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Tethys Geology and Tectonics Revisited. Steven K. Croft, Lunar & Planetary Laboratory, University of Arizona, Tucson, AZ, 85721.

Tethys, a medium-sized icy satellite of Saturn, was imaged by both the Voyager 1 and 2 spacecraft at sufficiently high resolution to allow some geologic analysis (Smith et al, 1982). One fairly complete (Moore & Ahern, 1983) and several brief descriptions of Tethys' geology (e.g., Smith et al., 1982; Soderblom & Johnson, 1982; Moore & Ahern, 1982; McKinnon & Benner, 1989) have been given. This report gives the partial results of a new analysis of Tethys' geology done as part of a comparative tectonic and cryovolcanic study of the saturnian satellites.

Geologic Description. A new geologic sketch map of Tethys' north polar area is shown in Figure 1. This map is based on a sequence of images (FDS #43980.27, 5.41, 95.58, and 44003.57) transformed to a polar stereographic projection at the same scale. The images present the same area under different illuminations, each of which brings out different features. A new global map is in progress. Tethys' surface has been divided into two primary geologic units (Moore & Ahern, 1982;1983): a heavily cratered unit which covers most of the surface (and most of Fig. 1), and a less heavily cratered plains unit which covers about 20% of the surface, an edge of which appears at lower right in Fig. 1. Individual geologic features are classified as impact craters or tectonic structures.

Tectonics. Ithaca Chasma: The most prominent tectonic feature on Tethys is the globe-girdling Ithaca Chasma, which is 60 to 100 km wide, 3-4 km deep, and can be traced through at least 270° of a rough great circle (Smith et al, 1982; Moore & Ahern, 1983). The nature of the chasma changes along its length, and is described here in 5 sections. Section 1: South Pole to about 20° S; here the chasma consists of two branches trending roughly N-S and parallel to each other for at least 100 km of their lengths. Each branch appears to be a simple, graben-like trough 30-40 km wide. The west branch, seen at moderate resolution (5 km/px) on the terminator in FDS #34937.06, is heavily cratered and about 3 km deep. The east branch, the southern extension of the main chasma, is seen in FDS #34926.18. Resolution is poor (11 km/px), but the east branch has relatively straight (i.e., unbroken by large craters) bounding scarps and reasonable definition compared to the west branch, which is nearly invisible in FDS #34926.18, suggesting that the east branch is not as heavily cratered as the west branch. Section 2: between 20° S and 5° N; here the chasma is a single branch about 40 km wide which makes a 40° turn and joins another short branch chasma to form a very broad scarp-bounded trough about 100 km wide with prominent upraised rims. The bounding scarps appear fresh and unbroken by craters along the chasma's entire length in the low-resolution image FDS #34926.18, an impression confirmed for the portion seen in the high resolution (2 km/px) image FDS #44003.57. Indeed, the scarps and floor of the chasma have virtually no visible superposed craters in this section. The lack of observed craters is not entirely due to the high sun angle because craters appear in abundance on the cratered terrain on either side of the chasma right up to the rim. The floor of the chasma is seen in the high-resolution section to have several subdued scarps/ridges paralleling the prominent bounding scarps, possibly the northward extension of the two branch chasmata at the south end of the wide section. Section 3: between 5° N and Telemachus (about 55° N); this section is entirely on the high-resolution image FDS #44003.57 and extends onto the map in Fig. 1. Topographically, the chasma consists here of at least three parallel shallow troughs continuing along the same trend as the broad portion of section 2. These troughs are not visible in 03.57, but are prominent in FDS #43995.58 where the scarp faces are nearly perpendicular to the solar direction. The prominent features in this section in 03.57 are a bundle of parallel grooves about 5 km wide and 12 km apart trending about 20° counter-clockwise of the main chasma. This section is more heavily cratered than section 2, but less heavily cratered than the surrounding terrain. Section 4: between Telemachus and Eurycleia; this section is nearly indiscernible in high-resolution in 03.57, but stands out sharply in 95.58. Here the branches combine into a single trough 60 km wide north of Telemachus which splits again into two 30 km wide branches near Eurycleia. The rims appear slightly raised along portions of the chasma. The crater density on this section of chasma is indistinguishable from the surrounding cratered terrain. Section 5: south of Eurycleia past the west rim of Odysseus; here the branches of the chasma become progressively shallower and less sharply defined towards the south (stereo pair: FDS #43985.41, 88.57), dwindling into isolated linear massifs in the section closest to Odysseus, and becoming lost south of the equator in the available images (e.g., FDS #43980.27). This section appears heavily degraded and is superposed by several 50-100 km diameter craters.

