

Tectonics on Iapetus: Despinning, respinning, or something completely different?

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ABSTRACT

Saturn's moon Iapetus is unique in that it has apparently despun while retaining a substantial equatorial bulge. Stresses arising from such a non-hydrostatic shape should in principle cause surface deformation (tectonics). As part of a search for such a tectonic signature, lineaments (linear surface features) on Iapetus were mapped on both its bright and dark hemispheres. Lineament orientations were then compared to model stress patterns predicted for spin-down from a rotation period of 16.5 h (or less) to its present synchronous period, and for a range of lithospheric thicknesses. Many lineaments are straight segments of crater rimwalls, which may be faults or joints reactivated during complex crater collapse. Most striking are several large troughs on the bright, trailing hemisphere. These troughs appear to be extensional and are distinctive on that hemisphere, because the interior floors and walls of the troughs contain dark material. Globally, no specific evidence of strike slip or thrust offsets are seen, but this could be due to the age and degraded nature of any such features. We find that observed lineament orientations *do not* correlate with predicted patterns due to despinning on either hemisphere (the equatorial ridge was specifically excluded from this analysis, and is considered separately). Modest evidence for preferred orientations $\pm 40^\circ$ from north could be construed as consistent with *respinning*, which is not necessarily far-fetched. Assuming the rigidity of unfractured ice, predicted maximum lithospheric differential stresses from despinning range from ~ 1 MPa to ~ 160 MPa for the elastic spheroid and thin lithosphere limits, respectively (although it is only for thicker elastic lithospheres that we expect a nonhydrostatic state to be maintained over geologic time against lithospheric failure). The tectonic signature of despinning may have been obscured over time because the surface of Iapetus is very ancient, Iapetus' thick lithosphere may have inhibited the full tectonic expression of despinning, or both. Several prominent lineaments strike E–W, and are thus parallel to the equatorial ridge (though not physically close to it), but a tectonic or volcanic origin for the ridge is highly problematic.

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1. Introduction

Tidal despinning is common to most regular satellites in the Solar System (Peale, 1977). Evolution towards a slower rotation rate is generally accompanied, on midsize satellites and larger, by relaxation of the body's equatorial bulge. The extent to which the bulge relaxes depends on the ability of the body to support nonhydrostatic topography during and after spin-down. Stresses arising from the change in flattening can create a tectonic pattern visible as faults or joints on the surface. This pattern can be complex depending on the thickness of the lithosphere and it can be modified by global expansion or contraction (Beuthe, 2010; Matsuyama and Nimmo, 2008; Melosh, 1977; Pechmann and Melosh, 1979). Nevertheless, if a structural signature is observed, it has the poten-

tial to reveal valuable information about a satellite's thermal and dynamical history.

This concept has been previously applied to the lineament patterns on several Solar System bodies. The theory was originally developed by Vening-Meinesz (1947) for thin elastic shells, and then extended by Melosh (1977) to an elastic shell of arbitrary thickness. Predicted stresses were interpreted as fault patterns, which were then compared to the "lineament grid" on Mercury (Dzurisin, 1978; Melosh and Dzurisin, 1978; Pechmann and Melosh, 1979; Melosh and McKinnon, 1988). Lineaments were defined by them as linear scarps, ridges and troughs in addition to linear crater rimwall segments (cf. Eppler et al., 1983). Linear features radial to craters were not included as they were considered to be exogenic in origin. Large, lobate scarps, which were and are inferred to be expressions of global contraction on Mercury (e.g., Melosh and McKinnon, 1988; Watters et al., 2009; Watters and Nimmo, 2010), were mapped separately. The mercurian lineament grid ostensibly consists of NE–SW and NW–SE trending lineaments in equatorial regions, whereas nearer the poles the

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lineaments begin to strike more E–W. The majority of lineaments thus exhibit azimuths indicative of shear faulting under E–W compression (Melosh and Dzurisin, 1978). Although subject to some uncertainty (debate over observational selection effects; Cordell and Strom, 1977), overall the lineaments have been taken to be a strong indicator of despinning (Melosh and McKinnon, 1988). This conclusion will likely be reassessed as MESSENGER data is analyzed.

Faults observed by Voyager on some icy satellites of Saturn have also lent themselves to comparison with despinning theory. Moore et al. (1985) and Moore (1984) analyzed polygonal crater rimwall segments, scarps, and troughs on Rhea and Dione, respectively. No strong correlation was found for Rhea, but tectonic features on Dione were offered to be generally consistent with despinning (Moore, 1984; cf. Thomas, 1988). Whether these assessments, based on lower-resolution Voyager images, are statistically robust, remains to be seen. Reexamination of these icy satellites using the much higher quality *Cassini* data available is warranted. This should be especially true for Rhea, which has been recently revealed to possess at least a modest tectonic history (Wagner et al., 2010).

Here we present measurements of lineaments seen on Saturn's moon Iapetus, based on *Cassini* images. Iapetus is a unique moon in many respects. The albedo dichotomy between its dark leading and bright trailing hemispheres, while known for centuries, remains striking. Large mountains were discovered on Iapetus by examination of limb profiles in Voyager images (Denk et al., 2000). The *Cassini* orbiter has since revealed them to be part of a prominent equatorial ridge system, which rises up to 20 km in height (Giese et al., 2008; Porco et al., 2005). Iapetus exhibits the most extreme topography (defined with respect to its geoid) of any body its size (or greater) in the Solar System. Independent of the ridge, Iapetus supports a biaxial ellipsoid shape apparently indicative of a body spinning at ~ 16 h (Thomas, 2010; Thomas et al., 2007). Iapetus' great distance from Saturn presumably allowed it to cool and develop a thick lithosphere before it reached its present synchronous rotation period of 79.3 days (see Table 6.1 in Peale, 1977). Thus, Iapetus has despun but far from relaxed its equatorial bulge.

