EVIDENCE FOR THE EXISTENCE OF MAJOR SHEAR ZONES ON GANYMEDE, Scott L. Murchie and James W. Head, Dept. of Geological Sciences, Brown University, Providence RI 02912.

Introduction. The surface of Ganymede is divided into two main material units. *Dark terrain* occurs as several large polygons thousands of kilometers across, and also as a large number of intervening smaller polygons. In the large polygons, hemispheric-scale sets of *arcuate furrows* are preserved in both the anti-Jovian and sub-Jovian hemispheres (1). The set in the anti-Jovian hemisphere is approximately centered on a large, faint palimpsest (2,3), leading to the suggestion that the furrows originated as ring graben formed by the collapse of a transient impact cavity (4). Separating the large dark polygons are bands and smaller polygons of resurfaced *light terrain*, generally pervasively cross-cut by sets of U-shaped *grooves* forming *grooved terrain* that is probably of extensional origin (1,5,7,8). Furrows in the two largest dark polygons in the anti-Jovian hemisphere ([1] and [3] in Fig. 1) have similar radii of curvature, but the centers of curvature appear offset. An abrupt change in furrow trends across the intervening light terrain has been used to support the hypothesis that an originally more concentric furrow set was disrupted by shear (3,6,9). Recently, (9) and (10) measured similar poles of furrow concentricity for these and two other large areas of dark terrain in the anti-Jovian hemisphere; those calculated by (9) are shown in Fig. 1 (unbracketed numerals) and correspond to furrows located in the following areas (bracketed numerals): Galileo Regio [1], northern Marius Regio [2], central Marius Regio [3], and southern Marius Regio [4]. In the central part of area [1] is a NE-SW oriented swath of terrain in which furrow traces are linear rather than arcuate or circular; an estimate of the pole based on only the more arcuate furrows is shown as "1'". Pole "3" is within the giant palimpsest at the center of the system (within area [3]), but poles "1'" and "4" are both several hundred kilometers to the west of pole "3". The apparent pole offsets support the hypothesis that misalignment of furrows is due to the disruption of a more concentric set by strike-slip faulting (3,6,9). If correct, this hypothesis may imply the shifting of large lithospheric blocks by multiple upper mantle convection cells (3,10). Alternatively, furrow misalignment has been attributed entirely to non-circularity of furrow traces (10,11). Here we summarize independent structural evidence that apparent furrow offset is due in large part to disruption of dark terrain by shear zones.

Constraints on possible shear. The main type of lithospheric deformation subsequent to furrow formation was formation of grooved terrain. Groove formation commonly occurred by reactivation of relict fracture zones, including the arcuate furrows and closely associated radial furrows (12,13). Blocks of lithosphere hundreds of km in size, occurring between the large dark polygons, were pervasively deformed by groove sets. Throughgoing fracture zones outlining the blocks both (a) structurally confined groove sets within the blocks, and (b) subsequently were reactivated by superposition of throughgoing grooves or groove bands (12). There is little evidence for shear during the main period of grooved terrain formation (6,12,14). The latter observation restricts the period during which major shear may have occurred to that (a) following furrow formation and (b) during or before earliest grooved terrain formation. In addition to this information, two observations constrain what types of independent evidence of shear may exist. First, the proposed shear offset is of the largest lithospheric blocks. Therefore, although some shear may have occurred across discrete strike-slip faults, it also may have been distributed across wide zones of smaller, deformed blocks. Second, the offsets suggested by poles of furrow concentricity are large: 400 km of left-lateral offset of areas [1] and [3], and up to 1000 km of right-lateral offset of areas [3] and [4]. Although some fraction of the apparent pole offsets may be attributable to non-circularity of furrows, the remaining fractions would require shear zones of hemispheric or global scale.

