compared. © 1998 Academic Press

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1. INTRODUCTION AND BACKGROUND

Grooved terrain on Ganymede consists of sets of subparallel ridges and troughs, typically organized in structural cells within swaths of bright terrain. Based on Voyager images, morphological evidence generally indicates an extensional-tectonic origin for the ridges and troughs, probably as normal fault blocks (Shoemaker et al. 1982). Imaging of Ganymede’s bright grooved terrain was a primary objective of the Galileo SSI (Solid State Imaging) experiment. Galileo imaged grooved terrain on Ganymede at a variety of resolutions, viewing and lighting geometries, and geographic locations in order to characterize its morphological variety and to address fundamental questions regarding the nature, origin, and evolution of grooved terrain and its constituent structures (Carr et al. 1995). Galileo observations of grooved terrain were designed to address specific questions regarding the nature and origin of its constituent ridges and troughs, the deformation style and strain represented, the stratigraphy and emplacement history of the terrain, the relationship of tectonism to the resurfacing process, whether single or multiple processes have operated to form grooved terrain, the implications of the spacing of its ridges and troughs, and the implications for the history of Ganymede and other icy satellites.

This work focuses on the nature of grooved terrain as revealed by the first of Galileo’s high-resolution target sites, a small patch of grooved terrain within Uruk Sulcus, centered near 11°N, 169°W. Though just six images of the site were obtained (four during Galileo’s first encounter with Ganymede, and two during its second encounter providing stereo coverage), these images contain a wealth of information about grooved terrain. These data are in agreement with the basic elements of the Voyager-based view of grooved terrain: that its formation is dominated by extensional tectonism, perhaps in combination with icy volcanism.

The order-of-magnitude resolution increase of the Galileo images also reveal remarkable new insights into the process of grooved terrain formation, notably (1) a prevalence of small-scale tectonic structures interpreted as domino-style tilt blocks, implying locally high extensional strain, (2) an inferred change in tectonic style from horst-and-graben to domino-style normal faulting through time, (3) the dominance of tectonism in shaping the terrain, with a limited role for cryovolcanism, (4) the importance of a strike-slip tectonic component in grooved terrain formation, (5) the inference that structures of different orientations may have formed contemporaneously, (6) revised stratigraphic interpretations for bright terrain units based on cross-cutting relationships, and (7) the presence of multiple wavelengths of deformation within grooved terrain. Thus, these first high-resolution Galileo images provide a basis for important modifications to previously proposed models for the formation of Ganymede’s grooved terrain.

The first section of this paper reviews Voyager-based models for grooved terrain and its constituent structures, and provides background on Galileo imaging of Uruk Sulcus. Second, we address the interplay of albedo and topography at the small scale as inferred from these low phase and stereo images, an important basis for geological interpretations of the region. Third, we address the style of grooved terrain extensional tectonism as elucidated by the Uruk Sulcus images. In the fourth section, we address evidence for horizontal shear and transtension in the imaged region. In the fifth section, we discuss implications for the nature, origin, and evolution of grooved terrain on Ganymede. The sixth section provides a summary of this paper’s conclusions.

Additional papers discuss other geological aspects of the Uruk Sulcus target site, notably the stratigraphy of its constituent units (Senske et al., submitted), implications of our tectonic interpretations for development of extensional instabilities on Ganymede (Collins, et al. 1998), topographic analysis of the stereo image data (Giese et al. 1998), and extrapolation of the Galileo high resolution data to the surrounding region imaged by Voyager and implications for the global history of Ganymede (Collins et al. 1998b). Future work will provide an overview of the grooved terrain sites on Ganymede as imaged by Galileo and will address specific geological interpretations and implications of those sites.

1.1. Voyager-Based Models of Grooved Terrain Formation

Ganymede’s surface consists of regions of dark, heavily cratered ancient terrain which are crosscut and divided into
polygons by lanes of bright, less heavily cratered younger terrain; much of the bright terrain is textured by subparallel ridges and troughs (Smith et al. 1979a,b). This “grooved terrain” on Ganymede was described by Shoemaker et al. (1982) as sets of curvilinear, subparallel ridges and troughs which can be continuous along their strike for hundreds of kilometers. The ridges and troughs of a set usually trend subparallel to the long axis of the elongate cell (or “lane”) of bright terrain in which they occur, although they can trend obliquely to the set’s bounds. Spacing of ridges and troughs within a single set is most commonly regular, with a reported mean trough spacing of about 8 km, although variation exists among sets (Grimm and Squyres 1985). Photoclinometric profiles (Squyres 1981) suggested that ridges and grooves have crest-to-trough height differences typically 300–400 m and as great as 700 m, with terraces apparent on the walls of some ridges. In Voyager-based models, bright cells of grooved terrain were thought to be broad graben that have been infilled by extrusion of relatively “clean” (silicate-poor) liquid water, warm ice, or ice-water slurry which hardened as it cooled to ambient temperatures (Parmentier et al. 1982, Allison and Clifford 1987, Kirk and Stevenson 1987). The occurrence of dark halo craters in regions of bright terrain supports the interpretation that bright terrain overlies older dark terrain (Schenk and McKinnon 1985).

A range of possible tectonic and magmatic models for creating subparallel ridges and troughs on icy satellites has been reviewed by Pappalardo and Greeley (1995). On Ganymede, crosscutting and termination relationships among troughs led to the interpretation of grooves as tectonic structures (Smith et al. 1979a, 1979b, Golombek and Allison 1981). A continuum of forms exists from single troughs to ridge-and-trough sets and complex grooved terrain, suggesting a genetic relationship (Parmentier et al. 1982, Squyres and Croft 1986, Murchie et al. 1986). Because graben and single troughs are features indicative of tensile stresses, this argues for an origin through extension; observations that grooved terrain generally lies lower than surrounding terrain and that relatively deep, primary troughs commonly define the margins of ridge and trough sets also argue for an extensional origin (Shoemaker et al. 1982). In an extensional-tectonic scenario, troughs have been interpreted as either graben, which resulted from normal faulting (Golombek 1982), or crevasse-like fractures formed through tensile failure and subsequently modified through viscous relaxation and mass wasting (Squyres 1982). It has been suggested that tension fractures could have formed as water-rich melt arched upward as it froze within the confines of a graben’s walls, and such fractures may have served as planes of weakness along which faults could propagate (Parmentier and Head 1984, Allison and Clifford 1987). If troughs are graben, their geometry permits estimates of the thickness, strength, and thermal profile of Ganymede’s lithosphere during their formation (Golombek 1982, Grimm and Squyres 1985, Golombek and Banerdt 1986). A regular spacing of troughs can also be accounted for by means of extensional necking instability in the lithosphere (Fink and Fletcher 1981; Herrick and Stevenson 1990). Domino-style normal faulting can create regularly spaced ridges and troughs and offers another mode of extensional-tectonic deformation potentially applicable to Ganymede grooved terrain (Pappalardo and Greeley 1995).

A spreading-analog model for grooved terrain has been suggested based on observations of central ridges and regions of apparent axial symmetry (Lucchitta 1980). Relatively little evidence has been found in Voyager data for the complete lithospheric separation or the large-scale horizontal shear expected to accompany lateral motion (McKinnon and Parmentier 1986), but Voyager imaging does provide some evidence for limited distributed strike-slip tectonism on Ganymede (Lucchitta 1980, Murchie and Head 1988). Voyager images do not show evidence for consistent asymmetry of ridges or for compressed craters, as might be expected if grooved terrain represents thrust faults or folds (Parmentier et al. 1982, Zuber and Parmentier 1984). Extrusion of icy material has been suggested as a possible means to create some isolated positive-relief ridges recognized on Ganymede (Shoemaker et al. 1982, Schenk and Moore 1995).

Examination of grooved terrain on Ganymede has constrained a large variety of models of surface tectonism and volcanism as well as the satellite’s interior differentiation, volume change, and mantle convection (see McKinnon and Parmentier (1986) for a review). Galileo images allow models of grooved terrain morphology, origin, and evolution to be tested, constraining models of the surface and internal history of the solar system’s largest satellite, and enabling comparisons to its neighbors Callisto and Europa.

1.2. Uruk Sulcus: Setting, Galileo Imaging Overview, and Stratigraphic Units

Uruk Sulcus is a ~300 km wide and 2500 km long swath of bright grooved terrain which crosses the low northern latitudes of the leading quadrant of Ganymede’s anti-Jovian hemisphere. Uruk Sulcus was relatively well imaged by the Voyager 2 spacecraft, at ~1 km/pixel. These images show that the sulcus contains many constituent cells of grooved terrain with a variety of trends and complex structural and stratigraphic relationships and also a hierarchy in the prominence and scale of its structures (Golombek and Allison 1981, Murchie et al. 1986). Based on Voyager images, the spacing of structures within structural cells is ~6.5 km, somewhat less than the Ganymede mean of 8.4 km (Grimm and Squyres 1985).

During Galileo’s first orbit of Jupiter, termed G1, the Solid State Imager (SSI) obtained 4 images at ~75 m/pixel.
of a region of bright grooved terrain within Uruk Sulcus (Fig. 1). The images are centered at 11.1°N, 168.9°W and cover an area approximately 100 × 120 km (Belton et al. 1996). The images were BARC (Block Adaptive Rate Controlled) compressed onto the spacecraft’s tape recorder, and DN values along most lines experienced truncation of two or three of their least significant bits, reducing the number of gray levels used to represent the scene to below the nominal 256. The BARC compressor’s response to unexpectedly high scene contrast resulted in the truncation of samples from the end of each image line.

To provide stereo data across a part of this area, two additional images were obtained at an average geometric resolution of 42 m/pixel (Fig. 1) from the mirror view geometry provided by Galileo’s second orbit, G2. Seventy percent of each stereo frame was downlinked from the spacecraft. These G2 images were ICT (Integer Cosine Transform) compressed by a factor of 11, a high value but sufficient to permit visual analysis of the stereo scene. Each of the two stereo images contains a losslessly (Huffman) compressed “truth window” 96 × 96 pixels in size, allowing evaluation of a small portion of the scene in absence of compression artifacts (Fig. 2).

