# Evidence for Europa-like tectonic resurfacing styles on Ganymede

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[1] Very high-resolution imaging and stereo topographic data obtained during the Galileo G28 encounter with Ganymede show 1) evidence for Europa-like, crustal spreading and resurfacing to form portions of the bright terrain, and 2) bright terrain that appears smooth at Voyager resolution (and thus a strong candidate for cryovolcanism) but instead is tectonically deformed and lacks embayment relationships when viewed at high resolution. In contrast to previous views, these new data show that tectonism has been the dominant process in shaping some very smooth areas and that Ganymede appears to have experienced Europa-like crustal spreading during its previous history. *INDEX TERMS:* 6218 Planetology: Solar System Objects: Jovian satellites; 5475 Planetology: Solid Surface Planets: Tectonics (8149); 5480 Planetology: Solid Surface Planets: Volcanism (8450); 5470 Planetology: Solid Surface Planets: Surface materials and properties; 5455 Planetology: Solid Surface Planets: Origin and evolution. **Citation:** Head, J., et al., Evidence for Europa-like tectonic resurfacing styles on Ganymede, *Geophys. Res. Lett.*, *29*(24), 2151, doi:10.1029/2002GL015961, 2002.

## 1. Introduction

[2] Voyager data revealed that the Jovian moon Ganymede consists of ancient heavily cratered dark terrain and younger resurfaced and tectonically deformed bright terrain (groove lanes and polygons) [*Shoemaker et al.*, 1982; *Lucchitta*, 1980], although intimate details of how the bright terrain was resurfaced could not be resolved. The general view was that the ancient dark terrain was downfaulted, flooded by water lava (cryovolcanism), and faulted further to create the bright terrain [*Parmentier et al.*, 1982]. Data from the nominal Galileo mission showed some areas of bright terrain that appear to have been resurfaced through tectonism alone [*Head et al.*, 1997a; *Patel et al.*, 1999], one area with strong evidence for cryovolcanism [*Kay and Head*, 1999], and moderate resolution topographic data showing two smooth lanes lying at relatively low and constant elevation, suggesting cryovolcanic emplacement of smooth plains [*Schenk et al.*, 2001]. Important remaining questions are the dominant processes of bright terrain resurfacing and whether the smooth areas observed in low to moderate resolution images are predominantly the result of cryovolcanic resurfacing [*Prockter*, 2001]. We report here on data from two areas of bright smooth terrain (one linear and one polygonal) targeted during the G28 encounter, when the Galileo spacecraft passed 809 km from the surface of Ganymede and obtained unprecedented very high resolution data, context frames, and stereo images.

## 2. Arbela Sulcus

[3] Numerous examples of smooth linear regions of bright terrain (smooth lanes) were imaged by Voyager and Galileo [*Shoemaker et al.*, 1982; *Pappalardo et al.*, 1998] (e.g., at the western boundary of Nippur Sulcus [*Collins et al.*, 1998; *Hiesinger and Head*, 1998]). In contrast to other areas of bright grooved terrain, smooth lanes are characterized by unusually straight margins over great distances, relatively narrow (15–20 km) and very constant widths, great lengths, general smoothness, and relative youth [*Collins et al.*, 1998, 2001]. Their smoothness relative to other areas of bright grooved terrain makes smooth lanes strong candidates for cryovolcanic resurfacing, emplaced as floods of clean water and/or ice bounded by the walls of graben [*Parmentier et al.*, 1982; *Allison and Clifford*, 1987]. Nominal mission Galileo data revealed that the smoothness of lanes in Voyager images was often a resolution effect, and that they actually contained fine-scale linear ridges and troughs [*Collins et al.*, 1998, 2001; *Hiesinger and Head*, 1998], although detailed topographic data did not exist to examine their embayment relationships with surrounding terrain.