Types of evidence for shear. On the basis of the above discussion, we can predict four types of evidence that may exist if there were shear offsets of large dark polygons. Major strike-slip faults must pre-date formation of most grooved terrain; these faults may act as long-lasting zones of weakness of the type outlining smaller, deformed lithospheric blocks in grooved terrain. Therefore, (a) hemispheric-scale lineaments of throughgoing grooves and groove bands may have been superposed on strike-slip faults. In addition, because the faults would act as barriers to groove propagation, (b) the strike-slip faults may be expressed as linear discontinuities in regional groove orientation, reflecting an abrupt change in the trend of furrows that were reactivated during groove formation. Where shear was distributed across wide zones of smaller blocks, (c) rotation and deformation of the smaller blocks may be evident. Where shear occurred across a discrete strike-slip fault, (d) offset of post-furrow dark terrain structures or very old grooves may be observed. We now examine evidence for each of these four predictions.

Hemispheric-scale lineaments. Three hemispheric-scale lineaments (dashed lines, Fig. 1) consisting of superposed throughgoing grooves and groove bands were identified in the area of Galileo Regio and Marius Regio. Two of these three define the boundaries of area [2], and continue to the southeast as the northern and southern boundaries of the grooved terrain separating areas [1] and [3]. The third major lineament defines the boundary of areas [3] and [4], and continues to the east as the southern boundary of area [3]. The locations and morphologies of these lineaments are consistent with those predicted for strike-slip faults (a) that separate areas [1], [3] and [4], and (b) that were reactivated during grooved terrain formation.

Discontinuities in groove orientation. Along the lineament defining the southern margin of area [1], ("A", "B", Fig. 1), there is an abrupt break in regional groove orientation. North of the lineament at "A", grooves are parallel to the radial furrows of area [1]; south of the lineament grooves are dominantly parallel to radial furrows of area [2]. North of the lineament at "B", grooves are dominantly parallel to the radial furrows of area [1]; south of the lineament, grooves are dominantly parallel to arcuate furrows of area [3]. At both "A" and "B", there is a 10-20° clockwise shift in the implied orientations of radial furrows to the north of the lineament. These observations are here interpreted to indicate (a) that the lineament represents a left-lateral strike-slip fault, and (b) that the break in groove orientations is the result of reactivation of furrows whose trends were earlier misaligned across the fault. The location and sense of offset of the fault are consistent with that implied by apparent left-lateral offset of the furrow poles of areas [1] and [3].

Block rotation. Area [2] consists of smaller dark terrain blocks separated by narrow, resurfaced groove bands. The pole of furrow concentricity for area [2] is 20° to the north of the poles of areas [1], [3] and [4]. We hypothesized that this anomalous furrow pole is the result of minor rotations of the smaller dark blocks within area [2]. To test this hypothesis, we retrodeformed the possible block rotations by removing 10-50% extension of the intervening groove bands, and then recalculated the pole of furrow concentricity. The pole was found to be restored nearly to that of area [3]. The retrodeformed groove bands have E-W orientations expected for extensional features if the lineament separating areas [1] and [3] is a strike-slip fault forming part of a zone of distributed left-lateral shear. In addition, the stratigraphically oldest of the groove bands are wedge-shaped and suggestive of counterclockwise block rotation (expected in a left-lateral shear

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zone). Therefore, the deformation of area [2] is consistent with its being a zone of distributed shear separating left-laterally offset areas [1] and [3]. At the lineament separating areas [3] and [4] ("C", Fig. 1; Fig. 2). a morphologically unique, N-S-oriented dark terrain trough superposed on partly degraded furrows in southeastern area [3]. Where the trough crosses two narrow groove bands that form part of the lineament, it is offset in a right-lateral sense by >100 km. The trough also is rotated in a clockwise sense to the south of each groove band. In addition, the blocks between the groove bands are internally deformed by "reticulate terrain" (1,3,12). We interpret the groove bands to be superposed on older strike-slip faults. The senses of trough offset and interpreted block rotation support the hypothesis that the adjacent lineament is a major strike-slip fault within a right-lateral shear zone separating areas [3] and [4]. This is consistent with the senses of offset of furrow poles "3" and "4".

