A Geometric Analysis of Surface Deformation: Implications for the Tectonic Evolution of Ganymede

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The visual nonalignment of the furrows and the circularity of impact craters are used to study surface deformation on Ganymede. The furrow system is examined to test the hypothesis that lateral motion has taken place between areas of dark terrain. Results show that while lateral motion cannot be ruled out, it may not be required to explain the geometry of the system. Initial noncentricity of the furrows or an early period of penetrative deformation shortly after furrow formation could also account for the present configuration. Centers of curvature of the furrows in Galileo and Marius Regiones are numerically determined and it is shown that if lateral movement did occur, it is not possible to determine the amount of displacement. The axial ratios of impact craters in the Uruk Sulcus region which separates Galileo and Marius Regiones are determined and show that large scale shear deformation has not occurred in that area since bright terrain was emplaced. Deformation of impact craters within Galileo Regio suggests that Ganymede's lithosphere has behaved rigidly throughout most of the satellite's evolution. The shapes and orientations of impact craters in dark terrain around wedges of bright terrain are used to place an upper limit on the amount of extension associated with bright terrain formation.

INTRODUCTION

The surface of Ganymede preserves the record of an active and diverse tectonic history. The major surface units consist of approximately equal portions of dark, heavily cratered polygons and bright, lightly cratered regions which penetrate and separate dark areas (Smith et al., 1979a,b). Fundamental observations of the nature of deformation within these units lead to basic conclusions about the tectonic history of the satellite. Deformation on Ganymede, at least since bright terrain formation, has been primarily extensional. Compressional deformation has not been identified within the dark terrain and is uncertain in bright terrain. Parmentier et al. (1982) cite evidence which suggests that bright terrain formed due to finite extension of the lithosphere, and Shoemaker et al. (1982) suggest that bright bands resemble normal fault patterns in terrestrial rift zones. The amount of extension associated with bright terrain formation, although of importance in understanding the mechanism of global rifting on Ganymede, has yet to be determined.

Evidence for shear deformation on Ganymede is localized and small scale (Lucchitta, 1980; Golombek and Allison, 1982; Parmentier et al., 1982). The most convincing examples are several impact craters whose rims are offset by not more than a few kilometers. Lucchitta (1980) has cited the nonconcentricity of the Ganymede furrow system as evidence for large lateral motion of dark terrain blocks. The existence of lateral displacements at this scale would place important constraints on the global tectonic history of Ganymede.

Also of considerable importance would be the recognition of smaller scale deformation within individual terrain areas. Constraints on the style, degree, and timing of deformation within isolated units has relevance not only to the tectonics, but to the physical properties of the lithosphere at the time of deformation. The manner in which
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the near surface deforms throughout time has implications for the rheological structure of the lithosphere, the geothermal gradient, and possibly the source of stress.

This study focuses on the identification of various types of surface deformation on Ganymede by a geometric study of the furrow system and an analysis of circularity of impact craters. First, we test the hypothesis that the furrow system was initially concentric and that the present configuration of the furrows provides a measure of lateral motion of dark terrain. This is accomplished by determining the present centers of the furrow system in several dark terrain blocks and observing the amount of deformation in bright terrain regions which separate these blocks. Second, we place an upper limit on the amount of extension associated with bright terrain formation by using the deviation from circularity of impact craters to calculate the strain field around wedge-shaped regions of bright terrain. Third, we attempt to identify penetrative deformation in Ganymede's lithosphere by examining the circularity of impact craters in dark terrain.

FURROW CONCENTRICITY

The Furrow System

The furrow system is a regional array of subparallel, arcuate structures that traverse several areas of dark terrain on the satellite's leading hemisphere. A furrow is characterized by a central depression flanked by raised rims with relief not exceeding a few hundred meters (Smith et al., 1979b). Furrows are locally discontinuous, but broad arcs can be traced up to hundreds of kilometers across individual dark areas. The furrows have been interpreted as ring graben formed as a consequence of a basin-scale impact into Ganymede's lithosphere (Smith et al., 1979b; McKinnon and Melosh, 1980), though evidence to substantiate this hypothesis is inconclusive. Whatever the origin, the formation of the furrow system marks the earliest event preserved on the satellite's surface, as it predates essentially all impact craters in the dark terrain (Smith et al., 1979b).