Individual tectono-stratigraphic units have been identified in the Uruk Sulcus target region, and their characteristics and stratigraphic relationships are summarized by Senske et al. (1997 and submitted). These units are illustrated in Fig. 3. In sections 3 and 4, we demonstrate elements of the crosscutting relationships among units that are critical to subsequent tectonic analyses. Overall, the units can be divided into three age categories, based on crosscutting relationships and crater densities (Senske et al. 1997 and submitted, Collins et al. 1998b). The oldest are the relatively heavily cratered Pitted and Lineated Terrain (PLT1, PLT2, PLT3) units, characterized by abundant pits (craters) and subdued striations and ridges. Intermediate units are Parallel Mesa and Ridged Terrain (PMRT1, PMRT2, PMRT3), consisting of parallel flat-topped mesas and narrower ridges, Braided Terrain (BT), which occurs as a wedge of distinctly braided structures, and Striated Terrain (ST1, ST2, ST3), characterized by narrow subparallel ridges of subdued relief. Younger units are Cuspat e Ridged Terrain (CRT1, CRT2), composed of relatively arcuate or cuspat e ridges and troughs, Parallel Ridged Terrain (PRT1, PRT2, PRT3, PRT4), consisting of abundant elongate parallel ridges and troughs of multiple scales, Parallel Ridged Terrain in Spindle-Shaped Occurrence (PRTS), which is an occurrence of PRT with a planform that tapers at either end, and En Echelon Ridged Terrain (EERT), characterized by relatively short sigmoidal shaped blocks in en echelon arrangement. Relative crater ages of the units (Chapman and Merline 1996) broadly support this stratigraphy. This unit definition depends on an understanding of the interplay of topography and albedo, which we expand upon next.

2. GROOVED TERRAIN TOPOGRAPHY AND ALBEDO

Contrast variations in the G1 and G2 Uruk Sulcus images are extreme, despite the low incidence angles (13° and 14°, respectively) and phase angles (16° and 47°) of these images. Here we investigate the interplay of contrast, albedo, and topography in the Uruk Sulcus images. We consider the illumination geometry of the G1 images and a range of plausible photometric models to show that the extreme contrasts observed are implausible to achieve solely by means of topographic shading and must result largely from differences in scattering behavior, specifically albedo. Stereo imaging confirms that these contrast (i.e., albedo) variations are controlled by topography. Only upon understanding the interplay of albedo and topography are we able to confidently infer and interpret grooved terrain morphology from these high resolution, low phase images.

2.1. Contrast, Albedo, and Topographic Shading

Paired bright and dark stripes occur throughout the Uruk Sulcus images, showing contrast variations of about three. This strong modulation of brightness has the appearance of topographic shading. In fact, the scene appears overall to be illuminated roughly from the west at a relatively large incidence angle, despite the actual illumination from the south at small incidence angle (Fig. 1). Here we investigate whether this can possibly be topographic shading or whether topography can be inferred from it.

2.1.1. Observations relevant to photometry. For the purposes of photometric analysis, features in the Uruk Sulcus images can generally be grouped in two classes. (1) Radially symmetric patterns of brightness are associated with impact craters and have a topology consistent with variations in albedo (or some other scattering parameter affecting brightness at constant surface orientation). The appearance of these features is similar to the appearance of craters seen in low-phase observations of the Moon. (2) Linear patterns of brightness (complicated by specifics of braiding, termination, etc.) appear to be principally slope related. For example, bright and dark stripes are mainly paired and vary in width and intensity together, so that it is possible to deduce whether a given bright line is paired with the dark line to its east or west. Some exceptions occur, such as unpaired dark lines and relatively dark streaks transverse to the lines, both topologies suggestive of nontopographic albedo effects. Such apparently strong slope-related shading is unexpected at the low phase angle (16°) of the G1 Uruk Sulcus images.

These brightness variations differ somewhat in ampli-
FIG. 1. Mosaic of Galileo G1 and G2 images of Uruk Sulcus superimposed on Voyager base mosaic. Simple cylindrical projection at a resolution of 74 m/pixel; Voyager image resolution is approximately 1 km/pixel. G2 coverage is delimited by the white box. Black boxes outline the locations of regions shown in detail in subsequent figures as labeled. Note that the images have the appearance of illumination from the west at large incidence angle, but the G1 and G2 images are actually illuminated roughly from the south at low incidence angles (13° and 14°, respectively). Marked are the sun azimuth (⊙) and spacecraft azimuth (s/c) of the G1 images (black arrows) and G2 images (white arrows). En-zu is the prominent 7 km dark-ray crater.
tude, but the bright lines are typically about three times as bright as the dark lines, regardless of orientation. Across bright zones, the data value is nearly constant (ignoring transverse streaks). This suggests both spatially constant scattering properties and either constant slope (from generally “triangular” ridges) or quasi-saturation of the photometric function at its maximum value over a range of slopes. In the dark zones, the regions of minimum brightness do not tend to be as broad, level, or clearly demarcated, but the minimum brightness reached is locally quite consistent.

2.1.2. Past photometric work. A Hapke-function fit to Voyager data for the bright terrain of Ganymede has been derived by Helfenstein (1986). The parameters are single-scattering albedo $w = 0.61$, asymmetry parameter $g = -0.4$, macroscopic roughness $\bar{\theta} = 3^\circ$. We would like to investigate the amount of topographic shading that might be visible in the Galileo images for a wider range of scattering behavior, including this fit. For this purpose, the full Hapke photometric function is unwieldy, but a much simpler function captures its full range of qualitative behavior. McEwen (1991) fits various Hapke functions with the lunar-Lambert function describing the intensity of scattered sunlight $I$ as

$$I = B_0[2L\mu_0/(\mu + \mu_0) + (1 - L)\mu_0],$$

where $\mu_0 = \cos(\iota)$ and $\mu = \cos(\varepsilon)$ for an incidence angle $\iota$ and emission angle $\varepsilon$, and $B_0$ describes the amount of backscatter from the surface. The fitted lunar weight $L$ lies in the range $-0.2$ to $1$ for a very wide range of Hapke parameters and phase angles, so this simple photometric function serves as a reasonable stand-in for the full Hapke equation in our modeling of the Uruk Sulcus images. McEwen’s curve closest to the Ganymede case is for $w = 0.7, g = -0.4, \bar{\theta} = 0$, and gives $L = 0.84$ at $16^\circ$ phase. This is far toward the lunar-like end making probable topographic shading even more subdued than the small phase angle alone would indicate. It is worth noting that the Galileo images are of higher resolution than those used in the above fit, and so should have equal or lesser unresolved roughness. Nevertheless, increasing the roughness parameter has very little effect on the fitted $L$ at this phase angle, and as shown below, changing $L$ substantially does not alter these conclusions.

2.1.3. Photometric analysis. We have attempted to model the achievable slope-related contrast of the linear features in Uruk Sulcus. For any given set of features with specified azimuth, we have two observations (dark and bright intensities) and three quantities appearing in the photometric law: slope dip (assumed to be symmetrical for the dark and bright sides; we discuss relaxing the assumption of symmetry below), $B_0$ (times normalization of the
FIG. 3. Map of tectono-stratigraphic units within Uruk Sulcus as identified and described by Senske et al. (1997 and submitted), shown on a simple cylindrical basemap of Galileo G1 and Voyager images. These units can be categorized from older to younger. (older) Pitted and Lineated Terrain (PLT1, PLT2, PLT3). (intermediate) Parallel Mesa and Ridged Terrain (PMRT1, PMRT2, PMRT3), Braided Terrain (BT), and Striated Terrain (ST1, ST2, ST3). (younger) Cuspat Ridge Terrain (CRT1, CRT2), Parallel Ridged Terrain (PRT1, PRT2, PRT3, PRT4), Parallel Ridged Terrain in Spindle-Shaped Occurrence (PRTS), and En Echelon Ridged Terrain (EERT).

image if this parameter is unknown), and $L$. It is therefore possible to relate the slope dip and $L$ for any given set of features.

The result is that the very strong contrast ($\sim 3:1$) between light and dark sides of a triangular ridge or groove can only be obtained for very steep dips: from $60^\circ$ ($L = 0$) to $66^\circ$ ($L = 1$) at the most favorable orientation. These values should be considered approximate, as the lunar-Lambert law may not reproduce the extreme limb-darkening behavior of the Hapke function, and McEwen (1991) fit data only to about $70^\circ$ dip. Nevertheless, it should be qualitatively true that very steep slope dips are required to reproduce the $3:1$ contrast ratio. While it is possible that normal faults on Ganymede could have formed with such steep dips, such slopes would be far beyond the angle of repose and are unlikely to be preserved over geologic time.

Such steep dips are also inconsistent with other aspects of the data. We find that the range of azimuths at which $3:1$ contrast can be obtained is limited. Obviously, the
bright face must lie within one 180° sector in azimuth and the dark face in the other, but in practice the needed slopes become so large that the image geometry requires that one or the other face may be invisible to the camera, or the dark face would be shadowed. The ranges of valid bright-face azimuths are 210°–325° (L = 0) to 225°–322° (L = 1), with these azimuths measured counterclockwise from east to the inferred dip direction of the bright ridge face. We measure bright face azimuths ranging from about 110° (CRT1) to 270° (CRT2), falling far outside the allowable photometrically induced range. Furthermore, when the 3:1 contrast is achieved, both the “bright” and “dark” sides are actually in the limb-darkening regime; a level surface with the same properties will be ≳1.5 times brighter than the “bright” face. This is not observed: in the lineated grooved terrain units (PLT and PMRT), which are interpreted to have level as well as dipping sections (see Section 3.1 and Fig. 5), the level sections are roughly half as bright as the bright sections. The assumption of symmetric dips is unrealistic, but relaxing it does not offer a solution to the problem. If one side is modeled as shallower, the other will have to be even steeper than 60° to achieve the same contrast ratio by shading.