There are many enigmatic aspects of Iapetus, and limited approaches to understanding them. Structures such as faults and joints, if expressed as lineaments, would be visible manifestations of the stress evolution Iapetus has undergone, and could potentially corroborate despinning history models (Castillo-Rogez et al., 2007; Robuchon et al., 2010). Analysis of a global-scale tectonic pattern arguably offers a better test of despinning predictions than models that focus solely on the equatorial ridge. Unfortunately, Iapetus does not have a strong tectonic signature. Indeed, there are few if any unambiguously identifiable faults. In particular, *Cassini* images of Iapetus do not reveal any of the global scale (extensional) rift systems that characterize the surfaces of other Saturnian mid-size satellites (Tethys, Dione, and Rhea), all bodies which otherwise might be expected to have comparable geologic histories. Nor are any large lobate scarps (indicative of global compression) to be seen.

There are nonetheless several classes of distinctly linear features on Iapetus. We have mapped these linear features and investigated them for any preferential orientations. As will be shown below, the resulting pattern and maximum principle stress direction are inconsistent with predictions from despinning models (Melosh, 1977), in so far as we can determine. It is also possible that the despinning signature has been obscured over time as the surface of Iapetus is very ancient, or the satellite's thick lithosphere may have inhibited full tectonic expression of relatively low magnitude stresses, or both. The pattern that does exist, however, is possibly consistent with a novel model of Iapetus' porosity and

shape evolution, or perhaps with respinning due to a "giant" impact, both of which we discuss in Section 4.

2. Theory: despinning stresses on Iapetus

The oblateness or flattening of a biaxial body can be described by the difference between the equatorial and polar radius divided by the mean radius. The shape of Iapetus is well described by a biaxial ellipsoid with radii of 745.7 and 712.1 km (Thomas, 2010). The current flattening (f) on Iapetus is $1/22$, which corresponds to an approximately 16.5 h rotation period for a homogeneous body in hydrostatic equilibrium (e.g., Melosh, 1977, Eqs. (2)–(5)). Whatever Iapetus' initial rotation rate, relaxation to a hydrostatic figure has presumably been prevented by the presence of a thick, strong lithosphere. Lithospheric thickness influences the magnitude of a stress field produced by despinning and the resulting tectonic pattern. Following the analytic model of Melosh (1977) for a despun Mercury, stresses as a function of latitude and lithospheric thickness for the surface of Iapetus were calculated (Fig. 1). In this model, the planet or satellite (mean radius $a = 734.3$ km for Iapetus) consists of an outer elastic shell of thickness H overlying an inviscid interior (with radius $b = a - H$). The meridional stress, $\sigma_{\theta\theta}$, acts in the N–S direction and the azimuthal stress, $\sigma_{\phi\phi}$, in the E–W direction. As the flattening of a body changes, the displacements of the spheroid in the radial (r) and colatitudinal (θ) directions are used to calculate strains, and the constitutive law is applied to determine the relevant stresses.

Fig. 1 is calculated for an initial spin period of 16.5 h, which is the *minimum* initial rotation rate Iapetus would have possessed. Iapetus could have been spinning more rapidly, of course. Melosh's (1977) theory is calculated to first order in f , and strictly applies to small deformations, where small means that the flattening is proportional to ω^2 , ω being the angular rotation rate of the body. Likewise the stresses are proportional to ω^2 , so that Fig. 1 can be rescaled to any suitable change in ω . Relative stress ratios (and their signs), and the tectonic patterns implied (discussed next) are unaffected.

Utilizing Anderson's theory of faulting (e.g., Turcotte and Schubert, 2002), a tectonic interpretation can be assigned to different latitude regions based on the direction of the most compressive stress (Fig. 1c). One possible diagnostic feature, or lack thereof, is the equatorial thrust fault zone that only occurs for lithospheric thicknesses of between 10% and 60% of the total radius of Iapetus (H/a of ≈ 0.1 – 0.6). The maximum differential stress occurs at the equator, and varies by two orders of magnitude between the two endmember scenarios of lithospheric thickness: one where the body is a solid, icy elastic spheroid ($H/a = 1$) and the other where only a thin, elastic icy lithosphere overlies a "fluid" (on a geological timescale) icy interior ($H/a \ll 1$). Greater shape change and thus much greater elastic stress naturally occurs when the lithosphere is thin. Maximum differential stresses at the surface range from ~ 1 MPa to ~ 160 MPa in the elastic spheroid and thin lithosphere limits, respectively (Fig. 1d and e), although it is only for thicker elastic lithospheres that we expect a non-hydrostatic state to be maintained through geologic time. That is, stresses at the surface that are too large will be relieved by faulting in a thinner lithosphere, and the lithosphere will relax "plastically." Lower limits on the thickness of Iapetus' lithosphere during despinning are in fact set by assumptions of lithospheric strength, and not by simple flattening estimates, a point that will be returned to in the discussion.

