BREAK-UP OF DARK TERRAIN AND THE FORMATION OF BRIGHT TERRAIN ON GANYMEDE: EVIDENCE FOR STRIKE-SLIP FAULTING Scott L. Murchie and James W. Head, Dept. of Geological Sciences, Brown University, Providence, RI 02912.

The surface morphology of Ganymede is dominated by two classes of tectonic features, furrows and grooves (1,2). Furrows are arcuate to concentric or linear troughs found pervasively in large polygons of ancient dark terrain (3,4,5). The furrows consistently are cross-cut by systems of grooves, which are developed most extensively in resurfaced areas (grooved or bright terrain). In recent studies we have examined in detail the structural and stratigraphic properties of grooved terrain (6,7,8), and have proposed a tentative tectonic history of the satellite (8). In this study we examine the style of breakup of dark terrain and attempt to identify its consequences for the formation of grooved terrain.

Two main types of tectonic features on Ganymede predate the formation of grooved terrain, fractures related to tidal despinning (7-10) and furrows (1-6). Within a few tens of thousands of years after its formation, the satellite would have despun and begun rotating synchronously with the period of orbit around Jupiter (11). Resulting stresses in the early lithosphere would have formed fractures parallel or at low angles to lines of latitude, and the fractures could have been preserved as zones of weakness. In a separate study (8), we noted that globally dominant groove orientations suggest a system of reactivated despinning fractures, centered at a paleopole of approximately 70^{o}N,110^{o}W. That location is consistent with a predicted location for the paleopole of 75^{o}N,95^{o}W, determined from computer modelling of global reorientation due to the formation of the basin Gilgamesh. It was therefore proposed that a major control of global patterns of groove orientation is a relict system of fractures from tidal despinning.

The second type of pre-grooved terrain tectonic feature is the furrows. Furrows form three systems of arcuate or concentric and subradial troughs. System I, in the anti-Jovian hemisphere, is dominated by arcuate troughs with fewer radial ones, both of which types are best developed in Galileo Regio. System II, also in the anti-Jovian hemisphere and best represented in Galileo Regio, is dominated by prominent subradial throughgoing troughs which cross-cut furrow system I. Associated orthogonal troughs are poorly represented, and are observed only in SW Galileo Regio. System III is of arcuate and very few radial furrows, in the sub-Jovian hemisphere. The furrow systems are found in separate large polygons of dark terrain, but in different polygons the same system is centered on different poles (3,12,13).

To examine structural relationships within the furrow systems, furrows were mapped in nine separate polygons of dark terrain and approximately 400 of the most prominent and linear furrows were digitized. Six areas of dark polygons with continuous furrow orientation were then assessed quantitatively (Fig. 1), and best-fit and ranges of possible poles of furrow concentricity were calculated for each of the six areas. Short-wavelength irregularities in furrow orientation were minimized by basing calculation on trends of 50-600 km furrow segments. Poles of concentricity could be determined to within 10^{o} or less and are distinctly separated (Fig. 1).