The same models can be used to ask what topographic shading can be expected from geologically more reasonable slopes. In short, the brightness contrast for small slopes is greatest for L = 0 and in the direction of the Sun, and amounts to a little less than 1% per degree of dip. This is achieved primarily by darkening of the dark side rather than brightening of the bright side. For 30° slopes, the brighter and darker slopes would be, respectively, −2 and −25% as bright as a level surface. For a given small contrast, the required dip increases as the azimuth departs from the downsun direction. Bright faces can only have dip azimuths in the range 165°–345°.

The behavior of the Hapke function is well captured by the lunar-Lambert function with −0.2 < L < 1 and cannot explain the observed contrast, nor can such contrast be obtained from an even broader (and nonphysical) range of L. Could some scattering process we have not considered lead to a photometric function that is qualitatively different from the two we have considered in order to explain the apparent “shading”? This seems highly unlikely, as we would require a scattering process that can produce a much higher contrast at modest dips, and which would do so for a wide range of azimuths. The first requirement is fairly easy to achieve (for example, by quasi-specular reflection, which can produce essentially arbitrary contrast for surfaces oriented in the specular direction), but the second point is not compatible: the greater the peak contrast, the more localized the effect is likely to be in azimuth. We conclude that the extreme contrast variations within Uruk Sulcus cannot be produced by topographic variations alone.

2.1.4. Interpretation. If topographic variations alone cannot produce the observed brightness variations, they must be produced by variations in scattering properties. Given the large contrasts and the small phase, incidence, and emission angles of the G1 images, it is primarily the albedo that must be varying, by a factor of about three. Actual topographic shading is much weaker (tens of percent or less, as indicated above), and to first order does not change our conclusions about the distribution or the strength of albedo variations.

The fact that albedo variations in the Uruk Sulcus images are in some manner controlled by topography is made apparent by Uruk Sulcus craters, where crater floors are dark and walls and rims are bright. Bright and dark lineations are also inferred to be topographically controlled, based on their paired widths and intensities, and on relationships seen at some unit boundaries, best explained as topographic variations of the older unit revealed in cross section, where truncated by the younger unit (see Section 3.2.3, below). The brightness relationship in craters suggests that steeper faces tend to be brighter while low lying areas appear dark. However, such trends alone cannot explain the linear contrast variations: we would then expect both faces of a ridge to be brighter than flat areas. In the next section we discuss the relationship between albedo and topographic variations as elucidated by stereo imaging.

2.2. Stereo Imaging

Stereo imaging during the G2 encounter allows topography and albedo variations to be correlated to topography within a portion of the Uruk Sulcus target site, allowing for extrapolation of topographic interpretations to regions beyond the limited area of stereo coverage. A portion of the stereo data is shown in Fig. 4; it is situated almost exclusively within unit PRT2 (see Figs. 1 and 3). Stereo viewing of the images demonstrates that contrast (albedo) variations are indeed controlled by topography, which shows a variety of types and scales. The topography can be broadly classified as (1) craters, (2) “Voyager-scale” ridge and trough topography (~4–6 km spacing), termed such because ridges and troughs of this scale comprise the “grooved terrain” imaged by Voyager, and (3) “Galileo-scale” ridge and trough topography (~1 km spacing), unknown before Galileo imaging of Uruk Sulcus. The Galileo-scale topography can be further divided into large ridges (~900 m spacing) and small ridges (~400 m spacing). (The inferred geometry of these ridge-and-trough topographic elements is summarized in Fig. 13 and Section 5.2.3.) We qualitatively divide materials into bright, intermediate, and dark; this general classification is supported by the trimodal distribution of DN values in the image data. The photometric analysis of the previous section suggests that these brightness differences represent, in large
part, true differences in albedo. The distribution of materials in relation to topography is discussed below.

2.2.1. Craters. As is evident from stereo viewing of Fig. 4, bright material is located on the rims, outer slopes, and uppermost inner slopes of craters. The central and lower portions of inner crater walls are of intermediate brightness. The darkest material is situated on the crater floors. The inner slopes of some of the larger Uruk Sulcus craters show streaks oriented downslope.

The dark material on crater floors might have been concentrated by the impact process and/or through collection of mass wasted dark material in topographic lows (cf. Prockter et al. 1998). Helfenstein et al. (1997) measured the albedo of dark material in 55 such craters in the G1 Uruk Sulcus images, assuming that this dark material represents a relatively pure concentration of dark material on Ganymede. The darkest material has an albedo of about 12%, similar to the value found by Schenk and McKinnon (1991) who measured the albedos of larger dark floor craters in Voyager images.

2.2.2. “Voyager-scale” ridge and trough topography. Multiple scales of ridge and trough topography are apparent in the stereo data. The largest-scale ridge and trough topography has been modeled by Giese et al. (1998) who construct a digital terrain model of the region. They find a topographic wavelength of \( \sim 4-6 \) km, amplitudes of up to 500 m, and slopes of up to 19º; Voyager-scale ridge slopes are commonly asymmetric and terraced, and good agreement is found with Voyager-based photoclinometric profiles obtained across grooved terrain in Ganymede’s south polar region (Squyres 1981). As direct comparison demonstrates (Collins et al. 1998a), the broad-scale ridge and trough topography resolved by the digital terrain model corresponds to grooved terrain observed in Voyager data of the same region of Uruk Sulcus. Comparisons of this “Voyager-scale” topography to brightness profiles across the Uruk Sulcus images show a general correlation between elevation and brightness (Oberst et al., submitted), indicating that dark material preferentially occurs in the broad-scale lows.
2.2.3. “Galileo-scale” ridge and trough topography. Visual inspection of the stereo images confirms that the albedo striping in the Uruk Sulcus region is correlated to ridge and trough topography that is below the resolution of Voyager imaging. These ridges of unit PRT2 appear to have a roughly bimodal distribution of ridge dimensions and spacings, and are here classified as large or small. Both the large and small ridges tend to cluster with ridges of similar dimension, but the ridge types also occur intermingled. Large ridges are triangular to somewhat rounded in cross section and have a spacing of about 900 m. By visual comparison to the Voyager-scale topography, quantified by Giese et al. (1998), we estimate that these large ridges are roughly 200 m tall. Small ridges appear to be convex in profile, are spaced about 400 m apart, and are probably less than 100 m in height.

Bright material is seen to be generally located on ridge crests and west- and southwest-facing slopes, most notably of the large ridges (some large ridges show some image saturation of this bright material). Dark material is concentrated in the narrow, commonly V-shaped, topographic lows between ridges. Materials of intermediate brightness are distributed elsewhere. Some brightness variations may be due in part to topographic shading (as discussed above, a few tens of percent darkening is possible, while brightening is more difficult to achieve).

Some intermediate and bright streaks on ridge slopes are oriented roughly parallel to the downslope direction. Some darker streaks appear to cut across ridge crests, suggesting that they have a topographic expression as narrow notches. Gravity-driven mass wasting may cause dark and bright materials to move downslope off ridges, utilizing (and perhaps amplifying) preexisting small-scale topography along the ridges.

2.2.4. Models for the topographic control of albedo. There is strong correlation of albedo to topography in the Uruk Sulcus region, especially in the tendency of dark material to occur in local topographic lows. Downslope movement of dark debris in Uruk Sulcus probably causes its accumulation in topographic depressions. Dark material is seen to be distributed toward the northeast from the 7 km crater En-zu (Fig. 1), due to impactor contamination or perhaps excavation of shallowly buried dark material, demonstrating that dark material can be distributed ballistically by impacts. As appears to be true of material distributed by the En-zu impact, such dark material will move downslope into the topographic depressions between ridges. Another source of dark material is micrometeoritic material (including dust), expected to rain onto the surface over time, and which may accumulate in topographic lows. A third possible source is release of dark material from an ice–rock mixture due to slow sublimation of the ice matrix (e.g., Moore et al. 1996). However, because the landscape is rich in fine-scale topography, sublimation (which should preferentially affect fine-scale topography) has probably not markedly affected the region. A similar correlation of low albedo with low elevation is noted in the G1–G2 Galileo Regio target site, where the tendency is similarly ascribed to mass wasting and concentration of dark material in topographic lows (Prockter et al. 1998).

Bright regions may owe their brightness to grain size effects, or they may be especially rich in ice or frost. An idea consistent with a model of tilt-block style normal faulting (investigated below) is that bright faces are faulted exposures of cleaner subsurface ice, whereas the dark faces represent the predeformation surfaces. In this model, the near-constant intensity of the bright sides would result from saturation of the photometric function combined with homogeneity of the exposed material. A problem presented by this model is the tendency for western-facing slopes in the Uruk Sulcus images to be generally brighter than east-facing slopes throughout the region; it is unlikely that faulted faces should be preferentially facing in one direction across the broad range of structural azimuths and terrain types which exist over the region.

Control of albedo by production of lag deposits on Sun-facing slopes has been suggested for the Galileo Regio area (Prockter et al. 1998); however, it is not obvious that this mechanism is operating in Uruk Sulcus, as dark bands do not have a distribution dip to the southeast, east, and northeast, not in a range centered on south or north as would be expected if diurnally averaged insolation is the principal controlling factor. A surface on Ganymede that is initially somewhat brighter may become a local sink for frosts (Spencer 1987, Prockter et al. 1998); therefore, bright materials may have concentrated in regions which originally had an albedo only somewhat greater than their surroundings. Such initial brightness variations might be attributed to fault exposure of subsurface materials, grain size differences correlated to slope, or other factors. The thermophysical properties of the uppermost regolith might also be important in initiating albedo heterogeneities, through differences in the local thermal inertia of surface and near-surface materials. While many factors could potentially contribute to the preferred concentration of bright material on ridge crests and west-facing slopes in the Uruk Sulcus region, the relative roles of these processes remains uncertain and is an important area for further investigation.