[4] The formation mechanism of smooth lanes might be explained in a cryovolcanic or tectonic framework. The primary evidence for cryovolcanism is the apparently smooth nature of their surfaces, as if low-viscosity cryolava had filled fault-bounded depressions [*Parmentier et al.*, 1982; *Allison and Clifford*, 1987]. Images and moderate resolution digital elevation models of smooth lanes in Sippar Sulcus show that a similar smooth swath is a) low-lying [*Schenk et al.*, 2001], b) associated with caldera-like features in this area [*Kay and Head*, 1999], and c) may have embayment relationships with older ridges [*Kay and Head*, 1999; *Schenk et al.*, 2001]. More definitive tests of the relative roles of cryovolcanism and tectonism in forming Ganymede's smooth terrains were not possible without the higher resolution stereo data recently obtained [*Prockter*, 2001].

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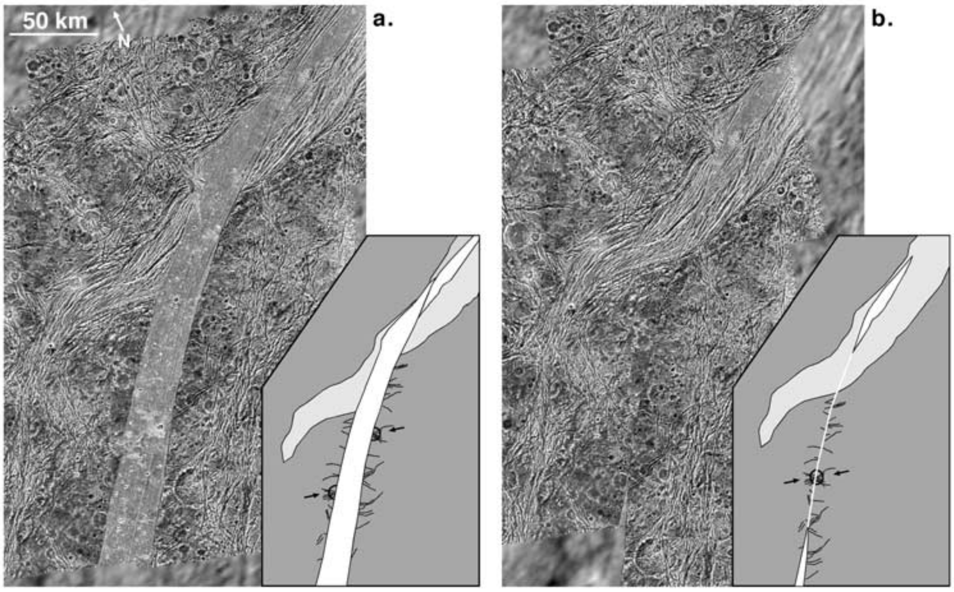


**Figure 1.** Arbela Sulcus. a. Mosaic of the Arbela Sulcus region, centered near (−15°, 346°), imaged at 133 m/pixel during Galileo orbit G28. Image mosaic also includes data from the Galileo G7 orbit (180 m/pixel) and is superimposed on Voyager 1 spacecraft data (1.6 km/pixel). Projection is orthographic about the Galileo sub-spacecraft point (−3.4°, 347.2°). Inset sketch map shows relevant features. Note that the relatively old dark terrain of Nicholson Regio (dark gray) is cross-cut by intermediate-age groove lanes (light gray consisting of subparallel ridges and troughs, which are in turn cross-cut by the younger smooth terrain of Arbela Sulcus (white). b. Image and sketch map of the inferred reconstruction, whereby reassembly of the southern boundary of the groove lanes (light gray) unites two crater halves and throughgoing fractures (arrows). Not all pre-existing structures are matched in the reconstruction, suggesting that some structures formed after initiation of this deformation. Note that southern Arbela Sulcus does not fully reconstruct, and there is minor overlap just north of the smooth lane; the map projection was selected to minimize these imperfections, which may be due to non-rigid behavior of Ganymede's lithosphere.