The closest analog to Ganymede's furrow systems is the closely-spaced ring system concentric to the basin Valhalla, on Callisto (1,2). Because of the similarity of rings to furrows, it is conceivable that Ganymede's furrow systems were once also concentric about single large basins. This idea was tested by determining if the furrow systems could be restored to concentricity, using calculated furrow poles and photogeologic observations. The furrow pole for central Marius Regio, 3, is not significantly separated from the location of a giant palimpsest on the southern margin, suggested by (3) to be the impact responsible for formation of furrow system I. Therefore, central Marius Regio was used as a fixed reference frame for retrodeformation of adjacent polygons of dark terrain. Restoration of pole 1 to pole 3 would require that there have been approximately 500 km of left lateral offset of Galileo relative to central Marius Regio (Fig. 1), as determined from offsets of both the furrow poles and a prominent NE-oriented trough predating grooved terrain formation. The intervening area, northern Marius Regio, has a furrow pole, 2, anomalously to the northwest of the poles of both Galileo (pole 1) and central Marius (pole 3) Regiones. Northern Marius Regio, unlike the other two areas, consists of several smaller blocks of dark terrain separated by narrow, wedge-shaped groove lanes. To test the idea that a false furrow pole was calculated for northern Marius Regio because of rotation of the smaller blocks, the area was retrodeformed by removing 1) apparent left-lateral shear and 2) extension equal to 30-50% of the widths of the narrow groove lanes. The recalculated furrow pole is consistent with that of central Marius Regio, suggesting that relative motions of Galileo and central Marius Regiones created a zone of distributed left-lateral shear with counterclockwise rotation of blocks. The southern boundary of this shear zone in northern Marius Regio is traceable as a lineament for >1000 km, and the northern boundary can be defined by an abrupt change in the orientations of grooves believed to have fromed in reactivated furrows (5,6). The furrow pole for southern Marius Regio, 4, is also anomalously to the west of the poles of Galileo and central Marius Regiones. This suggests either a major right-lateral offset from central Marius Regio, or clockwise rotation of smaller blocks due to distributed right-lateral shear resulting in a false furrow pole. Both possibilities are consistent with apparent right-lateral offset of local geologic features. The offset of the furrow poles for Nicholson and Barnard Regiones is poorly constrained, but offset of other geologic features strongly suggests right-lateral shear. A major ENE-trending lineament which truncates both a major N-S groove lane and a large palimpsest is the best candidate for the boundary across which shear may have occurred. Especially in the anti-Jovian hemisphere (furrow system 1, poles 1-4), it is clear that furrows can be restored to concentricity about a major impact feature by retrodeforming shear zones.

Both inferred and more clearly-defined boundaries of laterally offset lithospheric blocks are locally parallel to furrows, and on a global scale are at low angles or parallel to small circles centered on the inferred paleopole of satellite rotation (lines of paleolatitude). This is the same orientation described in (8) as the preferred orientation for grooves, resulting from structural control by both furrows and tidal despinning fractures. Therefore, there is accumulating evidence that tidal despinning and furrow formation together created a global system of zones of weakness that controlled much of the later tectonic activity on Ganymede.

It is possible to bracket the period during which the proposed lateral offset of large lithospheric blocks occurred using three observed cross-cutting and superposition relationships. First, both the older and younger furrow systems and the superposed NE-oriented troughs in the anti-Jovian hemisphere are offset. Second, young throughgoing groove lanes (7) are not offset at all, even though many cross or define boundaries of offset blocks. Third, some older areas of grooved terrain appear to be contemporaneous with the lateral offsets. Specifically, these areas include the wedge-shaped groove lanes separating the rotated blocks in northern Marius Regio. The lanes' taper in a direction consistent with the proposed counterclockwise block rotation, and they are cross-cut by most adjacent younger grooves. Therefore, lateral offsets of large lithospheric blocks postdate furrows, were contemporaneous with earlier stages of grooved terrain emplacement, and predate final stages of grooved terrain formation.

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Evidence that at least some grooved terrain formed contemporaneously with lateral offsets of large blocks suggests that the shear zones may have affected the development of large areas of grooved terrain. Grooves are widely believed to be extensional features, so the most likely relationship of them to the shear offsets is that some grooved areas developed as en echelon grabens or tension cracks. In regions near the boundaries of the lithospheric blocks containing Nicholson Regio, Galileo Regio, central Marius Regio, and within the region of proposed distributed shear in northern Marius Regio, groove lanes occur almost exclusively at high angles to the direction of least compressive stress expected for the local sense of shear (Fig. 1). In addition, these groove lanes are parallel to one of the local furrow trends. Therefore, lateral offset of major blocks may not only have been contemporaneous with earlier stages of grooved terrain formation, but shear stresses may have controlled over wide areas which zones of weakness were reactivated to form grooves.

In summary, we have investigated the structural relationships of furrows in separate large polygons of dark terrain on Ganymede. Six areas of dark terrain were found which have continuous and distinct furrow orientations. The furrows in at least three of these areas can be restored to near concentricity about a Valhalla-like impact feature by retrodeformation of shear zones that formed contemporaneously with older grooved terrain. The most well-defined of the proposed shear zones have orientations consistent with reactivated tidal despinning fractures, and may have subsequently controlled the orientations of grooves formed in adjacent areas.