The pattern of furrows is most distinct in Galileo Regio, shown in Fig. 1. Furrows in this region are approximately 10 km wide, spaced 50 km apart, and extend for hundreds of kilometers across the surface (Smith et al., 1979b). A number of linear bright bands along the southern border of Galileo resemble furrows in width, spacing, and orientation. The system continues into adjacent Marius Regio, however furrows in this area exhibit distinct morphological differences compared to those in Galileo (Zuber, 1982). The Marius furrows occur as shorter segments spaced an average of 22 km apart and 6 km in width. A faint secondary trend in the strike of furrows can be observed, where approximately nine percent of the Marius furrows trend at an angle greater than thirty degrees from the local mean orientation. These secondary furrows are either contemporaneous or postdate those of the main set; in no case do they predate furrows of the main trend. Therefore they must have formed concurrently or in a subsequent event to that which produced the main system.

The reason for the differences in widths and spacings of furrows in adjacent areas is unclear. From the theory of multiringed basin formation (McKinnon and Melosh, 1980; Melosh, 1982), ring spacing should increase with lithospheric thickness. If the furrow system was impact-produced, then the variation in furrow spacings may reflect a difference in lithosphere thickness between Marius and Galileo Regiones at the time of formation of the system. Differences in furrow geometry may instead be related to inhomogeneous mechanical properties in the Galileo and Marius areas. However, the regions are separated by a relatively narrow band of bright terrain and a gradual transition in furrow widths and spacings is not observed. It is enigmatic that two adjacent areas of the lithosphere should display such an abrupt change in ei-
Fig. 1. Part of the Ganymede rimmed furrow system as seen in Galileo Regio. Furrows continue into Marius Regio, which lies to the west of this region. The bright terrain unit Uruk Sulcus, shown in the lower left of this photograph, separates the Galileo and Marius Regiones (Voyager 2 frame 0104J2-001).

Asymmetries have also been noted in the morphology of the Valhalla ring system on Callisto in areas of high resolution Voyager coverage (Hale et al., 1980; Remsberg, 1981). These studies report an azimuthal transition from graben structures to outward-facing scarps as opposed to a simple change in graben dimensions. Because of mathematical intractibility, axial asymmetry has not been incorporated into present theoretical models of basin formation, therefore asymmetrical structures cannot be predicted.

The furrows in Galileo and Marius are not concentric, and it has been suggested that some degree of right lateral motion and/or clockwise rotation of Marius terrain blocks would restore the system to a circular geometry (Passey and Shoemaker, 1982; Shoemaker et al., 1982). If the two systems were initially concentric, then the present orientation of the furrows in the displaced dark terrain blocks provides evidence for lateral motion between adjacent blocks. If
lateral motion has taken place, then the offset of the respective centers of curvature provides a measure of the displacement which has occurred between the areas since their formation. Inherent in this approach are two basic assumptions: (1) the furrow systems were initially concentric, and (2) dark terrain areas acted as rigid plates since the formation of the system, such that penetrative deformation could not explain any present deviation from circularity.

Method

To determine the centers of curvature, we employed a numerical scheme to perform a linearized least-squares fit of the furrows to small circles about a center. For an assumed center of curvature, the deviation of each furrow from a corresponding small circle was determined using the standard least-squares formula

$$
\varepsilon^2 = \sum (R_i - \bar{R})^2
$$

where \( \varepsilon \) is the residual, \( R_i \) is the radial distance from the center to the \( i \)th point on a furrow, and \( \bar{R} \) is the mean radial distance of the furrow from the center. The center which minimized the mean squared residual of the deviation from concentricity for all furrows in the system was taken to be the best fit.

Over 300 furrows were digitized from the Voyager images. Measured points on the furrows were approximately equally spaced at about 4-km intervals along strike. Because of the large size of the data set, runs were made using various parts of the sample and results were compared to ensure consistency. The furrows in Marius which possessed the secondary trend in orientation described above were not included in the analysis.

The furrows were intrinsically weighted according to both length and distance from the center. Since a greater number of furrows are present farther from the center, and since longer furrows contain more digitized points, these features made a greater contribution to the total residual. However, since a longer furrow defines a greater arc, it provides a better constraint on the center of curvature.