[5] Arbela Sulcus in Nicholson Regio was targeted during Galileo's 28th orbit of Jupiter (G28) to provide very high-resolution (34 and 133 m/pixel) and stereo images to address the nature and origin of smooth lanes [*Head et al.*, 1997b; *Murchie and Head*, 1988; *Thomas and Head*, 1998]. In Voyager images, and in Galileo context images (Figure 1a), Arbela Sulcus and associated terrains may be divided into three parts, arranged in a sigmoid. The northern portion of Arbela (Figure 1a) exhibits two distinct morphologies, with one section showing a distinct grooved appearance (light gray on map), and the other section appearing smooth (white on map). It is evident in the Galileo data that the smooth portion of Arbela crosscuts the grooved portion (Figure 1a).

[6] The G28 high-resolution data (34 m/pixel) (Figure 2a) show that the smooth bright lane is 20–25 km wide and has extremely linear margins. At high resolution, the "smooth" surface within the bright lane is marked by long, narrow, subdued linear ridges and troughs ~100–200 meters wide extending parallel to the margins with the dark terrain (Figure 2a). No specific evidence of cryovolcanic activity, such as flow fronts or vents, is observed. A digital terrain model derived from the stereo observations (Figure 2b) shows that the smooth lane is generally low relative to adjacent dark terrain, consistent with earlier lower-resolution stereo models that have been interpreted to support cryovolcanic emplacement of smooth bright terrain [*Schenk et al.*, 2001]. The new high-resolution terrain models show, however, that the eastern boundary of Arbela in this area is locally higher in elevation than adjacent and interconnected dark terrain depressions. If Arbela was formed by cryovolcanic flooding, one would expect cryolavas to embay and fill the adjacent connected lows, but this is not observed. In order to explain the topographic data, a cryovolcanic interpretation must call on tectonic activity postdating cryolava emplacement to produce the linear texture, as well as raising of the level of the bright terrain to its present position above adjacent connected lows.

[7] These new data also show evidence for extension and shear that differs from that more commonly seen in bright terrain of Ganymede, where extension produces varieties of graben and tilt-block faults [*Pappalardo et al.*, 1998] and horizontal shear offset is minimal. By digitally matching the prominent southern bounding groove on the two groove lanes on either side of the smooth lane, the rest of the smooth lane closes with few gaps and minimal overlap (compare Figures 1a and 1b). Moreover, when this bounding groove is reconstructed, two crater segments in the dark terrain become aligned into what appears to have been a single 15 km crater; fractures that cut this crater in two different directions also align in the reconstruction (compare sketch maps in Figures 1a and 1b). One of the most intriguing findings in the new data is the significant degree of left-lateral motion of the terrain on either side of Arbela Sulcus (compare Figures 1a and 1b). This reconstruction implies that the bright smooth lane of Arbela Sulcus formed through ~65 km of left-lateral strike-slip motion, ~25 km of crustal separation, and ~4° counterclockwise relative rotation of the eastern "plate." There are a few minor fractures in the dark