3. MORPHOLOGIES OF TYPE EXAMPLE GROOVED TERRAIN UNITS

The strong correlation of albedo to topography allows landform morphology and structure to be recognized in Ganymede’s grooved terrain even under these conditions of high solar illumination. Relationships inferred from the
stereo data, most notably the tendency of the darkest material to be situated in topographic lows, can be extrapolated to the rest of the Uruk Sulcus site. Moreover, structural relationships among units and their constituent ridges and troughs, especially at the boundaries of grooved terrain units, provide insight into topographic relationships and formational process.

It is probable that some mass wasting has affected grooved terrain, as evidenced by the apparent movement of dark materials to local topographic lows. Small-scale mass wasting is also apparent in the highest resolution Galileo imaging of bright terrain on Ganymede, at 11 m/pixel (Yingst et al. 1997). However, the degree of mass wasting in bright terrain appears to be minimal in volume, as (1) large-scale slumping is not seen, (2) troughs do not appear to be filled and embayed by talus, and (3) small-scale topographic elements (craters, ridges, and troughs) appear to be well preserved. Therefore, we can interpret the structures of Ganymede’s grooved terrain as essentially primary morphologies, apparently little affected by mass wasting subsequent to their formation.

We broadly categorize the morphology of grooved terrain across the Uruk Sulcus mosaic as divided into two endmember types, here termed “lineated grooved terrain” and “parallel ridged terrain.” Below we explore the detailed morphology of these endmember units by concentrating on their type example occurrences. We then draw inferences about their origin and tectonic style, based on morphological predictions for ridges and troughs compiled by Pappalardo and Greeley (1995), who consider a variety of candidate formation processes. The morphologies and inferred origins of other grooved units within the Uruk Sulcus target site are investigated by Senske et al. (1997 and submitted), and the majority of grooved terrain units can be related to the endmember lineated grooved terrain and parallel ridged terrain units described here.

3.1. Lineated Grooved Terrain

3.1.1. Morphology of lineated grooved terrain. Figure 5 shows the type example of lineated grooved terrain, located in the northeastern corner of the Uruk Sulcus mosaic. Both the “pitted and lineated terrain” (PLT) and “parallel ridge and mesa terrain” (PMRT) units (Fig. 3) are encompassed within our definition of lineated grooved terrain. The type example location is characterized by lineated, plank-like blocks ~2–6 km wide (A of Fig. 5), with relatively constant brightness across their widths. Based on their relatively uniform brightness, these broad blocks are inferred to be relatively flat surfaces. Preservation of a relatively high density of craters on these surfaces and only modest deformation of the craters suggests that the broad blocks represent relatively old and pristine terrain. These broad blocks are transected by dark, small-scale (~100 m wide), slightly sinuous lineations, which trend subparallel to each other and to the long axes of the broad blocks they transect. Where the ubiquitous small-scale lineations cut older craters (B of Fig. 5), neither lateral nor vertical offset is apparent, so any such offset must be of small magnitude. As seen in Section 3.2.3 below, the impression that these dark lineations define troughs is confirmed by examining their outcrop pattern along the southwestern boundary of the PLT2 unit. These narrow dark lineaments define small-scale blocks ≤500 m wide, morphologically analogous to those which characterize units of striated terrain (ST units of Fig. 3), shown in Fig. 10. Very bright materials occur along some of these small-scale blocks and along crater walls and prominent structures.

The relatively broad and flat blocks are separated by prominent low albedo lineations ~1–4 km wide and sets of such lineations (C of Fig. 5). Based on their albedo characteristics, these relatively wide and dark lineations and sets of lineations apparently define relatively deep troughs, which separate the broad ridges. These prominent troughs are constructed of multiple small-scale blocks (defined by the narrow dark lineations), and their combined displacement is great enough to define the prominent troughs. Compared to the ridges they separate, these prominent troughs are of similar width or narrower. In Voyager images of the region, some are wide enough to be recognized as Voyager-scale grooves.

3.1.2. Horst and graben interpretation of lineated grooved terrain. The morphology of the broad blocks and prominent troughs can be compared to idealized formation models for ridge and trough terrain (Pappalardo and Greeley 1995). It is readily apparent that extrusive volcanism is unlikely to have formed the ridges and troughs of this terrain type, as extrusion would not preserve the preexisting cratered surface on the broad blocks. The relatively flat morphology of ridge-forming blocks is inconsistent with intrusive or compressional models, which predict upwarping of the terrain, generally rounded ridge crests, and ridge-widths ≤ trough-widths. Braiding or intersection of structures is not common, as would be expected if strike-slip tectonism shaped this terrain. The relatively large spacing of the broad troughs (i.e., ridge-width > trough-width) and the relatively unmodified nature of the broad ridges are characteristics indicative of extensional tectonism, in a style reminiscent of horst-and-graben normal faulting.

For comparison to lineated grooved terrain of Uruk Sulcus (Fig. 5), we reproduce in Fig. 6 the idealized morphological predictions of horst-and-graben style normal faulting as presented by Pappalardo and Greeley (1995). Rather than modify this predictive sketch to match the Ganymede observations, we compare the observations to the morphological predictions. In this model, the flat-topped, broad blocks of lineated grooved terrain (A of
Fig. 5. Detail of lineated grooved terrain in Uruk Sulcus (units PLT2 and PMRT1). Examples of (A) plank-like ridges. Examples of the ubiquitous small-scale dark lineations (B) are highlighted where they transect preexisting craters. These dark lineations define small-scale blocks between them. Prominent troughs (C and D) are marked across their widths and typically contain multiple subparallel small-scale blocks; trough D shows a ramp-like termination style toward the southwest. Note the abundance of craters, some of which are degraded, suggesting a relatively old age for the NE–SW trending PLT2 and PMRT1 units. In contrast, the NW–SE trending parallel ridged terrain unit (PRT2) shows few large craters. Boundary relationships suggest that the parallel ridged terrain formed at the expense of the lineated grooved terrain units.

Fig. 5) represent horsts of relatively unaltered terrain, and the broad prominent troughs (C and D of Fig. 5) are graben-like. Unlike shown in the idealized model of Fig. 6, however, the prominent troughs do not appear to be simple graben with paired antithetic (inward-facing) faults. Instead, they have a complex morphology consisting of many closely spaced small-scale elongate blocks. These prominent troughs may be created by displacement along one or many small-scale lineaments that act as normal faults to create the small-scale blocks, their combined displacement producing a prominent trough with a graben-like morphology overall. One such trough in unit PMRT1 (D of Fig. 5) appears to become shallow toward the southwest, approaching the surrounding topographic level in a manner reminiscent of a ramp termination (Fig. 6). The narrow dark lineaments (B of Fig. 5) that cut the horst-like blocks are interpreted as minor fractures and faults defining narrow troughs in which dark materials have collected. This interpretation is based on their association with the horst-and-graben-like blocks, and their large spacing relative to their widths (Pappalardo and Greeley 1995). Such minor normal faults and tension fractures are predicted in an extensional tectonic setting (Fig. 6). These observations and interpretations suggest that lineated grooved terrain has formed in place through tectonic segmentation of pre-existing terrain.
3.2. Parallel Ridged Terrain

3.2.1. Morphology of parallel ridged terrain. Well-defined sets of stratigraphically high ridges and grooves have been termed “parallel ridged terrain” (PRT) by Senske et al. (1997 and submitted). Figure 7 illustrates the type example of this grooved terrain style, unit PRT1. Unit PRT2 was imaged in stereo (Fig. 4), and this morphologic and topographic information is also critical to our characterization and interpretation of this style of grooved terrain. In both the PRT1 and PRT2 units, ridges and troughs occur in NW–SE trending lanes.

Stereo imaging reveals both large and small “Galileo-scale” ridges and troughs in unit PRT2, superimposed on broader “Voyager-scale” topography, as described in Section 2.2 above. The stereo data demonstrate that large Galileo-scale ridges and troughs are of roughly equal width, with no topographic break between. As demonstrated by the stereo data, these large ridges (e.g., E of Fig. 7) are triangular to somewhat rounded in cross section, and in the Uruk Sulcus region they are typically comprised of a bright western face and top and a darker eastern face. They are relatively continuous along their lengths. The large ridges generally terminate along their trend through decrease in width and height, tapering noticeably (F of Fig. 7); some terminate along their trends by merging into neighboring ridges (G of Fig. 7). Large ridges are separated by dark-bottomed, generally V-shaped troughs (H of Fig. 7). Marked asymmetry is not apparent in large ridges of the PRT2 unit, but stereo data over the large triangular ridges of the PRT2 unit suggests that they are somewhat asymmetric, with the darker face having a shallower dip than the bright face.

Small ridges in units PRT1 and PRT2 (e.g., J of Fig. 7) appear to be convex in cross section with cusparse dark troughs between them. These small ridges are concentrated along the northeastern edge of the PRT1 groove lane (Fig. 7), and they also occur interspersed within the large triangular ridges. Their morphology and scale is similar to the small-scale lineations and ridges of lineated grooved terrain (described above), and the small-scale lineations of striated terrain (see Fig. 10).

3.2.2. Domino tilt block model. The morphologies of the large ridges which characterize the parallel ridged terrain offer an important clue to the origin of this grooved terrain type. Consideration of the cross-sectional morphologies predicted from candidate formational processes shows that ridges of triangular to rounded cross section are limited to formation by low-viscosity fissure eruptions, by a particular style of folding, or by tilt-block (“domino” or “bookshelf”) style normal faulting. The “close-packed” or sawtooth-like spacing of the ridges and troughs (i.e., ridge width ≈ trough width, with no topographic break in between) and the V-shaped morphology of troughs combine to further limit the likely formation model to tilt-block normal faulting (cf. Pappalardo and Greeley 1995). The merging and tapering termination styles of ridges also match predictions of tilt-block style normal faulting.

