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Iapetus: Tectonic structure and geologic history.

Steven K. Croft, Lunar & Planetary Laboratory, University of Arizona, Tucson, AZ, 85721.

Introduction. Many papers have been written about the surface of Iapetus, but most of these have discussed either the nature of the strongly contrasting light and dark materials (e.g., Smith et al., 1982; Morrison et al., 1986; Bell et al., 1985) or the cratering record (e.g., Plescia & Boyce, 1985, Lissauer et al., 1988). Little has been said about other geologic features on Iapetus, such as tectonic structures, which would provide constraints on Iapetus' thermal history. Most references (Smith et al, 1982; Ellsworth & Schubert, 1983; Consolmagno, 1985; Squyres & Croft, 1986) have suggested that there is no conclusive evidence for any tectonic activity on Iapetus, even when thermal history studies indicate that there should be. The one exception is Murchie (1990), who noted the apparent existence of scarps in the north polar area of Iapetus. The minimal geologic analysis of Iapetus is probably due to the poor resolution (≈8 km/pixel) of even the best Voyager images. However, in a new study of Iapetus' surface involving the use of stereo pairs, an extensive tectonic network has been recognized. A few new observations concerning the craters and dark material were also made. Thus the geology and geologic history of Iapetus can be more fully outlined than before.

The tectonic network is shown along with prominent craters and part of the dark material in the geologic/tectonic sketch map in Figure 1. The base for the sketch map is FDS 43907.08, which shows the region around the north pole and anti-saturn facing hemisphere down to the equator. Features on the geologic/tectonic sketch map are based on examination of Voyager 2 images FDS 43885.45 (resolution: 12 km/px), 43894.20 (10 km/px), 43907.08 (9 km/px), and 43913.35 (8 km/px). These images were chosen because they represent the highest resolution images available, and because they allow viewing the surface in stereo, a great aid in recognizing geologic structures. Stereo discernment for the image pairs is: low for 85.45 and 94.20, good near the image centers for 94.20 and 07.08, and good globally for 07.08 and 13.35. The topography of crater rims and scarps are quite apparent and recognizable in the different image pairs. The heights and slopes of various features given below are based on comparison with the depths of craters 50 to 100 km in diameter, which are assumed to have the same depths (3-4 km) as craters of similar diameter on Rhea and Titania (see Schenk, 1989).

Tectonic Features. The primary tectonic landforms on Iapetus are individual scarps. The features mapped as scarps are typically on the order of 1-3 kilometers high, and 300 to 500 km long. The apparent scarp widths are ≈10-20 km, indicating nominal slopes of 5° to 10°. Several short segments a few tens of km long occur, as well as at least one, the OCO (Oliver-Charlemagne-Ogier) scarp, which is over 1000 km long. Some of the scarps appear to pair together to form chasmata, of which three fairly well-defined ones (Chasmata A, B, and C) are labeled on Figure 1. The chasmata are about 60-75 km wide and several kilometers deep. The crests of several of the scarps (e.g., the N bounding scarp of Chasma A and OCO scarp) appear to be raised somewhat (≤kilometer) above the terrain on the higher side of the scarp. A few features are mapped as ridges: n. Hamon and the parallel feature to the NW. These ridges may be simply scarps with raised crests. Certainly, n. Hamon is an asymmetric structure with a bright eastern slope ≈50 km wide and a western slope ≈10 km wide. Several lineaments are mapped near the north pole, the crater Ogier, and along the equator near the crater Baligant. These marginally resolved linear features are probably also scarps: they follow directional trends characteristic of the prominent scarps (see below), and one in particular, n. Baligant along the equator, extends into the region containing deposits of dark material and joins the remarkably linear northern boundary of the otherwise irregularly-shaped dark deposit centered near 5° N,225° W. The sharp, linear boundary suggests a topographic discontinuity like a scarp almost regardless of the assumed origin of the dark material. The lineament n. Marsilion may be a ridge along the light-dark material boundary.

The scarps may be placed into groups with distinct directional trends. The polar group trends parallel to the 180° Meridian through crater Marsilion right over the pole into the terminator. This group includes the majority of the mapped scarps and Chasmata A and C. The second "group" contains only the OCO scarp trending about 45° counter-clockwise from the polar group. The third group trends at roughly right angles to the polar group and consists of the BB (Baligant-Besgun) scarp and Chasma B near crater Besgun. The BB scarp appears to be a southward extension of the northern Chasma B scarp. The ridges near crater Hamon may fall into this group, but they are arcuate in plan rather than straight, and may only coincidentally parallel the BB scarp in the map area. Other trends may exist: the extant images of the map area are unfortunately all illuminated from about the same direction, and different lighting conditions could highlight different structural features. However, no other trends were seen despite the stereo analysis.