The linear least-squares formulation represented in Eq. (1) assumes a Gaussian distribution of errors, which is that observed on a plane surface. However, as noted in various studies of terrestrial plate tectonics (e.g., Minster et al., 1974), the distribution of errors on a sphere is characterized by the nonlinear Fisherian distribution. The nonlinear problem can be simplified by realizing that the error density on the surface of a unit sphere is proportional to \( \exp(k \cos \theta) \) where \( \theta \) is the angular error and \( k \) is a measure of the precision (Fisher, 1953). If the precision is large (\( k \gg 1 \)), such that errors are confined to a small section of the sphere in the area of the global (absolute) minimum, the error density reduces to a Gaussian distribution if \( k = 1/\sigma^2 \) where \( \sigma^2 \) is the variance of the distribution. This linear approximation is valid if the normalized residuals of the best-fit solution have a mean near zero and a variance close to one. Figure 2 shows the cumulative distribution of least-square residuals for the center of cur-

![Figure 2](image-url)
vature of Galileo Regio compared to the theoretical normal distribution function. The general agreement of the two curves, which was verified by the \( \chi^2 \) and Kolmogorov–Smirnov tests at the 99% confidence limit, indicates a close approximation to Gaussian errors. For this reason linearization is valid for the data set. Errors in the Marius areas show similar distributions.

A major difficulty with the nonlinear distribution is that a solution may not exist, and if it does, it may be nonunique. A good starting guess is generally necessary to assure convergence to the correct result. Multiple minima may still be encountered, in which case other criteria must be employed to determine the most physically realistic solution (Draper and Smith, 1977). In this analysis, two methods were employed to determine the best-fit center. The first was a grid search to locate the minimum residual within a specified area. Subsequently, a random search method was used to verify convergence to this solution. The centers of the Galileo Regio furrow system as initially estimated by Smith et al. (1979b) and Shoemaker et al. (1982) were first chosen as the starting centers. Numerous other starting points were then used in the attempt to identify other possible minima. The Smith and Shoemaker values proved to be appropriate starting guesses in the search for the Galileo Regio center, however unrealistic solutions were obtained when these were used in the Marius search, as will be shown later.

Centers of the Furrow System

Centers of curvature of the furrow system were found for three areas: Galileo Regio, and North and South Marius Regio. Results are shown in Fig. 3. The Galileo Regio system yielded a single, well-defined center at 39°S, 178°W. The initial estimate for the center of this region made by Smith et al. (1979b) at 30°S, 180°W lies within the 95% confidence interval of the least-squares solution.

![Fig. 3. Centers of curvature of the furrow system in Galileo Regio (GR), North Marius Regio (NMR), and South Marius Regio (SMR), with corresponding small circle fits. Multiple solutions were obtained for the centers of curvature of furrows in North and South Marius Regio. Subscripts refer to global (g) and local (l) minima. Small circle fits to furrows in North and South Marius are about the local minima. The 95% confidence contour is shown for the Galileo Regio system.](image)

Depending on the starting estimate, the North and South Marius areas each yielded two different centers of curvature, shown in Fig. 3. To choose between solutions, a visual match of the Marius furrows to small circles about each of the centers was employed. The local (relative) minima for North and South Marius at 48°S, 148°W and 44°S, 131°W, respectively, exhibited much better visual fits than the global minima. The multiple solutions obtained for this region are a consequence of the short furrow lengths, which make it difficult to strictly define the center of curvature. Because the final distribution of residuals for each of the Marius solutions was dominated by the global minimum, confidence contours could not be constructed about these centers.

The fit of small circles about the final cen-
 ters of all three regions is shown in Fig. 3. From the small circle fits, it is readily apparent that furrows in Galileo Regio deviate from the small circles about the best-fitting center. The deviation is greatest in the eastern Galileo area. This follows from the weighting factor employed in the least-squares formulation, whereby longer segments were given a greater weight. The center of curvature in Galileo Regio is controlled by the longest furrows which are located farthest from the center. However, since the longest arcs provide the best constraints on the center of curvature, this approach was deemed valid.

It may be possible to use a number of different weighting criteria to produce a somewhat "better" fit of the furrows. For example, it would be equally valid to minimize \( \sum (\phi_i)^2 \), where \( \phi_i \) is the angular deviation of the strike of the \( i \)th furrow from the strike of the assumed small circle at that point. However, allowing longer furrow arcs a greater weight in defining the "best" center reflects the fact that the longer arcs contain more information about the location of the center. Regardless of the criteria chosen and the "best" center thus determined, small circles that fit furrows in one part of the system will not fit those in other parts.

As shown in Fig. 3, the separation of the centers of curvature of the furrows between Galileo and the local minima in Marius is about 20° of surface arc. If an initially concentric system is assumed, then the difference in the calculated centers suggests significant lateral motion of dark blocks, and major shearing within the bright terrain which separates these areas. If the shearing postdated the formation of bright terrain, then surface features in the bright units should show evidence of shear deformation.