Figure 8 shows the idealized predictions of tilt-block
FIG. 7. Detail of parallel ridged terrain (unit PRT1) in Uruk Sulcus. Marked are examples of a large ridge (E), tapered large ridge terminations (F), merging ridges (G), a large V-shaped trough (H), and small ridges and troughs (J). Note that large ridges tend to concentrate along the southwestern side of the groove lane, and small ridges along the northeastern side. The moderately cratered, NW–SE trending PRT1 unit truncates the more heavily cratered and pitted PLT1 unit, which trends roughly N–S.

style normal faulting, as compiled by Pappalardo and Gree-ley (1995). On Earth, this is the most common normal faulting style (Wernicke and Burchfiel 1982, Mandl 1987). In such a model, subparallel faults dip synthetically, that is, in the same direction. Extension causes rotation of faults and backtilting of the original surface by an amount proportional to the degree of extension (Wernicke and Burchfiel 1982). Ridges terminate by tapering and merging as the degree of fault throw decreases and fault traces intersect. As discussed in Section 3.2.3., the boundary relationships along PRT units strongly support an extensional tectonic origin, as in the tilt block model. This faulting style is commonly associated with listric faulting, second generation tilt blocks, and a prominent breakaway fault and detachment at depth (Fig. 8). Possible implications for Ganymede grooved terrain are addressed later in this section and in Section 5.

In applying a tilt block normal faulting model to Gan-
ymede’s parallel ridged terrain, it is uncertain which surface of the large triangular ridge represents the faulted face. For a modest degree of extensional strain (a few tens of percent or less), the faulted face of a tilt block is predicted to be steeper than the backtilted face (Wernicke and Burchfiel 1982). Greater extension would produce roughly symmetrical blocks, and at very high strains (approaching 100%), the faulted face can become the shallower one. Collins et al. (1998a) determine a minimum extensional strain of \( \sim 50\% \) across unit PRT2. This implies that the steeper (brighter) faces of these ridges are more likely to represent the faulted faces. This scenario is consistent with the idea that bright material might represent bright subsurface material exposed in fault scarps; however, as discussed above, it is unlikely that all bright regions are fault exposures of bright material, as the orientation of bright slopes is too highly consistent over the entire imaged region.

The small ridges within the parallel ridged terrain may have formed through imbrication of originally larger blocks in regions of relatively great extensional strain. As a domino fault zone extends, faults can rotate into such shallow orientations that they become unfavorable for continued motion; new faults can form to allow extension to continue (Morton and Black 1975, Proffett 1977, Wernicke 1992). Imbrication of blocks can also occur as progressive rotation causes originally vertical tension fractures to rotate into orientations that make them favorable for fault motion (Angelier and Colletta 1983). In these ways, finer scale faults may form as extension proceeds. The spacing of domino-style tilt blocks is predicted to be proportional to the thickness of the faulted layer (Vendeville et al. 1987, Mandl 1987); thus, finer-scale faults within parallel ridged terrain might have formed where the faulted layer was relatively thin.

3.2.3. Boundary relationships. Relationships along the margins of the parallel ridged terrain elucidate the origin of these grooved terrain units (Fig. 9). Figures 9b and 9c show that the density of fractures (dark lineations marking topographic lows) trending parallel to the PRT1 and PRT2 ridges falls off rapidly beyond the margins of the PRT units. Some incipient fractures are observed to splinter the adjacent, more heavily cratered PLT units. Most notably, in Fig. 9c, several splays of a prominent structure trending subparallel to structures of the PRT2 unit can be seen to transect the preexisting PLT2 unit. Along the boundaries of the PMRT units (Figs. 9a and 9d), the margins of the PRT units are clearly marked by scarps that truncate the older PMRT units. Figure 9d shows that preexisting topography of unit PMRT is exposed in cross section along the faulted boundary, like a celery stalk chopped at an angle. We interpret the pinch-and-swell morphology of the bounding bright material as a bounding fault-line scarp (a fault scarp modified somewhat by mass wasting), its undulations reflecting variations in the original topography of unit PMRT2. Correlation can be seen between dark
FIG. 9. Detail of termination relationships, imbrication of preexisting terrain, and boundaries along units of parallel ridged terrain (PRT), supporting an extensional-tectonic origin for these units. Shown are boundaries between units (a) PRT1 and PMRT3, (b) PRT1 and PLT1, (c) PRT2 and PLT2, and (d) PRT2 and PMRT. In each case, the NW–SE trending PRT unit crosscuts preexisting terrain that has a N–S or NE–SW trend (north is approximately to the top). Black arrows on (b) and (c) mark examples of narrow lineaments, with trends subparallel to PRT trends, which cut and splinter older PLT units. White arrows mark examples of trough topography expressed along the boundaries of units (c) PLT2 and (d) PMRT2, where these units are cut by younger PRT units.

lineations of unit PMRT and the pinched portions of the bounding scarp, consistent with the dark lineations being topographic troughs. Similarly, some small-scale lineations of unit PLT2 are visible in section along the scarp delimiting the boundary with unit PRT2 (Fig. 9c). As illustrated by Head et al. (1997) and Collins et al. (1998b), preexisting structures of these older truncated terrains can be traced for a short distance atop blocks of the younger parallel ridged terrain units, notably along the more gradational PLT unit boundaries.

These margin relationships are inconsistent with a compressional or magmatic origin for parallel ridged terrain (cf. Pappalardo and Greeley 1995), and instead indicate that the parallel ridged terrain formed through extensional tectonism at the expense of preexisting terrains. As discussed by Collins et al. (1998b), these relationships indicate the reverse of the sense of stratigraphy inferred from Voyager imaging of Uruk Sulcus as proposed by Golombek and Allison (1981). Instead, these relationships are consistent with a model of “tectonic resurfacing” (Head et al. 1997), in which rotational normal faulting dissects and deforms an older surface to such an extent that its preexisting topography becomes unrecognizable. By stretching and backtilting preexisting topography while exposing new fault surfaces, domino-style normal faulting can reshape the preexisting terrain, potentially destroying older craters...
and tectonic structures. In this hypothesis, cryovolcanism of individual lanes of grooved terrain remains a possible, but not a necessary, component of groove lane formation on Ganymede.

A prominent bounding depression may form at the “proximal boundary” or “breakaway margin” (e.g., Wernicke 1992, Davison 1994) of a zone of domino-style tilt blocks (Fig. 8), due to rollover and antithetic faulting of the hanging wall block above a prominent marginal fault. This is aided if the marginal fault has a listric (i.e., spoon-like) geometry (Hamblin 1965, McClay and Ellis 1987). This geometry may account for the prominent bounding grooves apparent in Voyager imaging of grooved terrain (e.g., Shoemaker et al. 1982). An example of such a bounding trough occurs along the margin between unit PRT2 and PLT2 (Figs. 5 and 9c).

4. EVIDENCE FOR SHEAR AND TRANSTENSION

Several stratigraphically high units within the Uruk Sulcus target site show evidence that they are related to horizontal shear; that is, a component of strike-slip tectonism is implied. Here, we present this evidence and compare the latter-stage geology of the target site to that predicted by dextral simple shear. We also discuss the possibility that regional extension affected the area simultaneously with dextral shear, creating a transensional stress environment.

4.1. Interpretation of Shear-Related Units

A prominent ~7 km wide, zone (unit EERT) cuts NW–SE across the Galileo Uruk Sulcus mosaic (Figs. 3 and 10). This unit is characterized by en echelon, sigmoidal shaped blocks (Figs. 10 and 11a). This unit transects and splinters many other units in the region, specifically units ST1, ST2, PLT1, and BT (Fig. 10). It also deforms the CRT units, which may owe much of their high degree of deformation to the formation of the neighboring PRT and EERT units (Fig. 10). In the eastern portion of the imaged region, the EERT zone bends toward the southeast (Fig. 10b); just west of this bend is a spindle-shaped unit (PRTS) consisting of elongate, sigmoidal blocks that mimic the shape and dimensions of the bend (Fig. 11b). The boundary between units EERT and PRTS is gradational, suggesting that their structures may be contemporaneous. Fractures associated with unit PRTS transect neighboring units PRT4 and ST2 (Fig. 10b), implying that PRTS formed at the expense of these older units.

No clear crosscutting relationships are observed between unit EERT and units PRT1 and PRT2. Instead, structures of the units seem to avoid crosscutting one another: structures of unit PRT1 arc slightly toward the west as they encounter unit EERT (Fig. 10a), and those of unit PRT2 arc slightly toward the east as they encounter unit EERT (Fig. 10b). This suggests that unit EERT does not crosscut the PRT units, but was formed contemporaneously, in response to related stresses. (This may also be true of unit PRT3, but only a small portion of that unit was imaged.) The EERT unit does not have a geometry like that of an accommodation zone between extensional fault domains (e.g., Faulds et al. 1990), because the EERT cuts across many different units, rather than being associated only with similarly aged tectonic units which terminate against it.

The braided appearance of en echelon and sigmoidal structures within the EERT unit (Figs. 10 and 11a) are characteristic of right-lateral (dextral) horizontal shear, as illustrated in Fig. 12a (Woodcock and Fisher 1986). The shape and orientation of the lensoid (spindle-shaped) PRTS unit is also suggestive of right lateral motion along the EERT unit. The lensoid shape of the PRTS unit is characteristic of a fault duplex (a system of imbricate faults), as are formed at releasing bends in terrestrial strike-slip settings and in model experiments, illustrated in Fig. 12b (Woodcock and Fischer 1986; Swanson 1990). Right-lateral motion along the EERT unit would create a releasing bend at the location of the PRTS unit, forming the spindle-shaped fault duplex and imposing a right-lateral shear component on its constituent structures.