We note that these stress estimates for a despun Iapetus are less than those calculated for the despinning of Mercury from an initial ~ 20 h spin period to one of 58.6 days; for Mercury the stresses range from ~ 30 MPa to ~ 300 MPa for the two endmember cases

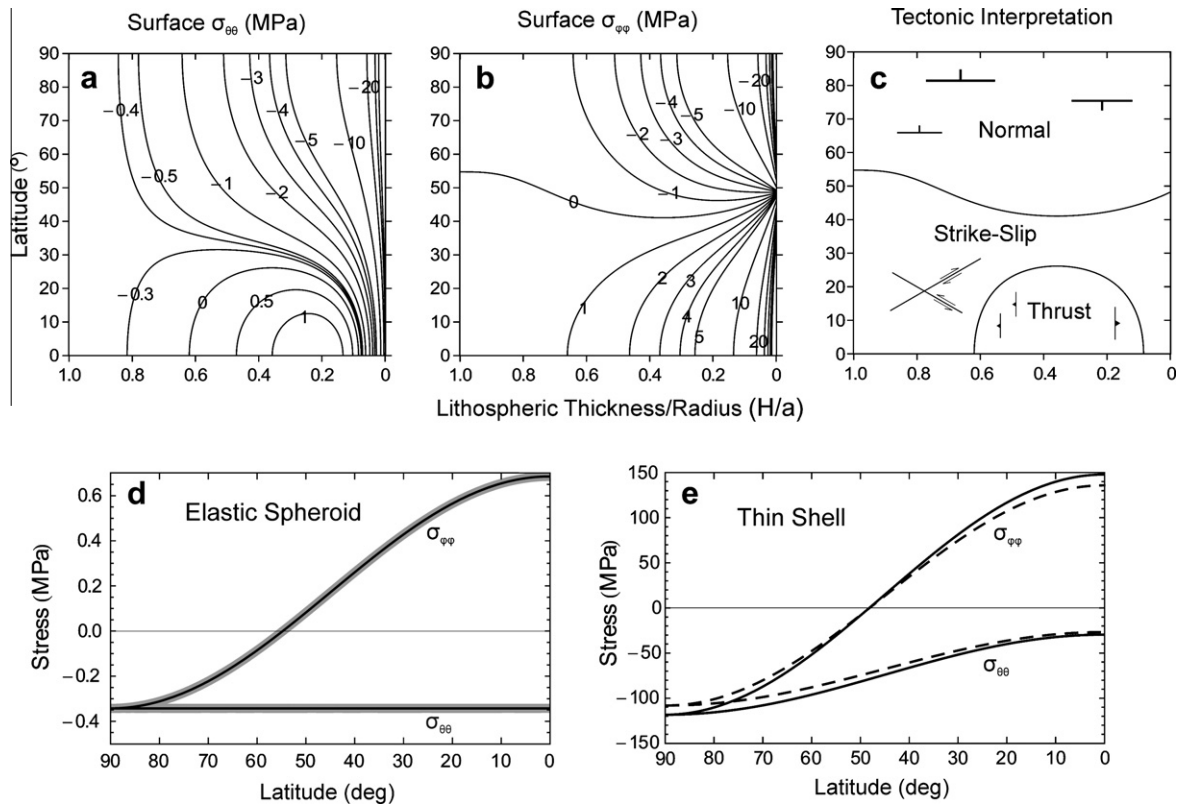


Fig. 1. (a and b) Surface stresses as a function of lithospheric thickness and latitude for a despinning, incompressible lapetus. Stresses were calculated using appropriate physical parameters for a uniform, incompressible, spherical lapetus (mean radius $a = 735$ km, density $\rho = 1.083$ kg m $^{-3}$, Poisson's ratio $\nu = 0.5$) and a pure ice I rigidity ($\mu = 3.52$ GPa; Petrenko and Whitworth, 1999). Spin down from 16.5 h to 79.3 days was assumed. Stress calculations are based on Melosh (1977; see Appendix) and were evaluated using Mathematica 7. Compression is positive. (c) Tectonic interpretation. Equatorial thrust faults are predicted to trend N–S if present, mid-latitude strike-slip faults would trend approximately $\pm 30^\circ$ off of E–W, and polar normal faulting would trend E–W. (d) Surface stress $\sigma_{\theta\theta}$ and $\sigma_{\phi\phi}$ as a function of latitude for the endmember, solid elastic spheroid case. Elastic spheroid stresses calculated from the full solution (black curve) match exactly those from the well-known analytic solution (gray curves, from Eqs. (21) and (23) in Melosh (1977)). (e) The thin lithosphere endmember surface stresses $\sigma_{\theta\theta}$ and $\sigma_{\phi\phi}$ are shown for both an incompressible ($\nu = 0.5$, black curves) and a compressible ($\nu = 0.325$, dashed curves) lapetus.

(Melosh, 1977). A governing dimensionless parameter, $\rho ga/\mu$, where ρ is the mean density, g is the gravity, a is the mean radius, and μ is the shear modulus, is much larger for Mercury (0.76) than for lapetus (0.05). This reduces the flattening achieved by our elastic lapetus with respect to that of Mercury, and of course μ is much less for an icy body compared with a rocky one, which calibrates the overall stress level regardless of flattening. In this regard, Mercury's lithosphere must have been thin enough for the body to be able to relax to its nearly spherical current shape, and shell stresses measured in the 100s of MPa should have been more than sufficient to cause lithospheric faulting and failure (Melosh, 1977).

We also note that the lower limit of ~ 1 MPa for lapetus' despinning stress is close to the tensile strength of intact ice and near the low end of the unconfined compressive strength of ice, for ice at temperatures between -10°C and -50°C (Schulson and Duval, 2009). Stress of this magnitude, however, may still cause faulting in near-surface ice that is already pre-weakened by fractures due to impacts, temperature changes, etc. What really matters, however, is the strength profile with depth (Beeman et al., 1988), also discussed below.