To define the circularity of furrows within Galileo Regio, the area was broken into three sectors of twenty degree angular width, and the centers of curvature of the furrows in each area were determined. The centers in the northwest and central sectors fell close to or within the 95% confidence ellipse of the Galileo Regio center, but the center of the furrows in the southeastern section of Galileo markedly deviated from the best-fit center for the full system. This requires either that the furrow system was initially noncircular or that deformation has occurred within Galileo Regio.

CRATER CIRCULARITY

One test for the occurrence of deformation on a surface is the analysis of the present geometry of objects with known initial shapes. Impact craters, which are ubiquitous on all terrain units on Ganymede, are possible strain markers. The shape of an impact crater can be described in terms of the circularity index, which for a circular or elliptical feature is the ratio of minor/major axes (i.e., axial ratio). If measurable deformation has occurred, then initially circular impact craters which predate the episode of deformation should be modified into ellipses whose axial ratios and orientations characterize the strain field.

Axial ratios were determined for craters digitized from the Voyager images. In order to detect the smallest possible strains, corrections were made for Voyager viewing geometry. Approximately 10 to 50 rim points were digitized for a given crater, depending on its size. The crater area \( A \) was found from the equation for the area of an \( N \)-sided polygon, where \( N \) is the number of rim points. The center of the crater was taken to be the centroid of the area. All points on the crater were translated into a local coordinate system whose origin was the centroid. The best-fit ellipse was defined by the eccentricity and the orientation, \( \phi \), of the major axis which minimized the mean square residual of the equation

\[
\frac{\pi R^2}{A(1 - e^2)^{1/2}} \left\{ 1 - e^2 \cos^2(\psi - \phi) \right\} - 1 = 0
\]

for rim points \((R, \psi)\). The axial ratio was determined from the eccentricity
fig. 4. Histogram of crater axial ratios in Uruk Sulcus (centered at 0°N, 160°W), divided into transverse and longitudinal groove bands. N is the number of craters. The long–short dashed lines refer to the mean axial ratio in a given region. The dashed line is the lunar mean.

\[ b^{2/3}/a \]

where \( a \) and \( b \) are the semimajor and semiminor axes of the best-fit ellipse. To assure a good fit, the normalized residual was required to be less than the quantity \((a - b)/a\). This selection criterion was satisfied by every crater.

**Shear Deformation**

Since bright terrain is thought to have formed in progressive stages (Golombek and Allison, 1981; Parmentier and Zuber, 1982), at least some of the craters within bright terrain regions should be deformed if lateral motion occurred during or after its emplacement. As a test of this hypothesis, axial ratios were measured for 48 craters in Uruk Sulcus, an area of bright terrain which trends along the south and west borders of Galileo Regio. This region is marked by a conspicuous pattern of grooves, which run both longitudinally (subparallel) and transverse (at high angles) to bright terrain borders. No craters in this area are offset along grooves, therefore significant lateral movement cannot be attributed to displacement along possible faults.

Craters in this study were grouped according to whether they occurred in longitudinal or transverse groove bands, in an attempt to determine whether possible deformation might concentrate in a particular unit. Results are shown in Fig. 4. The average axial ratio of craters in longitudinal terrain is 0.840 ± 0.024 and that in transverse terrain is 0.873 ± 0.017. This result can be compared to a similar study of lunar craters, since it is generally thought that the lunar lithosphere has behaved rigidly throughout its evolution. Ronca and Salisbury (1966) measured the circularity of lunar craters and identified two populations. The majority of craters had a mean axial ratio of 0.8984 ± 0.0076 and a much smaller subgroup had a mean of 0.8097 ± 0.0089. Therefore, craters in Uruk Sulcus are less circular than most lunar craters. To check whether the observed deviation from circularity of craters is due to lateral motion of dark terrain blocks, it is necessary to examine the orientations of the major axes of the best-fit ellipses.

Shoemaker *et al.* (1982) suggest that Marius Regio has been rotated counterclockwise or translated to the left with respect to Galileo Regio. This would require the major axes of deformed craters to be aligned NW–SE if deformation occurred due to pure shear. If deformation occurred by simple shear, the orientation of the craters would depend on the amount and sense of rotation which accompanied the deformation. Figure 5 shows the orientation of craters from the combined Uruk Sulcus data set, which

fig. 5. Orientations of the major axes of the best-fit ellipses of craters in the combined Uruk Sulcus data set. The peak near 80° is not in the direction expected if lateral motion of dark terrain blocks has occurred. See text for explanation.
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shows a sharp peak 80–90° east of north. We believe that this preferential orientation is predominantly due to the position of the sun in the Voyager images, where lighting at oblique incidence resulted in nonuniform illumination of the crater rims, and introduced a systematic bias in the identification of the rim crests. This is supported by the observation that the orientations of crater major axes are consistent with the lighting geometry in the images.