Also consistent with this strike-slip interpretation is a trough ~7 km wide which extends northward from the en echelon unit EERT into unit ST1, tapering toward the north (Figs. 10a and 11c). This structure is consistent with the morphology and orientation expected of a “horsetail” structure (e.g., Davison 1994), which splays into the ST1 unit, induced by the dextral shear to its south. Based on the inferred structural displacements, right-lateral motion along the imaged segment of the EERT shear zone was likely a few kilometers or less.

The stratigraphically high structures interpreted to be associated with strike-slip tectonism do not appear to crosscut the stratigraphically high groove lanes that we interpret as being due to domino-style faulting in response to NE–SW-directed extension (units PRT1 and PRT2). As discussed above, these groove lanes and the EERT-related structures avoid each other and could have formed contemporaneously, with the PRT units deflecting into and merging with the tectonic trends of EERT. As discussed in Section 3.2., PRT units are likely to be of extensional tectonic origin, with the direction of opening (the least compressive stress direction, or the “extension axis”) oriented perpendicular to the trends of the parallel ridges, as illustrated in Fig. 12c. Also illustrated is the sense of strike-slip offset within those units interpreted as directly related to the right-lateral shear zone.

The PRT units and the strike-slip-related units can be explained as having formed contemporaneously, due to the action of right-lateral simple shear. The predicted structural pattern of dextral simple shear is shown in Fig. 12d.
FIG. 10. Detail of the stratigraphically young EERT unit and neighboring units. Black arrows show where incipient fractures associated with units EERT and PRTS (which are inferred to be contemporaneous) transect neighboring units ST1, ST2, PLT1, BT, and PRT4. The highly deformed CRT2 unit also shows splintering by EERT-associated structures, and unit CRT1 is deformed by en echelon and sigmoidal blocks similar to those in the adjacent portion of unit EERT. Short white arrows point to some of the sigmoidal and en echelon structures which characterize unit EERT all along its length. Long white arrows illustrate the tendency for structures of units PRT1 and PRT2 to deflect away from unit EERT, rather than either unit crosscutting the other, suggesting that these PRT units and the EERT unit formed contemporaneously. Note that unit BT is bounded to the west by a prominent dark depression and a structure which appears to be a ridge. North is approximately to the top.

(Harding 1974, Reading 1980). In a zone of simple shear, the strain ellipse has its long axis (minimum principal stress direction) oriented about 40° counterclockwise from the shear couple direction, and its short axis (maximum principal stress direction) about 50° clockwise from the shear couple direction. Normal faults are predicted to form perpendicular to the direction of minimum principal stress (parallel to the “extension axis” of Fig. 12d); folds or thrust faults can form perpendicular to the direction of maximum principal stress (parallel to the “compression axis”). Reidel shears (synthetic strike-slip faults) typically form 30° counterclockwise from the maximum principal stress direction and with the same sense of offset as the shear couple; less common are opposite-sense antithetic Reidel shears, which form 30° clockwise from the maximum principal stress direction. The structural predictions of dextral shear (Fig. 12d) closely match the sense and orientation of the stratigraphically high structures in Uruk Sulcus (Fig. 12c), with the lanes of domino fault blocks perpendicular to the long axis of the regional strain ellipse and the prominent shear zone serving as a Reidel shear. One apparent difference is a lack of compressional features in the Uruk Sulcus region.

4.2. Transtension Model

The lack of recognizable compressional features in the imaged region of Uruk Sulcus can be explained if transtensional stress affected the area, emphasizing extensional deformation. A transtensional zone can be envisioned as one in which regional horizontal extension accompanies shear, acting at an angle to the shear plane (Harland 1971, Sanderson and Marchini 1984). This results in a counterclockwise rotation of the strain ellipse with respect to the shear couple. In such a transtensional zone, compressional features are uncommon, and instead extensional features are predominant, especially when the regional extension acts nearly perpendicular to the shear direction (Sanderson and Marchini 1984). The match of Uruk Sulcus extensional and shear structures to the predictions of dextral simple shear, but with a lack of compressional structures, suggests that transtension has affected the region during this late-stage deformational episode, with the regional extension occurring nearly perpendicular to the local shear direction (Fig. 12c).

This tectonic scenario of regional transtension implies
that the shear couple affecting the imaged portion of Uruk Sulcus was oriented roughly parallel to (or slightly counterclockwise of) the EERT shear zone, plus regional extension acted approximately perpendicular to that direction.

At the local (Galileo) scale, the net least compressive stress direction would be similar to that shown in Fig. 12d. At the Voyager scale, the regional extension direction would be oriented perpendicular to the long axis of Uruk Sulcus.
FIG. 12. Structures produced by strike-slip systems can account for the morphologies and structures of some late-stage units in the Uruk Sulcus target region. (a) En echelon Reidel shears form at a shallow angle to the trend of a developing dextral strike-slip fault zone, linking into throughgoing structures as the amount of strike-slip displacement increases (after Woodcock and Fischer (1988)). The pattern of structures created in this manner is similar to those defining blocks in unit EERT. (b) A releasing bend along a strike-slip fault is the site of local extension, promoting tectonic imbrication alongside the bend. Unit PRTS may have had such an origin, formed in a releasing bend of unit EERT. (c) Extension and shear directions inferred from late-stage structures in Uruk Sulcus. Shaded areas represent (A) units PRT1 and PRT2 (interpreted as formed by tilt-block normal faulting), (B) unit EERT (interpreted as a right-lateral shear zone), (C) unit PRTS (interpreted as a releasing-bend fault duplex), and (D) a prominent trough (interpreted as a horsetail structure) which cuts across unit ST1. Full black arrows indicate inferred extension direction perpendicular to major structures of parallel ridged terrain units PRT1 and PRT2. Half arrows indicate right-lateral strike slip along inferred shear-related structures. A local transtensional stress environment would result in Uruk Sulcus from the superposition of a dextral shear couple and a component of regional extension (represented by the open white arrows). (d) Strain ellipse and associated structures predicted from dextral simple shear (half arrows); the predicted structures and their orientations are as shown (after Reading (1980) and Harding (1974)). Open white arrows represent the corresponding principal stress directions; the maximum compressive stress \( \sigma_1 \) and minimum compressive stress \( \sigma_3 \) can be visualized as indicating the “extension axis” E and “compression axis” C, respectively. Superposition of regional extension as implied by the open white arrows on (a) would induce a slight counterclockwise rotation of the orientations of structures and stresses of (b). In such a transtensional stress environment, extensional deformation would be emphasized and compressional structures would be suppressed.

and to the trend of nearby arcuate furrows of Galileo Regio. Thus, the stresses inferred for the imaged portion of Uruk Sulcus may relate to extension throughout Uruk Sulcus as a whole, and perhaps to the stresses which opened the furrows of Galileo Regio.

In summary, a right-lateral shear couple would explain the contemporaneous formation of the EERT shear zone and the PRT1 and PRT2 zones of normal faulting. The En Echelon Ridged Terrain (EERT) would represent a synthetic Reidel shear, the spindle-shaped PRTS unit would represent a transtensional fault duplex formed in a releasing bend, and a trough extending northward from unit EERT into unit ST1 would be a horsetail structure related to the dextral shear. The ubiquity of extensional structures and lack of recognizable compressional structures in the region suggest a transtensional stress environment, rather than one just of simple shear, with regional extension acting in a direction roughly perpendicular to the long axis of Uruk Sulcus and nearby Galileo Regio furrows.

5. DISCUSSION AND IMPLICATIONS

Galileo observations of Uruk Sulcus provide fundamental new insight into the nature, origin, and evolution of grooved terrain on Ganymede. Some Voyager-based hypotheses have been confirmed, others have been modified, and still others have been disproved. Here we summarize some of the insights gained and lessons learned.

5.1. The Nature of Grooved Terrain

5.1.1. Styles of extensional-tectonic deformation. As described above, we interpret that grooved terrain in the Uruk Sulcus region is generally of extensional-tectonic origin, as horsts and graben and as domino-style tilt blocks. A component of right-lateral shear was apparently involved in the latter stage of grooved terrain formation in this region of Uruk Sulcus. There is no direct morphological evidence for ridges and troughs that might have formed through compression, as reverse fault blocks or folds.
Horst-and-graben-style normal faulting was strongly suspected to be the principal process that shaped grooved terrain on Ganymede (e.g., Golombek 1982). In the Uruk Sulcus region, horst-and-graben-like structures have shaped stratigraphically low units, here collectively termed lineated grooved terrain. Horst-and-graben-like blocks are raked with small-scale lineations, which are probably minor faults. Rather than being smooth-walled and smooth-floored, Uruk Sulcus troughs with graben-like morphologies are generally comprised of smaller scale blocks. Displacement along multiple small-scale structures apparently combined to create larger scale troughs, some of which are visible at Voyager resolution.

Domino-style faults appear to be common within Uruk Sulcus grooved terrain, notably in stratigraphically higher units. The ≤1 km scale of these structures is below the resolution of all but the very highest resolution Voyager imaging of Ganymede. Although domino-style faults have been recognized on Miranda (e.g., Pappalardo et al. 1997), it was generally unexpected that they would exist on Ganymede because of the high degree of local strain that they imply relative to horst-and-graben-style faulting. Tens of percent to ~200% local extension occurs along domino-style faults on Earth. The amount of local strain across a set of domino faults can be estimated (Wernicke and Burchfiel 1982) if there is knowledge of the initial fault dip, the amount of backtilting that has occurred, and the subsurface fault geometry (planar or listric). A minimum estimate of extensional strain across lanes of tilt-block style faults in Uruk Sulcus is ~50%, assuming a planar fault geometry and 40° to 60° initial fault dips (Collins et al. 1998a). This is much greater than the few percent strain estimates obtained by assuming that groove lanes are comprised of simple graben bounded by individual steeply dipping faults (Golombek 1982). It remains uncertain how such large local strains could be accommodated across Ganymede, especially in light of a ~1% limit on global expansion imposed by the large-scale coherence of dark terrain in Galileo Regio (McKinnon 1981). One possibility is that high-strain lanes of grooved terrain are so narrow that their cumulative extensional strain is small (Collins et al. 1998b).