3. Linear features on lapetus

3.1. Mapping methods

Lineaments are defined here as “mappable, planimetrically linear surface features, presumably reflecting subsurface structure”

(Thomas, 1988). In this regard, image resolution is generally insufficient to determine the nature, and in some cases even the exact topography, of the lineaments in question. For lapetus, linear features were identified in images obtained during the 31 December 2004 and 10 September 2007 *Cassini* flybys. During the December 2004 flyby images were primarily acquired of the dark, leading side, with resolutions as great as 740 m px $^{-1}$, along with a few images of the bright, trailing hemisphere in saturnshine. The bright hemisphere was imaged in sunlight during the September 2007 flyby, at resolutions as great as ~ 30 m px $^{-1}$ (Denk et al., 2008). High resolution images of the tallest portions of the equatorial ridge between $\sim 135^\circ\text{W}$ and 200°W were also obtained during this flyby (up to ~ 10 m px $^{-1}$). Approximately 60% of lapetus' total surface was mapped. Our mapping of lineaments on the leading side was limited to mid-latitude and equatorial regions ($\sim 50^\circ\text{N}$ to 30°S), due to the increasingly oblique observation angles at the poles or lack of adequate high-resolution image coverage. On the trailing side, image coverage allowed a slightly greater latitude range to be mapped, from approximately $\sim 55^\circ\text{N}$ to 70°S . All features were identified in original images, and then mapped in ArcGIS on a simple cylindrical basemap.

3.2. Morphologic types

We classify lineaments into five categories, one type only observed on the bright hemisphere and four found globally. This survey concentrated on features that appear linear on a scale of ~ 10 or more kilometers. At the resolution of the images, it is difficult to

discern the origin of many of the lineaments. Some features are more likely to be tectonic (endogenic), whereas others may be related to impact processes (exogenic).

3.2.1. Large troughs (class 1)

A set of large troughs or fault scarps were identified, but appear only on the bright, trailing side (Fig. 2). These large troughs, located near and on the equator between 270°W and 300°W, are the most distinctly “tectonic” features on Iapetus (other than the equatorial ridge, which may or may not be tectonic). The morphology suggests an extensional origin, rather than a compressive one. The most prominent trough, ~90 km long, 10 km wide and a few hundred m deep (based on stereo), has a complex structure and albedo pattern (Fig. 2b). This feature intersects the wall of a large degraded crater and terminates in a dark albedo patch on the wall and floor of that crater. A second large trough (Fig. 2c) has less lin-

ear walls and is more segmented by narrow bright ridges or higher-standing terrain. In general, these and other topographic features are easier to identify on the bright hemisphere because their interior floors and walls contain dark material. Thus it is possible this type of feature is present but (so far) not identifiable on the dark hemisphere. In addition, the resolution of the image data set varies greatly across Iapetus, with better resolution over a larger area on the bright hemisphere. Given the present image coverage and resolution, however, there is nothing identifiable on the dark side that is morphologically similar to the large troughs on the bright side.

It is possible these troughs are secondary impact features, but they have a wide range of azimuths and are not all radial, or concentric, to any large basin. Great circles through the features were traced over Iapetus to check for a possible secondary crater chain origin. Only one feature (the 90-km long trough in Fig. 2b) could