Offset of non-furrow structures. The most convincing example of a feature offset across the suspected shear zones is the dark terrain trough, because of its linear trend and morphological uniqueness. In addition to the offset trough in southeastern area [3], (dotted line, Fig. 1; Fig. 2), a morphologically similar, throughgoing, NE-oriented trough is superposed on the arcuate furrows of area [1] (dotted line, Fig. 1). The trough segments in areas [1] and [3] do not form a single linear trend. However, removing the 400 km of left-lateral offset of the two areas suggested by furrow pole offsets would restore these two unique troughs to near-linearity. In addition, three possible large offsets of grooved terrain structures across the lineaments were identified. Stratigraphic relations (12) suggest that the structures are among the oldest locally. This age relation is consistent with the constraints placed earlier on the timing of possible shear. The three features are a NNW-oriented groove band offset left-laterally by 75 km (D, Fig. 1); a WNW-oriented, elongate block of dark reticulate terrain offset left-laterally by 15 km (E, Fig. 1); and a curvilinear band of grooves offset right-laterally by 40 km (F, Fig. 1). The senses of these offsets are consistent with those of the proposed shear zones; the lesser amounts of offset than of the dark terrain trough may be due to some shear having pre-dated the grooved terrain structures.

Summary. Apparent offsets of poles of concentricity of arcuate furrows in large blocks of dark terrain in the anti-Jovian hemisphere suggest the disruption of a more concentric set of furrows by shear zones. Although some of the apparent offset is due to non-circularity of furrows, there is independent evidence that some also is due to shear. The large dark blocks are separated by hemispheric-scale lineaments suggestive of throughgoing fracture zones. Offsets across the lineaments of (a) non-furrow structures and (b) regional groove orientations interpreted to be furrow-controlled both are observed. There is also evidence for block rotations associated with the lineaments. The senses of both types of offset and of block rotations are consistent with the senses of shear implied by furrow pole offsets.

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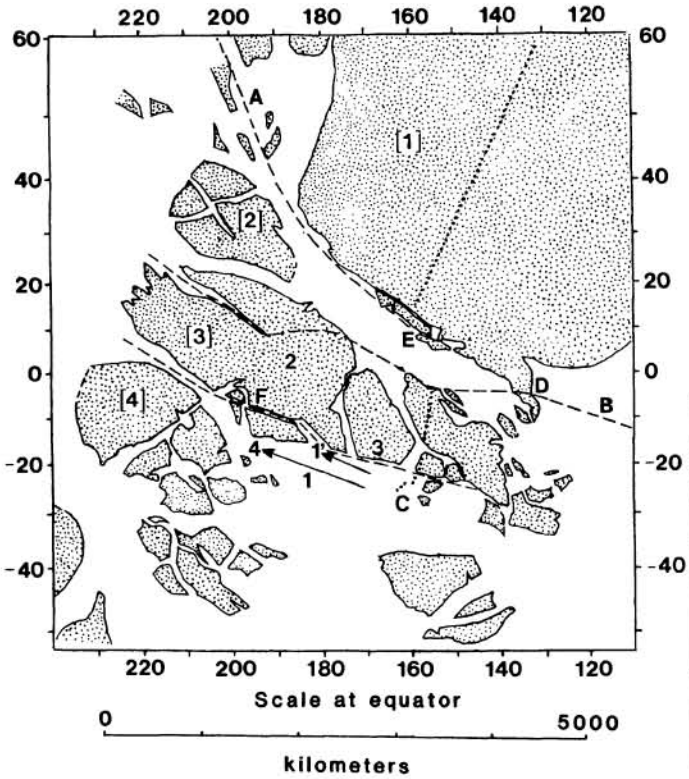

Figure 1. Interpreted offsets (arrows) of poles of arcuate furrows (labelled in unbracketed numerals) for four areas of dark terrain (bracketed numerals) in the anti-Jovian hemisphere. The dotted line is the unique dark terrain trough. Dashed lines are grooved terrain lineaments interpreted to represent reactivated strike-slip faults. Letters identify locales discussed in the text.

Figure 2. Right-lateral offset of morphologically unique dark terrain trough (located at "C" in Fig. 1). White areas are light terrain; gray areas are dark terrain. Fine solid lines are grooves, and the heavy solid line is the dark terrain trough. The heavy dashed line shows possible locations of strike-slip faults. Cross-hatched areas are reticulate terrain. Arrows show interpreted senses of shear and block rotation.