Craters in the range 100–180° east of north, which is that expected if lateral motion of dark terrain blocks has occurred, have an average axial ratio of 0.853 ± 0.024, which is similar to craters in Uruk Sulcus as a whole. Hence, craters aligned in the direction predicted by the current position of the furrow system do not show evidence of large scale shear deformation, and any lateral motion that may have occurred between Marius and Galileo Regiones must have preceded the formation of Uruk Sulcus. Thus, the formation of bright terrain in this area cannot be directly related to an episode of shear deformation.

Deformation around Bright Terrain Wedges

Crater shape can also be used to place an upper limit on the amount of extension beneath wedge-shaped bands of bright terrain (cf. Voyager Frame 0102J2-001). If wedges formed in a manner similar to a mode I extension crack, then deformation should be concentrated in dark terrain surrounding the tips of the wedges. Impact craters which predate the wedges can be used as a measure of this deformation. As shown in Fig. 6, the extension $\alpha/\beta$ beneath a wedge of angular width $\beta$ with net angular separation $\alpha$ can be found if the components of strain at a point $(r, \theta)$ are known. The predicted minor/major axes in a deformed crater can be determined from the stream function solution of an opening crack in a viscous layer. If along the crack face the shear stress vanishes and the tangential displacement is a linear function of the distance from the tip, then the predicted axial ratio of a crater near the tip is

$$\frac{b}{a} = 1 - \sqrt{2} \frac{\alpha}{\pi} \left\{ 1 - \frac{\pi \sigma_n}{\alpha \mu} \right\} \left[ 1 - \cos 2\theta \right] + \frac{1}{2} \left[ \frac{\pi \sigma_n}{\alpha \mu} \right]^2 \frac{1}{u^2}$$

where $\dot{\alpha}$ is the rate of angular separation, $\mu$ is the viscosity of the layer, and $\sigma_n$ is the normal stress along the crack face. The results of Eq. (3) can be compared to the observed circularity of craters on the surface. The mean axial ratio of 29 craters around 6 wedge-shaped bands is 0.826 ± 0.018. However, the orientations of these craters again show a sharp peak around 80°. Thus, craters do not align in the orientations expected around an opening extension crack, and therefore much of the discernible noncircularity of craters around band tips is not a consequence of extension across the band. Values obtained in this analysis, however, define an upper limit on extension. Measurements indicate that the extension across wedges with $\beta > 16^\circ$, which occur in several areas of Ganymede, is less than 100%. Higher resolution images covering a range of phase angles would be required to recognize smaller amounts of deformation or similar amounts associated with narrower wedges.

Penetrative Deformation

To determine whether the deviation of furrows from small circles resulted from de-
formation of dark terrain after the formation of the furrows, crater axial ratios were measured for 164 craters in two areas within Galileo Regio: the southeast where furrows deviate most from the best-fit small circles, and the central region (Voyager 2 frames 0546J2-001 and 0449J2-001) where the furrows show a better fit. Figure 7 shows mean axial ratios of 0.828 ± 0.014 and 0.805 ± 0.012 in these respective regions.

The amount of locally homogeneous deformation which may have occurred in a region can be expressed as an angle of simple shear, $\psi$. The angular deviation of furrow segments from the best-fitting small circles provides a measure of this angle. From this, the shear strain, $\gamma$, can be obtained from the simple relation $\gamma = \tan \psi$ (Jaeger, 1969). For a given shear strain, it is possible to calculate the axial ratios which would be expected if the craters in these regions were present during a period of deformation. Measurements of the angular deviation of the furrows in southeastern Galileo Regio from the corresponding small circle fits in Fig. 3 yields values of $\psi$ from 15 to 25°. This corresponds to axial ratios in the range 0.64–0.77. Twenty percent of the observed craters in this region fall in that range; however, most of these craters again have a major axis orientation near 80°. If a crater deformed in a manner consistent with the deviation of the furrows from the best-fit small circles, then the orientation of its major axis should be aligned approximately N–S. Those craters whose major axes fall within 30° of N–S have a mean axial ratio of 0.894 ± 0.016, which is not in the range expected due to the predicted shear deformation. Therefore if deformation occurred within Galileo Regio, it must have postdated furrows but predated most of the observed craters in the area.