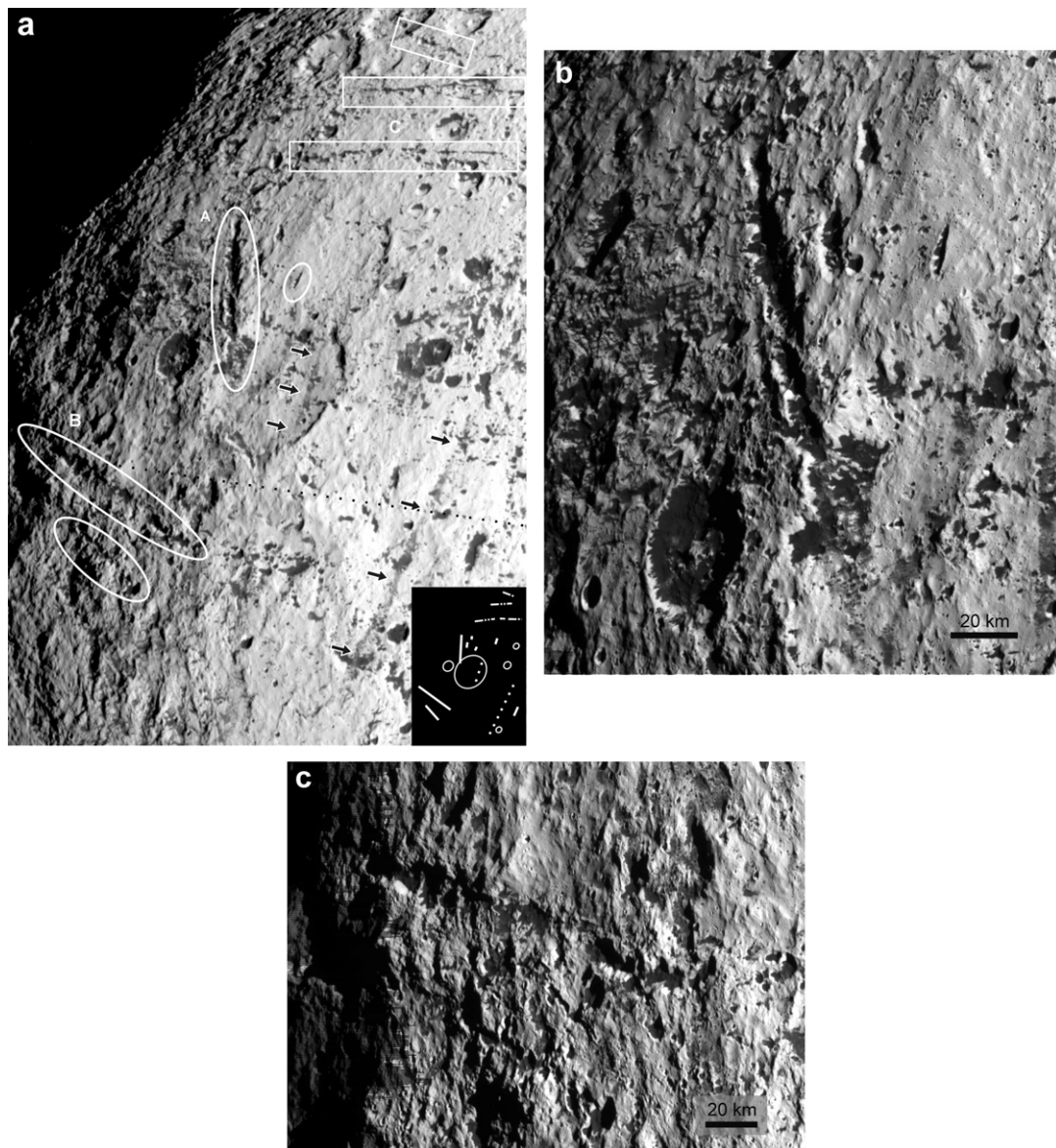


Fig. 2. Examples of lineaments (linear features) on Iapetus. North is towards the top unless otherwise indicated. (a) Scene (centered on 6°N, 297°W) illustrates feature class 1, large troughs, which are only identifiable in this area on the bright trailing hemisphere. Troughs are circled (A and B), and two other, less prominent, large scarps are indicated by arrows. In addition, a few of the features labeled non-crater lineaments, or class 3, are boxed in the upper portion of the image. Features near A, B, and C are shown at higher resolution in Fig. 2b, c, and Fig. 4, respectively. Dots indicate the equator. From *Cassini* image N1568159640; resolution 454 m px⁻¹. (b) This large trough is the most distinct linear feature on Iapetus (after the equatorial ridge) and is 90 km in length. Smaller features to the right are potentially smaller troughs, one of which is very linear and narrow (also circled in Fig. 2a). From *Cassini* image N1568137291; resolution 141 m px⁻¹. (c) Two large troughs with a less continuous structure than in Fig. 2b (largest trough is 140 km in length). From *Cassini* image N1568137129; resolution 138 m px⁻¹. See section 3.2.

be construed as radial to a basin, the ~450-km-diameter Engelier (centered near 40°S, 265°W). If these large troughs are secondary features, however, it would be unusual for them to originate from different basins and only appear in one area on the surface. Therefore, we favor a tectonic origin.

3.2.2. Linear crater rimwall segments (class 2)

Linear rimwall segments are seen as defining craters from ~20 km in diameter to up to some of the largest basins. We presume that such linear crater rimwall segments reflect pre-existing structural control on slumping, rim collapse and terrace formation. Several 30-to-85-km craters have 3 or more linear rimwall segments, giving them a polygonal appearance (several are shown in Fig. 3a and b). Similar “basement” structural control on crater morphology has been previously inferred for the Moon (e.g., Eppler et al., 1983), Mercury (e.g., Dzurisin, 1978), Venus (Aittola et al., 2010), Earth (Kenkmann et al., 2011), Mars (Öhman et al., 2008, and references therein) and other planetary bodies. Slumping and other forms of mass wasting are common processes on Iapetus, whether they occur in concert with crater formation or not (Singer et al., 2009).

Approximately half of the crater rimwall segments are adjacent to another rimwall segment, forming a corner. It has been suggested that in some cases, particularly for simple craters such as Meteor crater, faults bisect adjacent linear rimwalls, rather than running parallel to them, and allow enhanced excavation in these directions during crater formation (Eppler et al., 1983; Öhman et al., 2008, and references therein). It is not clear that this is relevant to the larger complex craters on Iapetus under consideration here, however. In any event, bisectors from 26 crater rimwall “corners” on Iapetus were checked for a preferential orientation and none was found. We did find five cases of potential landslides occurring at the intersection of linear rimwall segments.

3.2.3. Non-crater lineaments (class 3)

Non-crater lineaments are those not positively associated with a crater rim or ejecta pattern and not possessing an identifiable scarp. Lineaments in this class have a large variety of morphologies, the origins of which are not obvious; thus this term is nongeometric. Examples are given in Fig. 2a, and Figs. 4 and 5. In some cases these features may be shallower, narrower, or less continuous versions of class 1 features (large troughs), but with present image