Small-scale normal faults may exist throughout the Uruk Sulcus site, manifest as the small-scale lineations of the lineated grooved terrain, small ridges of the parallel ridged terrain, and striations that characterize striated terrain (ST) units. In the parallel ridged terrain, such faults may form in regions that are locally more extended, as discussed below. Some small-scale lineations may be (or may have evolved from) narrow, small-scale tension fractures, but tension fractures may generally be below the resolution of Galileo images.

Voyager-scale ridges and troughs are generally seen to consist of smaller-scale tectonic structures. Though the lighting geometry of the Galileo Uruk Sulcus images emphasizes the Voyager-scale topography, it is apparent in stereo images of the region. This topography is not constructed of simple horst and graben, as was generally suspected based on Voyager data. Instead, smaller “Galileo-scale” ridges and troughs are superimposed, imbricating the Voyager-scale topography into smaller scale blocks. It is clear from Galileo images that grooved terrain is not comprised of large-scale V-shaped tension fractures which have relaxed isostatically or filled with mass-wasted debris to form Voyager-scale troughs (Squyres 1982, cf. Golombek 1982).

The thickness of Ganymede’s brittle lithosphere has been estimated from Voyager data based on the widths of Voyager-scale troughs, under the assumption that Voyager-scale grooves are simple graben (Golombek 1982). However, Galileo data makes it clear that many Voyager-scale troughs are not simple graben. Even those troughs revealed by Galileo to have graben-like morphologies are composed of many smaller scale blocks. (This is in contrast to observations of typical fossae on Mars, for example, which do show the straight walls expected of simple graben.) These observations cast doubt that a simple graben geometry is a valid assumption for estimating the depth of Ganymede’s brittle lithosphere. In model experiments, domino-style faults are found to have a regular spacing that is proportional to the thickness of the faulted layer (Vendeville et al. 1987), and this spacing may be related to the strain softening properties of the faulted material (Mandl 1988, pp. 64–70).

On the basis of Voyager data, it has been suggested that the Voyager-scale topography may be induced by extensional necking instability within the lithosphere as extension occurred (Fink and Fletcher 1981, Herrick and Stevenson 1990). In light of the Galileo observations of domino-style normal faulting, this model now appears more likely, as a high degree of strain helps to promote the growth of extensional instability (Collins et al. 1998a). In this scenario, “Galileo-scale” topography represents deformation of the near-surface brittle layer in response to the extensional instability of ductile ice at depth. Galileo-based constraints on this model can be used to derive plausible strain rates ($10^{-13}$ to $10^{-15} \text{ s}^{-1}$) and thermal gradients (~20 to 30 K km$^{-1}$) during the formation of Uruk Sulcus grooved terrain, in turn implying a brittle-ductile transition near 2 km depth (Collins et al. 1998a). Implications for the cross-sectional geometry of faults is explored in Section 5.2.2. below.

At the Voyager scale, many groove lanes on Ganymede show prominent bounding grooves (Shoemaker et al. 1982). Such structures are a natural consequence of tilt-block style normal faulting, forming in response to rollover of
the hanging wall near the margin of a rift zone. This process
may explain a prominent Voyager-scale trough within the
parallel ridged terrain unit PRT2 of Uruk Sulcus, along
its boundary with unit PLT2. Additional Galileo imaging of
grooved terrain may reveal whether hanging wall rollover
provides a possible explanation for prominent bounding
grooves elsewhere on Ganymede.

There is no direct evidence that a plate-tectonic-like
spreading model (Lucchitta 1980) is applicable to grooved
terrain as observed in the Uruk Sulcus region. Observa-
tions of lineated grooved terrain suggest that it has formed
in place through tectonic segmentation of preexisting ter-
rain. Attempts to reconstruct features across lanes of paral-
lel ridged terrain have been unsuccessful, or at best equivo-
cal. Partial separation across lanes of parallel ridged terrain
cannot be ruled out, however, on the basis of the present
data. Analysis of other Galileo grooved terrain targets is
necessary to test this possibility.

5.1.2. Shear happens. Based on Voyager imaging of
grooved terrain, some workers have proposed that a com-
ponent of horizontal shear has shaped grooved terrain
(Lucchitta 1980, Murchie and Head 1988). Galileo observa-
tions suggest that right-lateral displacement has shaped
stratigraphically high units of the Uruk Sulcus target site
(see Section 4, above). Although the amount of strike-slip
displacement across the target site is probably minor (a
few kilometers or less), there is a noticeable effect on the
morphology of some units, specifically units EERT and
PRTS. Voyager images show that many grooved terrain
structural cells have a lensoid, or spindle-shaped, geometry
overall. Such a fault pattern is characteristic of strike-slip
fault duplexes, suggesting that a strike-slip component of
tectonism may have been important in shaping much of
Ganymede’s grooved terrain.

In the transtensional shear scenario described above,
several grooved terrain units within Uruk Sulcus formed
contemporaneously. Contemporaneous formation of an in-
tegrated pattern of structures of different orientations has
important implications for interpretation of the stratigra-
phy and evolution Ganymede’s grooved terrain (Collins
et al. 1998b).

5.1.3. Cryovolcanism. There is little direct evidence
for cryovolcanism in the Uruk Sulcus region imaged by
Galileo, such as volcanic vents, flow fronts, or embayment
relationships. Moreover, there is sparse evidence for truly
smooth terrain. Indeed, most “smooth” units (i.e., the ST
units) contain small-scale lineations (Figs. 10 and 11c); the
only truly “smooth” patch we observe at this resolution is
unit ST3 (Fig. 5). In fact, the units that are most heavily
cratered at Galileo resolution, and therefore are among
the oldest in the region (specifically, PLT1 and PLT2),
appear at Voyager resolution to be relatively smooth (Sen-
ske et al. 1997, Collins et al. 1998b). This may be because
impact gardening has smoothed topography relative to
younger, sparsely cratered regions of grooved terrain that
have substantial tectonically generated relief.

In contrast to the sparse evidence for volcanic resurfac-
ing in the Uruk Sulcus region, there is abundant evidence
that tilt-block-style normal faulting has modified preex-
isting terrain through destruction of the older surface. It
appears that rotational normal faulting alone is capable of
“tectonically resurfacing” groove lanes on Ganymede
(Head et al. 1997). This model does not exclude cryovolcan-
ism as an integral part of the grooved terrain emplacement
process, for example, if icy volcanism initially covered dark
terrain to form bright terrain. However, the dearth of iden-
tifiable cryovolcanic features in the Uruk Sulcus region
implies that cryovolcanism must have either (1) played a
minor or negligible role in grooved terrain formation, (2)
ocurred early in the grooved terrain emplacement se-
quence, so its signature was erased by subsequent tecton-
ism, or (3) was interlaced with tectonism so as not to be
readily apparent.

The predominance of tectonism over volcanism makes
it unlikely that the freezing and doming of a cryovolcanic
flow (Parmentier and Head 1984, Allison and Clifford
1987) was instrumental in shaping the final morphology of
grooved terrain. Furthermore, relationships at the margins
of groove lanes show that extensional tectonic deformation
is not limited to the confines of a volcanically resurfaced
graben, as expected from the freezing and doming model.
The great areal consistency of groove trends and hence
formational stresses across Ganymede (Collins et al. 1998b)
also argues against this cryovolcanism-based model of
groove formation. There is no evidence in the imaged
region for radiating fractures that might mark the rise of
solid-state icy material to the surface in circular-plan dia-
pirs, as per the solid-state diapirism model of Kirk and
Stevenson (1987). Also, there is no evidence in this region
for linear vents, sheet-like flows, or pooling of volcanic
material in topographic lows, as predicted if ridges were
constructional features built by extrusion of icy material
(Pappalardo and Greeley 1995, as hypothesized by Shoe-
imaging of Ganymede includes targets that are candidate
cryovolcanic features (Carr et al. 1995), and analysis of
those images will allow further investigation of the relative
role of cryovolcanism in forming grooved terrain.

5.1.4. Isostatic adjustment. It has been proposed on the
basis of Voyager data that viscous relaxation might have
played a key role in shaping the morphology of grooved
terrain (Squyres 1982, Parmentier et al. 1982). Craters in
older terrains in Uruk Sulcus are preserved, and these
craters must have been subjected to thermal gradients simi-
lar to those in nearby younger grooved terrain. These
larger scale craters would be affected more than smaller
scale tectonic structures by the wavelength-dependent process of viscous relaxation. There is no evidence from the cratering data that the region's larger craters are depleted (Chapman and Merline 1996; Neukum 1997), as might be the case if viscous relaxation were important in shaping the smaller scale topography.

Isostatic adjustment may have elevated the footwall topography alongside a braided unit in the southeast portion of the Uruk Sulcus target site (Fig. 11b). It is possible that the viscous or elastic properties of ice played a role in producing uplift alongside prominent depressions in Ganymede’s grooved terrain (cf. Pappalardo et al. 1997), but this process and the relative roles of the elastic and viscous properties of ice remain to be investigated.

5.2. Models of Grooved Terrain Emplacement

5.2.1. Modifications to Voyager-based models. Galileo-based interpretations of cross-cutting relationships and stratigraphy in Uruk Sulcus imply modifications to Voyager-based models of grooved terrain emplacement, as discussed by Collins et al. (1998b). In short, truncation and tectonic resurfacing of older grooved terrain structures by younger ones contradicts a proposed sequence in which structures terminate abruptly in “T-terminations” when encountering older structures (Golombek and Allison 1981). Instead, Galileo Uruk Sulcus images show that structures forming the cross-bar of the T are the younger, having crosscut the older structures of the T stem (Figs. 5 and 9c). The recognition of contemporaneous formation of an integrated pattern of structures of different orientations in a transtensional tectonic scenario also has important implications for interpretation of the stratigraphy of Ganymede’s grooved terrain.