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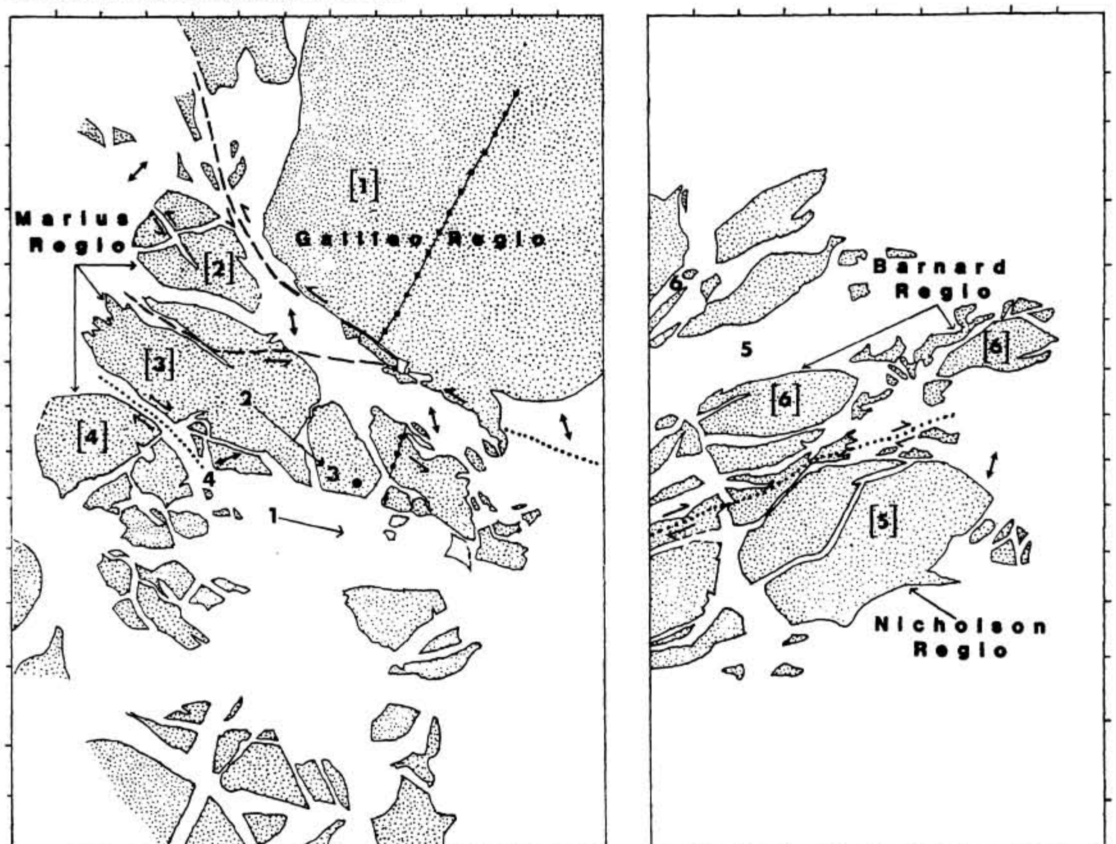

Fig. 1. Generalized map of bright and dark terrain, showing the six regions of dark terrain with separate poles of furrow concentricity and the senses of offset between the areas where identifiable. Identifying numbers mark best-fit furrow poles of concentricity. Areas of dark terrain corresponding to the poles are labelled with the same numbers in brackets. These areas are Galileo Regio (1), northern Marius Regio (2), central Marius Regio (3), southern Marius Regio (4), Nicholson Regio (5), and Barnard Regio (6). Approximate boundaries of large, laterally offset lithospheric blocks are shown as heavy dashed lines, and inferred boundaries are shown as dotted lines. Double-headed arrows show locally expected orientations of least compressive stress; in these areas, many to most older grooves are parallel to a furrow trend which is at high angles to the least compressive stress. Pairs of arrows show shear offsets, and single arrows show retrodeformation of furrow poles in a central Marius Regio-reference frame. The left-laterally offset post-furrow troughs in Galileo and Marius Regiones are shown, as is the approximate center of the giant palimpsest that is the origin of furrow system I (heavy dot).