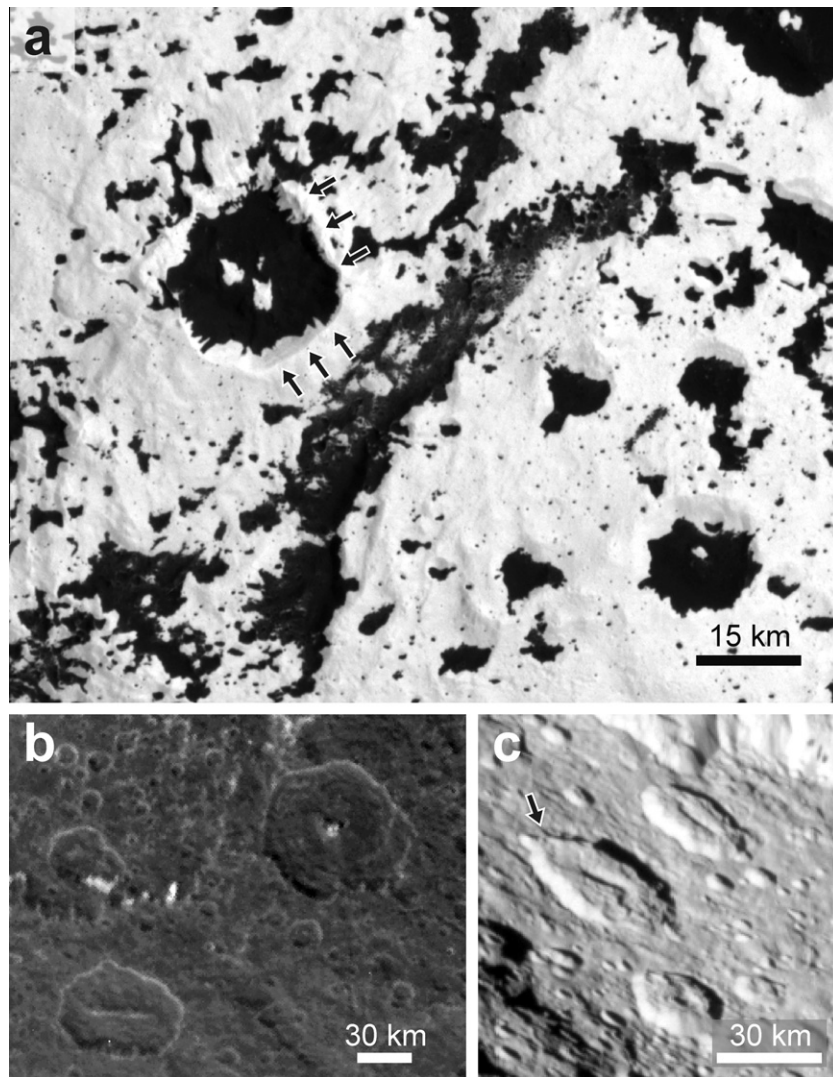


Fig. 3. (a) Example of a crater (~21-km diameter) with linear rimwall segments on the trailing hemisphere (class 2 lineament). Note the interesting arc of dark material to southwest. This may be the remnant of a large crater, but if so the remainder of the crater has been degraded beyond recognition. From *Cassini* image N1568136601; resolution 130 m px⁻¹. (b) Close up of polygonal crater (~35-km diameter) and linear central peak located on the leading hemisphere. From *Cassini* image N1483173746; resolution 869 m px⁻¹. (c) Two linear central peaks located near 60°S, 272°W on the trailing hemisphere; each is ~15–20 km in length. Arrow indicates a potential area of collapse due to mass wasting, which could have elongated the larger crater. From *Cassini* image N1568160962; resolution 473 m px⁻¹.

resolutions it is difficult to distinguish which other feature class they might be most closely associated with. Some non-crater lineaments do have a morphology similar to a chain or row of small secondary craters, but in the absence of an obviously associated primary crater, it is also possible that they are drainage pits aligned over vertical fractures beneath a thick lapetian regolith, in the manner proposed for Phobos (Horstman and Melosh, 1989).

3.2.4. Linear central peaks (class 4)

Several (4) craters on Iapetus exhibit linear central peak segments, the most prominent of which are ~15–35 km in length (Fig. 3b and c). These features may or may not indicate structural control, as it is also possible they formed by oblique or closely-spaced, similar-sized impactors. Linear central peaks are associated with highly oblique impacts such as Schiller on the Moon and certain craters on Mars (Schultz and Lutz-Garihan, 1982). The topographic profile of the longest linear peak (at ~12°N, 83°W) is provided in Giese et al. (2008, their Fig. 13) and shows that the peak is tallest at both ends. The likely formation mechanism was interpreted by them to be two central peaks that merged to form one elongated ridge. One of the linear peaks on the trailing side (~64°S, 270°W) has a hook on the eastern side giving it a “J” shape (Fig. 3c). The three most prominent examples of linear central peaks segments (out of 5 total) occur in somewhat elongated craters. At least one of the craters may have been affected by mass wasting, however, which could have caused or augmented the elongation (indicated in Fig. 3c). Nominally, such elongation would be *prima facie* evidence of a very oblique impact, or a closely spaced set of impacts, but without additional information it is hard to definitively assess the origin of these features (i.e., with respect to oblique impact, ejecta facies are too degraded to be discerned).

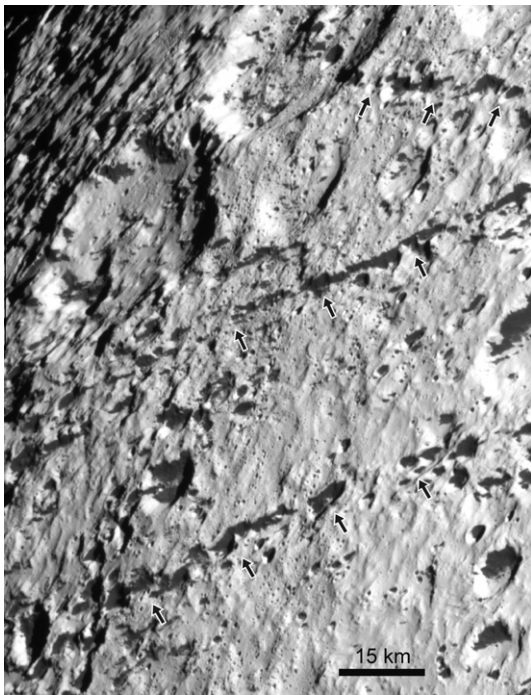


Fig. 4. High resolution image of some non-crater lineaments (class 3). These particular features are not radial to a large basin, and their morphology somewhat resembles more discontinuous and shallower versions of class 1 features (troughs). From available images and stereo-derived topography (P. Schenk, personal communication, 2010), it is difficult to tell if class 3 lineaments have a distinct topographic character or offset, though the albedo patterns on the trailing side are consistent with shallow troughs. From *Cassini* image N1568137456; resolution 142 m px⁻¹.