5.2.2. Change in tectonic style with time. In general, the lineated grooved terrain units in Uruk Sulcus which show horst-and-graben-like morphology (the PLT and PMRT units) have a relatively high crater density, indicating that they are relatively old (Figs. 5, 7, and 9); moreover, their constituent structures are oriented NE–SW to N–S, suggesting extension perpendicular to these trends during their formation. These older polygons are crosscut by swaths interpreted to consist of domino-style normal faults (PRT units), which show lesser crater densities, indicating that they are younger. These younger groove lanes and their constituent structures are oriented NW–SE overall, indicative of NE–SW extension.

The general correlation of faulting style with relative terrain age suggests that there has been a general change from horst-and-graben to higher-strain domino-style faulting over time. Moreover, regional analyses suggest there has been a systematic counterclockwise rotation of structural orientations and thus principal stress orientation during formation of grooved terrain in Uruk Sulcus (Senske et al. 1997 and submitted, Collins et al. 1998b). Analysis of additional grooved terrain targets suggests that these trends are regional in extent (Collins et al. 1998b). A change in extensional-tectonic style over time may reflect change in the strain, strain rate, and/or thermal gradient with time during grooved terrain formation. Observations of lineated grooved terrain imply that extensional deformation might amplify preexisting small-scale fault structures. This introduces the possibility that preexisting horst blocks, like those which comprise lineated grooved terrain, might have been imbricating by extensional straining and faulting to create terrain such as the pervasively tectonized parallel ridged terrain. In evaluating candidate models for the global evolution of Ganymede (Collins et al. 1998b), the issue remains to be explored of why more straining might occur in the latter history of grooved terrain emplacement.

5.2.3. Tectonic model for parallel ridged terrain. As described in Section 3.2, parallel ridged terrain is interpreted as consisting of domino-style blocks. Here we explore a schematic tectonic model for lanes of parallel ridged terrain which is consistent with the Galileo Uruk Sulcus observations (Fig. 13).

Based on correlation seen in the stereo data, we infer that the Galileo-scale small ridges have formed in regions of locally enhanced stretching and thinning of the lithosphere. Where stereo topography is available over unit PRT2, it is seen that Galileo-scale large ridges correlate with Voyager-scale ridges, while Galileo-scale small ridges correlate with Voyager-scale grooves (Collins et al. 1998a). Voyager-scale grooves are expected to be regions of locally high strain, for example as predicted by the extensional necking model (Fink and Fletcher 1981). Thus, it is expected that these grooves should be the locations of most intense deformation of fault blocks. As depicted schematically in Fig. 13, Galileo-scale small ridges may form through the creation of second generation normal faults in regions of greatest extension, where the first generation domino faults can rotate to orientations unfavorable for continued motion (cf. Morton and Black 1975). Galileo-scale large ridges can be preserved preferentially along the Voyager-scale ridges, expected to be regions of lesser extensional straining and fault rotation. If domino-style normal fault blocks have the same facing direction, as depicted in Fig. 13, then faults must shallow in the more highly extended regions (in Voyager-scale grooves), and retain steeper dips in less extended regions (on Voyager-scale ridges).

Domains of domino-style blocks are generally expected to be asymmetrical in geometry, and lanes of parallel ridged terrain on Ganymede can be asymmetrical in several ways. At the “proximal” or “breakaway” boundary with preexisting terrain, a prominent bounding trough may be produced by rollover of the hanging wall block above a prominent marginal fault (Figs. 8 and 13). As discussed in
FIG. 13. Schematic illustration of possible fault geometry in lanes of parallel ridged terrain in Uruk Sulcus, roughly to scale. The longer wavelength of topography represents “Voyager-scale” ridges and troughs, and “Galileo-scale” ridges and troughs are superimposed. Voyager-scale blocks may be associated with extensional necking of the lithosphere, and large-scale shear zones (dotted; marked with half arrows) are envisioned as reaching to the brittle–ductile transition (dashed). Large Galileo-scale structures are depicted as concentrating on Voyager-scale ridges, and small Galileo-scale as concentrating in Voyager-scale grooves; the latter expected to be regions of greatest extension, thinning, and imbrication of the brittle lithosphere. Hanging wall rollover is depicted along the breakaway margin (left), and a possible progression is shown to more highly imbricated fault blocks in the distal region of the rift zone (right). The geometry of Galileo-scale domino blocks at depth is highly uncertain, but they may sole out on a detachment surface such as the brittle–ductile transition, or perhaps a subsurface dark terrain boundary.

Section 3.2.3 above, this geometry may account for the prominent marginal trough in parallel ridged terrain unit PRT2, along the boundary with unit PLT2 (Figs. 5 and 9c). Topographic analysis of the Uruk Sulcus stereo data indicates that Voyager-scale ridges of unit PRT2 tend to be somewhat asymmetric, with their steeper sides generally facing away from the inferred breakaway margin (Giese et al. 1998). Furthermore, unit PRT1 shows a noticeable concentration of large ridges on one side of the groove lane, and small ridges on the other (Fig. 7). A prominent bounding groove is not apparent in unit PRT1, but the boundary with unit PMRT3 to its southwest (Fig. 9a) is more abrupt than the boundary with unit PLT1 to the northeast (Fig. 9b); therefore, the southwestern boundary of unit PRT1 (opposite the concentration of small ridges) is the more likely to represent the breakaway margin of this unit.

Figure 13 is a representation of faulting across a lane of parallel ridged terrain which accounts for the morphological and topographical characteristics described above. At the proximal boundary, rollover of the hanging wall block can create a prominent bounding trough above the breakaway fault. Voyager-scale topography is shown as somewhat asymmetric, with the fault geometry implying steeper ridge slopes facing away from the inferred breakaway margin. The scale of these blocks is likely controlled by the brittle–ductile transition depth, as predicted by the extensional necking model (Fink and Fletcher 1981, Grimm and Squyres 1985, Collins et al. 1998a). Galileo-scale ridge and trough topography is superimposed, with the spacing of this topography correlated to the local degree of extension, fault rotation, and thinning of the brittle lithosphere, with relatively high degrees of extension and thinning envisioned in Voyager-scale troughs.

The geometry of fault blocks at depth is highly speculative, for example as to whether faults are planar or listric and whether they dip synthetically across the entire groove lane. Galileo-scale topography might be detached along its base by a preexisting mechanical discontinuity. If so, the brittle–ductile transition is a candidate fault detachment surface. Alternatively, if cryovolcanism occurred early in the history of grooved terrain, then faults might detach along the base of a cryovolcanic unit. Galileo imaging of dark terrain in Galileo Regio suggests that dark material forms a thin veneer on the surface of Ganymede’s dark terrain (Prockter et al. 1998), and such a layer could potentially form a mechanical discontinuity that would allow bright terrain to extend and fault above it.

6. CONCLUSIONS

Galileo high-resolution observations of grooved terrain in Uruk Sulcus have provided a wealth of information regarding the nature, origin, and evolution of grooved terrain on Ganymede, testing Voyager-based models of its origin. The principal conclusions of this study are as follows.

1. Contrast variations in the Uruk Sulcus images are extreme (~3:1). It is implausible to achieve such an extreme contrast and the observed azimuth range of bright ridge faces solely by means of topographic shading, so the contrast must result largely from differences in scattering behavior, specifically albedo. Stereo imaging confirms that contrast variations are controlled by topography. “Voyager-scale” and “Galileo-scale” topography are observed in stereo images, with the “Galileo-scale” of topography showing both larger and smaller scales of topography. Bright material is generally located on ridge crests and west- and southwest-facing slopes, notably of the large Galileo-scale ridges. Dark material accumulates downslope in the topographic lows between ridges. The broad Voyager-scale deformation may have an origin by necking of Ganymede’s lithosphere, while the finer Galileo-scale of deformation may reflect brittle faulting of the surface layer, with additional imbrication of these faults into a finer wavelength scale in regions of greatest local strain.
2. Endmember grooved terrain types are the stratigraphically lower “lineated grooved terrain,” which shows morphologies indicative of horst-and-graben-style normal faulting, and stratigraphically higher “parallel ridged terrain,” which exhibits ridges of roughly triangular cross section, suggesting that it has been shaped by tilt-block-style normal faulting. Boundary relationships support an extensional-tectonic origin for grooved terrain and are consistent with tectonic imbrication of older terrain to create parallel ridged terrain. Domino-style faulting implies a high degree of local extensional strain (tens of percent), much greater than that inferred from Voyager-based horst and graben models. Small-scale lineations in older terrain along the margins of parallel ridged terrain may be incipient normal faults that promote the imbrication of grooved terrain blocks. Hanging wall rollover above a prominent bounding fault offers a possible explanation for prominent bounding troughs aside some lanes of grooved terrain on Ganymede. No evidence is found to support a grooved terrain origin through compressional deformation or cryomagmatism.

3. En echelon and sigmoidal blocks demonstrate that a component of strike-slip deformation has shaped some stratigraphically high units of grooved terrain in the Uruk Sulcus target site. The most recent tectonic episode is interpreted as right-lateral transtension, with this integrated tectonic pattern superimposed on older units of grooved terrain. A least compressive stress direction roughly perpendicular to the orientation of the candidate zone of dextral shear could account for the lack of compressional features in the region, and may be related to late-stage stresses which affected Uruk Sulcus as a whole.

4. There is little direct evidence for cryovolcanism in the Uruk Sulcus region. If cryovolcanism occurred, evidence for it may have been eradicated by concurrent or subsequent tectonism. Viscous relaxation has probably played a minor role in shaping Galileo-scale ridge and trough topography.

These observations and conclusions regarding grooved terrain are based on images of a single region of grooved terrain imaged on Galileo’s first and second orbits. They can serve as a valuable basis against which later Galileo observations of grooved terrain can be compared.

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