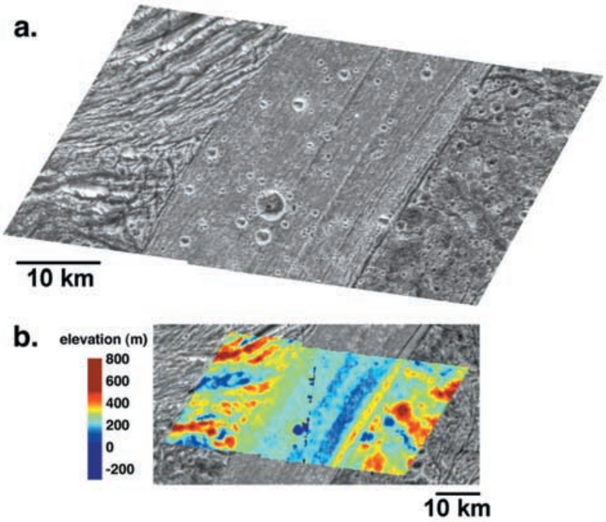


**Figure 2.** High resolution image and topographic data of Arbela Sulcus. a. Viewed at very high resolution (34 m/pixel), Arbela Sulcus exhibits small-scale lineations and straight margins indicative of tectonic deformation. b. Digital elevation model derived from stereo images between the images of Figures 1a and 2a. Note that the eastern margin of Arbela is elevated relative to local depressions in adjacent dark terrain, arguing against a primary origin by cryovolcanic flooding. Topograpic model has a horizontal resolution of 600 m and a vertical resolution of 15–25 m. Mosaics are centered at (−15°, 347°), and north is to the top.

terrain which do not have a counterpart on the other side of Arbela (sketch map in Figure 1b), and the southern part of the smooth lane (imaged at much lower resolution by Voyager 1) does not fully reconstruct, potentially because the dark terrain surrounding Arbela Sulcus has behaved nonrigidly. Such behavior is analogous to inferences made for Europa in which crustal separation may be accomplished by "tearing" of the lithosphere along with distributed small-scale deformation [*Pappalardo and Sullivan*, 1996].

[8] Formation of the smooth lane of Arbela Sulcus by crustal spreading means that Ganymede would join Europa as the only other known example of this style of crustal renewal beyond Earth. Evidence for shear in some other smooth lanes on Ganymede [*Lucchitta*, 1980; *Collins et al.*, 2001] suggests that they could have originated similarly. If crustal spreading was widespread during the later phases of Ganymede's groove formation, it implies that a warm, mobile substrate existed at shallow depths at that time, perhaps related to the presence of a relatively shallow liquid water layer interpreted from Galileo magnetometer data for Ganymede [*Kivelson et al.*, 2002]. This is similar to the shallow crustal structure implied during the formation of bands on Europa [*Prockter et al.*, 1998; *Sullivan, et al.*, 1998], with a steep thermal gradient, a ductile ice substrate, and potentially an ocean at depth.

## 3. Harpagia Sulcus

[9] Voyager data showed the presence of smooth bright terrain in numerous polygonal areas which were interpreted to represent relatively young cryovolcanic flooding [*Allison and Clifford*, 1987]. Higher resolution Galileo data have failed to show compelling evidence for embayment or lobate flows (except in one area [*Kay and Head*, 1999]) and instead show that in some of these areas tectonic structures, not volcanic features, dominate the surface [*Pappalardo et al.*, 1997, 1998; *Collins et al.*, 1998]. To investigate the nature and origin of the smoothest regions of bright terrain at the highest resolution, especially the relative roles of tectonism and cryovolcanism, very high resolution images (16 m/pixel) were obtained of an unusually smooth (at Voyager resolution) region of Harpagia Sulcus (Figure 3). The context images (116 m/pixel) show that the polygonal area in the SW is much smoother than the heavily grooved terrain toward the NE, suggesting that the polygon may have been cryovolcanically flooded [*Allison and Clifford*, 1987]. The very high resolution images straddle this terrain boundary and show that the "smooth" area is actually rough at the small scale and contains common degraded linear ridge segments, interpreted to be tectonic in origin. In addition, this smooth terrain is truncated by younger grooved terrain along its northeastern margin, as demonstrated by the steep scarp and tectonic cross-cutting relationships there (Figure 3). A digital terrain