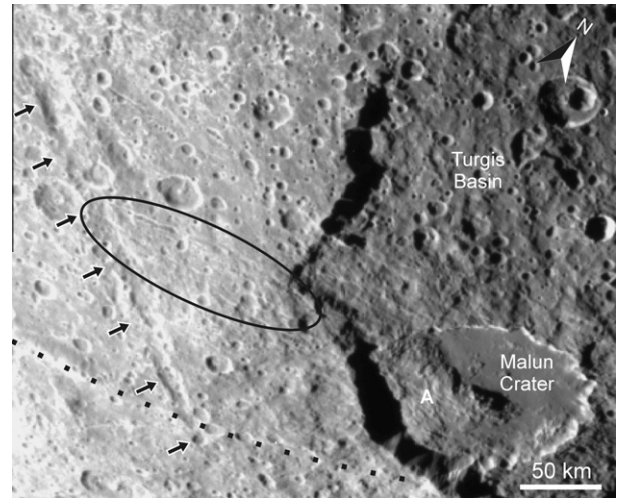


Fig. 5. Example of a class 5 lineament, a probable secondary cratering chain/feature (arrows), which overprints the equatorial ridge (dotted). These secondaries are either radial to the 550-km diameter Falsaron basin to the northwest, or radial to the even larger, older, degraded basin that Falsaron overlies (as seen in topography by Giese et al. (2008)). In addition, several class 3 lineaments are seen (circled). These lineaments continue up the edge of Turgis basin, which has been modified by a large landslide (A). These lineaments are also not likely to all be secondaries of Malun crater, as they are not all radial to it. From *Cassini* image N1483195169; resolution 763 m px⁻¹.

3.2.5. Secondary crater chains (class 5)

A particular lineament was classified as a secondary crater chain if it had the morphology expected of multiple small impacts in a row *and* was obviously radial to a nearby, large crater (one large example is shown in Fig. 5). Because secondary crater chains would not reveal information about the stress field, mapping of these features was not exhaustive in this work. Several long features on the leading hemisphere appear to be radial to the large (~350-km-diameter) basin Falsaron (centered near 30°N, 90°W) and overprint the equatorial ridge, lending more confidence to the interpretation that they are of an impact origin.

3.3. Results

The global distribution of features is presented in Fig. 6 and no immediate pattern is obvious. Although all imaged regions were surveyed, the lack of features over large areas in Fig. 6 is not necessarily meaningful as those areas have lower resolution or were viewed only very obliquely by *Cassini*. We also note that feature identification was more difficult where the albedo pattern is patchy in the transition regions from dark to bright material. The length and azimuth of each linear segment was determined (Table 1). On the leading (dark) hemisphere, 69 features were identified with a total length of ~2020 km, and on the trailing (bright) hemisphere, 93 features were identified with a total length of ~2500 km. Note that we are excluding the equatorial ridge and ridge segments from our statistical analysis, an issue we will return to below.

The lengths of all lineaments per 10° bin of azimuth were totaled and are presented as rose diagrams in Fig. 7. We generally sum over all latitudes, as (1) mapped features are sparse poleward of ±60° (where tectonic orientations are predicted to change) and (2) small amounts of global contraction (quite plausible for a cooling Iapetus) would only shift the predicted strike-slip province poleward (Melosh, 1977) (see Fig. 1c). The plot of all lineament data shows a broad, multicomponent distribution. There are several concentrations of lineament orientations: a peak between 20° and 50° NNW, an E–W concentration, and overall, more