Other Tectonic Features. Odysseus Tangent Chasma: A prominent chasma 60-80 km wide and at least 800 km long (90° arc), visible in 80.27, is tangent to the rim of Odysseus, trending about 10° east of north. The chasma intersects a ridge-bounded trough radial to Odysseus (see Fig. 1 and below) and is then lost in the zone around the North Pole that is shadowed in all of the extant images. However, extrapolation of the trend over the pole connects almost directly into the trend of the grooves just south of Telemachus (Fig. 1). Continuation of the same trend farther south passes close to the short branch in section 2 of Ithaca Chasma. Two other poorly defined troughs, each 35-40 km wide and at least 300 km long, are visible in 80.27. One is a linear feature parallel to the Odysseus Tangent feature, and the other defines a broad curve along the equator sub-radial to Odysseus. The features intersect near 10° N,190° W. Another prominent trough about 35 km wide and 120 km long runs N-S of the crater Penelope (85.41 & 88.57). It is radial to the crater, but it appears more degraded than Penelope, suggesting that it is a pre-existing tectonic structure. Lineaments: a set of lineaments running NE-SW are visible in FDS #34937.06 and.10 north and south of the crater Circe. The lineaments appear to be graben-like troughs about 10 km wide. The lineaments cut degraded appearing craters (keeping in mind the 5 km/px resolution) and are cut by fresh appearing craters up to about 30 km in diameter. A number of graben-like lineaments trending NE-SW also cross Odysseus from the south, cutting both the rim and floor.

All of the tectonic features on Tethys appear extensional. The analysis of the global areal expansion inferred from the observed tectonic features is not yet complete. Preliminary estimates have been made, however. Assuming the features are simple grabens, the method of Golombek (1982) yields estimated minimum global areal expansion for Ithaca Chasma alone of 0.25% (assuming an average depth of 3 km). Noting the branching of the chasma (usually two parallel branches) doubles the estimate to about 0.5%. The total area of Ithaca Chasma is about 6% of Tethys' surface, but, recognizing resolution limitations, the morphology is similar to graben-like chasmata on other icy satellites, and not to a giant extension crack, thus the total area of the system does not represent the areal expansion. The Odysseus Tangent system is comparable in extent to the Ithaca system, increasing the estimated expansion to about 1%. The lineaments are numerous, but shallow, indicating little net expansion, leaving the global estimate near 1%, which is similar to the estimated expansions on several other icy satellites (Croft & Soderblom, 1990; Croft, 1991a).

Craters. The largest and most prominent crater on Tethys is Odysseus, visible at upper left in Fig. 1. The crater consists of a primary rim with some evidence of terracing and a central complex of concentric ridges and massifs. RMS fits yield a diameter of 441+14 km for the rim and 169+9 for the central complex. Limb profiles and photoclinometry (Schenk, 1989) show a crater about 8 km deep. The central complex is uplifted 2-3 km and has a narrow central depression. Chapman & McKinnon (1986) suggested the crater may be an incipient pit crater; alternatively, Odysseus may be a peak ring basin.

Ejecta facies have not been previously recognized for Odysseus. However, several features noted in the current study may indicate Odysseus ejecta. 1) A number of crater chains are mapped in Fig. 1. Most of these correspond to chains mapped by Moore & Ahern (1983). They also mapped a number of chains to the east of Odysseus, most of which have been confirmed in this study. As may be seen in Fig. 1 (and in Moore & Ahern's Fig. 6), nearly all of the long axes of the chains are radial to Odysseus, suggestive of secondary crater chains. The diameters (15-25 km) and ranges from Odysseus' center (600-700) of the largest chain craters correspond to the scaled sizes and ranges of secondaries on other planets in the solar system (Croft, 1991b), supporting their interpretation as Odysseus secondaries. 2) The overall density of craters 40-50 km in diameter mapped in Fig. 1 decreases sharply within about 500 km of Odysseus' center. Large (50-100 km) craters within 500 km of Odysseus also appear significantly degraded compared to craters farther away. It is recognized that the resolution of the images used to make Fig. 1 changes from 8 km/px near Odysseus' rim to 5 km/px near Elpenor crater, however, craters >40 km in diameter are large enough that they should be visible even at the poorer resolution if they were present. Thus their absence near Odysseus appears real. The lower crater density and greater degradation of craters near Odysseus may be explained by the presence of a continuous ejecta blanket. The approximate radial extent of the putative blanket, 500 km, again corresponds to the expected scaled size (Croft, 1991b). 3) A number of ridges are mapped in the center and lower right of Fig. 1, most of which are radial to Odysseus. The pair of parallel ridges over the North Pole bound a deep trough that extends at least to Ithaca Chasma. The smaller ridges SE of Telemachus parallel the crater chains. The morphology, location, and orientation of these features are reminiscent, respectively, of radial gouges and ray-like ejecta deposits seen around large impact basins such as Orientale on the Moon.