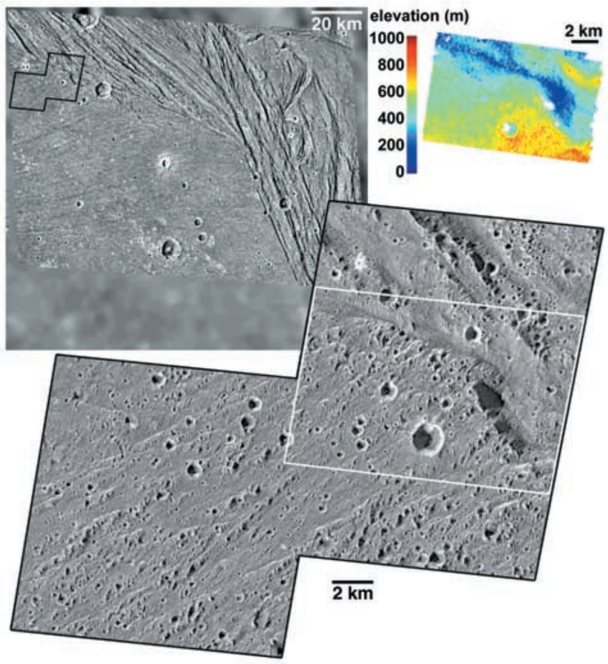


**Figure 3.** Bright terrain of Harpagia Sulcus, an area identified as remarkably smooth in Voyager 1 images (1.5 km/pixel). The area appears smooth even in Galileo G28 context images (upper left; 116 m/pixel), superimposed on Voyager 1 data, with north to the top. High resolution Galileo G28 images (lower right, 15 m/pixel), centered near −15.7°, 309.8° reveal small-scale ridges and troughs. Stereo topography (upper right) obtained in overlapping high-resolution frames (marked by white box) demonstrates that these structures have relief of ∼100 m, and that the very smooth terrain of Harpagia Sulcus stands several hundred meters higher than, and does not embay, the tectonically modified grooved terrain to its northeast. The topographic model has a horizontal resolution of ∼150 m and a vertical precision of ∼50 m.

model derived from stereo images (inset in Figure 3) demonstrates that the ''smooth'' terrain stands several hundred meters above the adjacent tectonic trough and grooved terrain (and does not embay it), and so was not confined by it. Thus, these new data reveal that some of the smoothest terrain identified at Voyager resolution is tectonized and stratigraphically old at high resolution. While no definitive evidence for vents, flow fronts or embayment is observed here, cryovolcanism is a plausible origin for the relatively smooth material between individual ridges. Most importantly, these new images show that some of the evidence previously cited to support extensive cryovolcanism in the bright terrain in fact supports a strong role for tectonism, further strengthening similarities in tectonic resurfacing styles between Ganymede and Europa, whose bright plains are resurfaced primarily through tectonism [*Greeley et al.*, 2000].

## 4. Discussion and Conclusions

[10] Several scenarios have been previously proposed to explain dark terrain and its relationships to the resurfacing and emplacement of bright terrain on Ganymede [*Parmentier et al.*, 1982]. In one scenario, dark terrain fracturing and sea-floor-like spreading of bright material occurs [*Parmentier et al.*, 1982]. In another, a large downfaulted graben is cryovolcanically flooded to produce the bright terrain which is subsequently deformed [*Parmentier et al.*, 1982; *Golombek and Allison*, 1981; *Schenk and McKinnon*, 1985; *Murchie et al.*, 1986]. Alternatively, resurfacing could be predominantly due to faulting; in this scenario, tilting of fault blocks in zones of extension results in tectonic resurfacing through destruction of older features and shedding of the dark veneer off of the tilted blocks to reveal brighter ice, producing the bright lanes [*Head et al.*, 1997a; *Patel et al.*, 1999]. The new Galileo observations reported here firmly establish the pervasive nature of tectonic deformation throughout major phases of bright terrain formation, and show that some regions have undergone large-scale crustal spreading and horizontal shear similar in scale and magnitude to that seen on Europa. Renewed examination of other such areas on Ganymede, and ultimately additional high-resolution imaging by future missions, will lead to further definition of these similarities to Europa, their abundance and significance, and to improved models of the subsurface thermal structure of Ganymede during the formation of bright terrain.

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