The scarp groups appear to have formed over an extended period. The BB scarp group is cut by all of the others and appears very degraded: its trace is completely lost in a few spots. The ridges are also very degraded and are cut by the OCO scarp. Thus the BB scarp group is oldest, and the OCO scarp is next. The polar group of scarps is the youngest, cutting across scarps of the other groups. These scarps also appear morphologically less degraded morphologically than the others. Even so, the polar scarp group is geologically old since its members are superposed by nearly all of the craters visible on the surface.

Two elevated plateau-like blocks are marked by hatched patterns near the craters Oliver and Besgun. The sides of the blocks are formed by members of different scarp groups.

Crater Morphology. As far as can be discerned given the poor resolution, the morphologies of fresh craters on Iapetus are similar to crater morphologies on the other icy satellites (cf. Schenk, 1989; Croft & Soderblom, 1990): larger craters have relatively shallow, flat floors and central peaks typical of complex craters, while smaller craters appear to have the relatively deeper, bowl-shaped interiors of simple craters. The central peaks (many marked with crosses on the map) are usually solitary conical massifs typical of central peaks on other icy satellites. In particular, Marsilion (≈230 km in diameter) has a massive, conical central peak similar to that of Dido or Aeneas on Dione. Marsilion's central peak is located off-center, its only unusual feature. The smallest craters with discernable central peaks are 40-50 km in diameter, somewhat larger than the simple-complex morphology transition seen on similar-sized icy satellites (Schenk, 1989). However, since the smallest observed central peaks are about a pixel pair across, the difference is probably due to poor resolution and not a real difference. The consistency of crater morphologies between satellites and the consistent correlation of complex crater depths with simple-complex transition diameters provide the basis for the crater depths assumed above.

Dark Material. As has been noted before (e.g., Smith et al, 1982; Bell et al., 1985), the dark material forms a broad oval deposit, Cassini Regio, centered in the leading hemisphere. The oval has irregular borders. Numerous detached and semi-detached patches of dark material are found along the boundaries of the oval, with complex clusters extending off of the east and west ends. The planform of most of these patches are subcircular, leading Smith et al. (1982) to suggest that the patches were deposits on the floors of craters. The large, 300 km diameter ring at the east end of the oval is particularly reminiscent of annular flooding in a large central peak crater. In contrast, Bell et al. (1985) suggested that the dark patches were instead located on slopes facing the leading apex of motion rather than in depressions on crater floors. The location of the dark material on apex-facing slopes would be more consistent with an orbital origin of the dark material (Bell et al.'s hypothesis) than locations in sheltered depressions, which would be more consistent with an internal flooding origin. The only contribution to that discussion here is the observation that at least a few of the dark patches occur on the bottoms of craters whose rims are topographically perceptible in stereo, notably crater A and a smaller crater to the south. The dark materials in Baligant, its two neighbors to the NW, and Hamon also appear to be on the crater floors, but topographic discernibility decreases rapidly toward the limb, where these craters lie. The material in Hamon may extend up the apex-facing crater rimwall. The large dark patches south of Baligant again appear to lie in large depressions while the light patches appear to form high-standing massifs, but unfortunately, topographic discernibility is low. Similarly, two bright spots on the limb of 07.08 appear to extend above the limb defined by the darker material, but a numerical limb analysis will be needed to test this. Finally, if the lineament n. Baligant is indeed a scarp, then the straight border it forms to the dark material strongly suggests topographic confinement of the dark material. Thus the observations made in this study tend to confirm the location of dark material in low spots, suggesting either an internal origin for (part of?) the dark material, or an active process driving orbitally-derived dark material on slopes downward into depressions.

Comparisons and Interpretations. Titania and Oberon are two icy satellites very similar in size to Iapetus. To first order, similar heat flows and thermal histories might be expected for all three bodies, thus it is of interest to compare their surface features. The scarp/chasma network on Iapetus is similar in planform and topography with the chasma networks observed on Titania and Oberon (Croft & Soderblom, 1990). Dimensionally, the mean major chasma widths are 50-60 km on Titania and 70-80 km on Oberon, compared with 60-75 on Iapetus; chasmata on all three satellites are typically several hundred kilometers long. Features comparable to the smaller, graben-like structures seen on Titania and Oberon would be below the limits of resolution on Iapetus. Chasma morphology is similar on all three satellites, apparently including raised crests on some chasma-bounding scarps. Unpaired scarps are found on all three satellites, but they appear to be more common on Iapetus than on Titania or Oberon.