Two other large degraded craters not previously documented were found in this study: a 260 km crater centered near 43° S,7° W (FDS #34926.18), and a 190 km crater centered near 50° N,20° W (FDS 343995.58 & 44003.57), mapped in Fig. 1. The morphometry of smaller craters on Tethys was discussed by Schenk (1989).

Discussion. Most of the discussions of Tethys' geology (e.g., Smith et al., 1982; Soderblom & Johnson, 1982; Moore & Ahern, 1983; McKinnon & Benner, 1989) have been dominated by analyses of the two most prominent features: Odysseus and Ithaca Chasma. The location of Odysseus near the center of the great circle of Ithaca Chasma led early to the suggestion that Ithaca was genetically related to the Odysseus impact (Smith et al, 1982). Suggested mechanisms included impact induced seismic fracturing (Moore & Ahern, 1983) and viscous stresses generated in mantle flow due to isostatic rebound of Odysseus' interior (McKinnon, 1985; McKinnon & Benner, 1989). Non-Odysseus related suggestions, such as expansion due to internal freezing (Soderblom & Johnson, 1982), did not provide a ready mechanism for localization of tectonic strain into a single, apparently unique, global system.

One question relevant to the relationship of Odysseus to Ithaca that can be considered geologically is: what is the stratigraphic relation between Odysseus and Ithaca? Several features suggest that portions of Ithaca Chasma predated the Odysseus impact. 1) There appear to be significantly more 30+ km diameter craters superposed on at least section 5 of Ithaca and elsewhere on the heavily cratered terrain (Fig. 1 and Moore & Ahern, 1982) than in and around Odysseus, suggesting that this part of Ithaca existed before Odysseus. 2) Several of the crater chains in Fig. 1 cross Ithaca, and a few appear to breach the bounding scarps. If the chains are Odysseus secondaries, then Odysseus formed later than the chasma. 3) The trace of Ithaca Chasma is most poorly defined closest to Odysseus, and virtually disappears for a short distance east of Eurycleia. This may be due to obscuration by Odysseus ejecta: in this location, the chasma is near the apparent edge of Odysseus' continuous ejecta, and mounds of material (Fig. 1) that may be ejecta come very close to, and may cross the chasma. On the other hand, the large trough radial to Odysseus is cut by the north scarp of Section 4 of Ithaca, though there is a breach in the south scarp that may be a continuation of the trough. If the trough is a radial gouge, then the chasma scarp came later than the impact. However, reactivation of older fractures is common in extensional tectonic environments, and activity may renew scarps on one side of a chasma and not on the other (e.g., the 340° Chasma on Miranda, see Croft & Soderblom, 1990). It is important to note that, based on the variation in crater density in the various sections of Ithaca, the chasma did not form all at once: section 2 appears younger than nearly any other feature on the satellite, whereas sections 4 & 5 appear as old as the average cratered terrain. Thus reactivation may have occurred in section 4.