Deformation within Galileo Regio would violate the initial assumption that dark blocks acted as rigid plates. However, if deformation has occurred within this area it is appropriate to question whether penetrative deformation without large lateral displacement is able to account for the apparent noncircularity of the furrows in Galileo and Marius Regiones. To test this hypothesis, the small circles around the Galileo Regio center were extended to pass through the Marius area, as shown in Fig. 8. The fit of the Marius furrows to the small circles about the Galileo center can be compared to the small circle fit of furrows in southeastern Galileo Regio. The angle $\psi$ in North and South Marius averages 21 and 28°, respectively, which is similar to the deviation of a number of furrows in southeastern Galileo.

The implications of this are twofold. First, the short furrow lengths in Marius Regio seem to preclude the unambiguous determination of a best-fit center of curvature for the area, by either visual or numerical small circle fit. Second, since furrows in Marius show approximately the same amount of deviation from small circles around the Galileo Regio center as many furrows in southeastern Galileo, large scale lateral motion may not be required to account for the present configuration of the system. The nonconcentricity of furrows between Marius and Galileo Regiones can alternatively be explained by a component
of early penetrative deformation without major shear displacement or by an initially noncircular furrow system. While it is not possible to rule out global scale lateral motion between the regions, the geometry of the system does not require it.

Impact craters within transverse bright terrain in the Uruk Sulcus region are more circular than those within longitudinal bright terrain. Golombek and Allison (1981) suggested that longitudinal terrain in this area predates the transverse. If this is true, then the greater degree of ellipticity associated with craters in the older terrain may be a consequence of strain associated with subsequent bright terrain formation. Craters in Galileo Regio are more elliptical than those in either region of Uruk Sulcus. This is probably the case because craters in bright terrain are in general less degraded (i.e., have sharper rims) than those in dark terrain. Most craters in Uruk Sulcus are fairly well-preserved, while in almost every case those within Galileo Regio are highly degraded.

CONCLUSIONS

The apparent offsets of the centers of curvature of the furrow system in Marius and Galileo Regiones suggests that global scale lateral motion of dark terrain blocks may have taken place in Ganymede's past. If large scale displacement did occur, it must have preceded the emplacement of bright terrain which separates the two areas. It is not possible to determine the magnitude of the displacement of the blocks because numerical solutions for the center of the furrow system in Marius Regio are poorly constrained. Due to the short furrow lengths in this region the center of curvature based on the resolution of the Voyager data is not uniquely defined.

Alternatively, lateral motion may not be required by the geometry of the furrow system. Many furrows in Marius Regio deviate from best-fit small circles by amounts similar to some furrows within Galileo Regio, which suggests that the present geometry could be a consequence of either penetrative deformation or an initially nonconcentric system.

The assumption that the furrow system was initially circular is difficult to justify, in part because of the morphological differences between the furrows in Galileo and Marius Regiones. There is no definite proof that the system was produced by impact, although this hypothesis remains the most attractive. The calculated center of curvature for Galileo Regio lies beneath the Osiris ejecta blanket and as a result, no trace of the proposed site of impact remains.

Impact craters in Uruk Sulcus are more circular than those within Galileo Regio. This is most likely a function of the degree of preservation of the crater rims. Both craters in dark and bright terrain are less circular than lunar craters. This may be a consequence of either the contrasting physical properties of the lunar and Ganymedian surfaces in controlling both the initial form
and subsequent modification of craters, or the resolution of the Voyager images.

Measurements of the ellipticity of craters in both bright and dark terrain are strongly affected by the position of the sun on the images. Therefore in many cases the actual amount of surface deformation must be less than that measured for the craters in this analysis. Multiple phase angle coverage of the surface would remove the effect of the sun and allow the detection of smaller degrees of deformation. The amount of deformation associated with several wedges of bright terrain on the surface of Ganymede is <100%, which is consistent with bright terrain formation by finite lithospheric extension.

The circularity of impact craters within Galileo Regio suggests that only limited penetrative deformation has occurred over the period of time in which present impact craters are preserved. For the greatest part of its evolution, Ganymede’s lithosphere has behaved rigidly and has been dominated by extensional tectonics with deformation concentrated in regions of bright terrain. This extensional deformation was confined to a period of time during or shortly after bright terrain emplacement.

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REFERENCES