The morphology of the scarps and chasmata on Iapetus imply formation by extensional tectonic stresses. The areal extension represented by the classes of tectonic features can be estimated using the method of Golombek (1982), in which the new area (A) for each scarp is related to the length (L), depth (d), and assumed angle of dip (Θ) for the underlying faults by: $A = Ld/\tan(\Theta)$. Adopting $\Theta = 60^\circ$ and noting that chasmata have 2 scarps yields the following areal increases from the cumulative measured lengths of the tectonic groups: 1) prominent scarps (adopted $d = 2$ km): 0.26%, 2) smaller scarps ($d = 2$ km): 0.20%, 3) lineaments ($d = 0.3$ km): 0.03%, and 4) ridges (interpreted as asymmetric scarps with $d = 2$ km): 0.10%. The cumulative areal increase is 0.59%. This is somewhat smaller than the 1-1.5% seen for the uranian satellites, but is probably due to poor resolution and the heavily degraded state of most of the tectonic features.

The scarps extend across the entire mapped area, indicating at least regional, and probably global, sources for the stresses. The predominance of extensional morphologies indicates an overriding tensional stress, probably thermal expansion. Several possible sources of secondary stress are capable of modifying the overall tensional field to produce the observed directional patterns. Tidal despinning (Melosh, 1977) may account for the trends of the older scarps, like the BB and OCO scarps, but does not obviously account for the younger polar band. That band, which extends from the Saturn-facing hemisphere over the pole to the anti-Saturn hemisphere, follows the trend predicted for orbital recession (Melosh, 1980). Unfortunately, the maximum increase in semi-major axis for Iapetus' orbit due to tidal evolution allowed by the minimum dissipation factor, Q, for Saturn determined by Goldreich & Soter (1966) is only about one part in 10^7, corresponding to a maximum tidal stress of order 10^{-7} bars. This level of stress is completely negligible compared to the ≈170 bars estimated from friction-dominated strength (Golombek & Banerdt, 1986) required to generate Iapetus' chasmata. Another possible source of stress is interior convection (e.g., Zebib et al., 1983). A single axisymmetric cell with fluid rising at one pole (in this case, under the north pole) of the convection pattern and falling at the other could produce the correct stress field. Another possibility is a 2-cell, axisymmetric convection pattern with fluid rising along the equator of flow and falling in at the poles of flow, where the equator of flow is oriented along the 180° meridian through the North Pole. This latter type of flow provides the best means of producing the consistent directional trends of the polar band.

The raised crests of several of the scarps on Iapetus may indicate the existence of cryovolcanic plutons at depth (Croft, 1991) in a largely undifferentiated interior. The large plateau-like blocks appear structurally to be horsts. Plateau-like features appearing in the limb profile of Titania (Thomas, 1988) may be similar structures.

The large ridges near the crater Hamon are sufficiently different in morphology and trend from the other scarps to suggest the possibility of a different origin. The arcuate pattern of n. Hamon and its counterpart to the west, and the asymmetry of the ridge profile - steep on the inside of the curve and broad on the outside - are both consistent with an origin as rim elements of a large, heavily degraded impact crater. If so, the inferred crater would be about 1000 km in diameter and centered near 30N,300W. The western rim would pass near craters Othon and Turpin seen in the Voyager 1 images, but unfortunately the resolution is too poor in these images (≈50 km/line pair) to show either a degraded rim structure or a remnant depression on the limb that might confirm the postulated crater. If the crater is real, it is large compared to the satellite (≈1.4x Iapetus' radius), and substantially larger than the next largest impact structures: Marsilion and the inferred crater associated with the 300 km diameter dark ring seen in Voyager 1 images near 5N,325W.

The chronology of geologic activity on Iapetus differs somewhat from that observed on Oberon and Titania: all of Iapetus' scarps predate most of the craters; Oberon has geologically old chasmata like Iapetus, but it also has a set of chasmata that largely post-date the large craters; Titania's chasmata almost entirely post-date the large craters. Thus, Iapetus' tectonic activity preceded the last stage of heavy cratering. There is also evidence of extensive (global) resurfacing on Titania and Oberon, but, unless one counts the dark material, there is no positive evidence for endogenic resurfacing on Iapetus.

The geologic history of Iapetus may now be outlined as follows: 1. Accretion to final size, saturated cratered surface (time scale 10^4 -10^5 yr based on Safronov, 1972). 2. Continued heavy bombardment of surface, formation of n. Hamon structure, possibly by impact. 3. Global expansion due to internal heating generates older scarps (time 10^8 yr). 4. Continued expansion generates polar band of scarps, possibly after onset of interior convection (few times 10^8 yr). 5. Heavy bombardment, which has continued through events 3 and 4, tapers off. 6. Dark material is emplaced, either by extrusion of internal carbon-bearing melts or by modification of surface materials by orbital debris.

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Figure 1. Geologic sketch map of the North Pole area of Iapetus.