Unfortunately, poor resolution prevents any of the above observations from being unambiguous, but the current evidence favors formation of parts of Ithaca before Odysseus. If true, then there is no genetic relation between the two features. Theoretical relaxation calculations for Odysseus in progress (Bus & Melosh, 1990, private communication) explicitly including a lithosphere are as yet unable to produce a stress field capable of generating an Ithaca Chasma, contradicting earlier models which did not include a lithosphere. In this context, it is worth noting that there is a non-negligible chance that the location of Odysseus near a pole of Ithaca is purely fortuitous. Calculations assuming a purely random impact locations indicate a 15% chance of the center of Odysseus being within 28° of the great circle pole. However, the pole is only about 24° from Tethys' apex of motion. If the Odysseus projectile originated external to the system, then its probability of landing near the apex of motion, and hence near the great circle pole, is several times higher than the random probability, making it likely that the location of the crater near the pole is only fortuitous. While a genetic relation between Odysseus and Ithaca is certainly not ruled out, there is enough evidence that they may not be related to search for other possible mechanisms for Ithaca's origin.

A second relevant question is: is Ithaca Chasma unique, thus requiring a unique explanation? Two features of Ithaca have been cited (Smith et al., 1982; Moore & Ahern, 1983, McKinnon & Benner, 1989) as unusual (unique?): first, the chasma traces 3/4 of a great circle, and second, most of the apparent tectonic strain on Tethys is concentrated in a narrow lane rather than more evenly distributed around the globe. Recent work has turned up other tectonic systems with similar attributes. As noted above, there is apparently a second great circle system on Tethys, the system tangent to Odysseus, that can be traced through at least 200° . The system may extend farther, but the rest of the putative circuit is in the unimaged portions of the satellite. This system is tilted 20° to 30° to the Ithaca system, predates it, and represents a tectonic strain similar to Ithaca's. There is no crater comparable to Odysseus near its poles. Another pair of great circle systems has been identified on Mimas (Croft, 1991a). Herschel, the giant impact on Mimas, is substantially farther from the poles of those systems than Odysseus is from Ithaca Chasma's pole. A relative concentration of strain is seen in the chasmata systems of Oberon and Titania, although these are not great circle systems. Therefore, Ithaca Chasma may not be unique.

There is evidence for some cryovolcanism on Tethys. The plains unit centered in the trailing hemisphere is probably due to flooding by melted material (Smith et al., 1982; Moore & Ahern, 1983). The edges of the unit are diffuse and lack raised edges, indicating material of relatively low viscosity. Crater statistics (Strom, private communication) show a paucity of craters in the 20-40 km diameter range, but preservation of larger craters. This indicates a regional thickness of the melt sheet of at least several hundred meters, enough to overtop the rims of the vanished craters. Long sections of Ithaca chasma have upraised rims. In analogy with terrestrial rifts, this suggests the possibility of low density intrusions under the axis of the chasma. However, there are no recognizable deposits on the floors of Ithaca comparable to the plains materials. The western margin of the plains unit do not reach Ithaca at any point, indicating that the source vents for the plains are not in these sections of Ithaca Chasma. Poor resolution at the eastern border of the plains prevents definitive determination of the relationship there.

References.

Chapman, C.R. and W.B. McKinnon (1986) Cratering of planetary satellites. In Satellites, J.A. Burns and M.S. Matthews, editors, pp. 492-580. Univ. of Arizona Press.

Croft, S.K. (1991a) Mimas: tectonic structure and geologic history. This volume.

Croft, S.K. (1991b) Scaling of impact crater ejecta features on the terrestrial planets and the icy satellites. Icarus, submitted.

McKinnon, W.B. (1985) Origin of Ithaca Chasma. Bull.Am. Astron. Soc. 17: 922.

McKinnon, W.B. and L.A.M. Benner (1989) Origin of Ithaca Chasma, Tethys, II: the importance of the lithosphere. In Lunar Planet. Sci XX, p. 679-680.

Moore, J.M. and J.L. Ahern (1982) Tectonic and geological history of Tethys. In Lunar Planet. Sci. XIII, p. 539-539.

Moore, J.M. and J.L. Ahern (1983) The geology of Tethys. Proc. Lunar Planet. Sci conf. 13th, part 2, In, J. Geophys. Res., Suppl. 88: A577-A584.

Schenk, P.M. (1989) Crater formation and modification on the icy satellites of Uranus and Saturn: depth/diameter and central peak occurrence. J. Geophys. Res. 94: 3813-3832.

Smith, B.A. and the Voyager Imaging Team (1982) A new look at the Saturn System: the Voyager 2 images. Science 215: 504-537.

Soderblom, L.A. and T.V. Johnson (1982) The moons of Saturn. Sci. Am. 246(#1): 100-116.

Figure 1. Geologic sketch map of north polar area of Tethys. Polar stereographic projection.