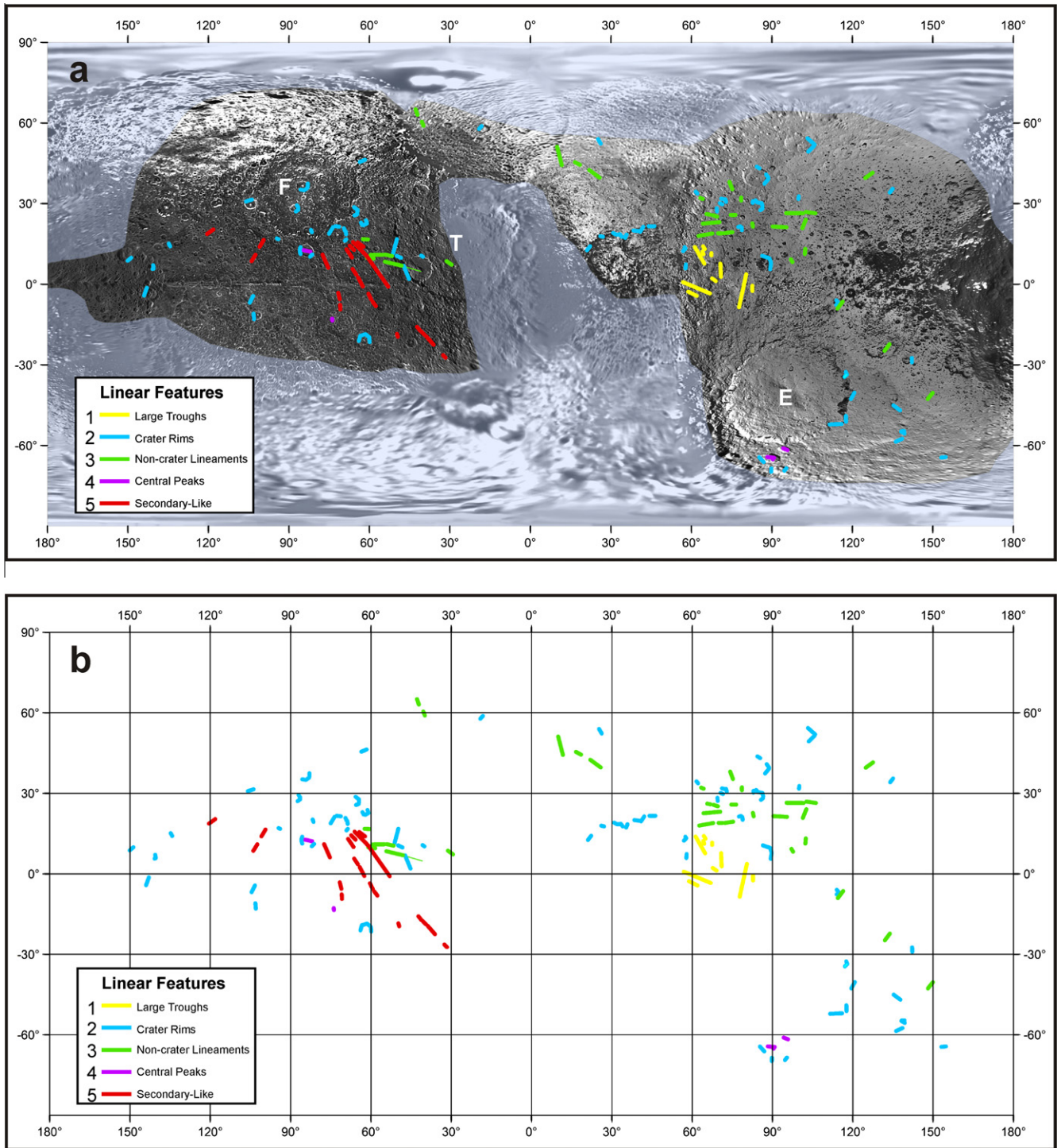


Fig. 6. (a) Simple cylindrical projection of Iapetus with mapped linear features and (b) mapped features alone. Identification of features was limited by the resolution and coverage of images taken by the two *Cassini* flybys of Iapetus. The blue shaded areas indicate portions of the surface that were only viewed at low resolution or very obliquely by *Cassini*. E, F, and T indicate the Engelier, Falsaron, and the Turgis basins, respectively. Basemap courtesy NASA/JPL/Space Science Institute.

features are found between $\pm 40^\circ$ from N. Only the last is potentially meaningful, as will be explained. The broad peak between 20° and 50° NNW is derived mainly from lineaments on the leading (dark) hemisphere, and is made up primarily of several large secondary-like features (class 5) radial to the Falsaron basin. Additionally, there is no associated conjugate trend to the NNE, which might give indication of the strike-slip faulting theoretically predicted for this latitude range. The incident solar illumination was

from the south-west for most observations of the leading hemisphere (and from the north-east for the trailing hemisphere). This could introduce a bias for preferential identification of shadows from features trending NW–SE. However, these features are quite large and in some cases overprint the equatorial ridge, and thus would be hard to miss regardless of orientation. For these reasons, this subset of the data (class 5) is not interpreted by us as indicative of a tectonic pattern.

Table 1
Iapetus lineament data.

Classification		Number of features		Approximate length (km)	
Class	Description	Dark side	Bright side	Dark side	Bright side
1	Large troughs	0	10	0	588
2	Crater rimwall	39	56	791	974
3	Non-crater	8	24	315	902
4	Central peak	2	3	45	36
5	Secondary-like	20	0	872	0
Totals		69	93	2023	2500

Considering only classes 1–3 features (Fig. 7, Row 2), i.e., excluding secondary-like features and linear central peaks whose origin is plausibly exogenic, the resulting azimuth distribution is neither smooth and even nor entirely random (in a Poisson sense). Kuiper's Test was used to test for uniformity of the data. The lineaments were broken up into 1 km lengths with a given azimuth. The

Kuiper's V statistic (Mardia and Jupp, 2000; Eq. (6.3.30)) is ~ 10 for classes 1–3 (and also for classes 1–4). This indicates a large deviation from uniformity, as a V statistic of ~ 2 would mean the null hypothesis (a uniform distribution) is rejected at a 1.0% significance level (Stephens, 1970). There are several discrete peaks in Fig. 7, but the statistics of small numbers (per bin) makes the significance of these peaks open to question. There is an apparent concentration trending E–W in the global data set, but the lineaments in these bins are primarily made up of a few long non-crater lineaments located in one area on the trailing hemisphere (near 23°N , 280°W). Overall, however, this distribution shows a concentration of lineaments trending between $\pm 40^\circ$ from N, which is also seen in the subset of the data consisting solely of crater rim segments (class 2).

In terms of despinning models, the distribution of lineament azimuths in Fig. 7 does not offer much support. Overall, more lineaments trend between $\pm 40^\circ$ (with respect to north), and there is a lack of features at approximately $\pm 60^\circ$ from north, the angles

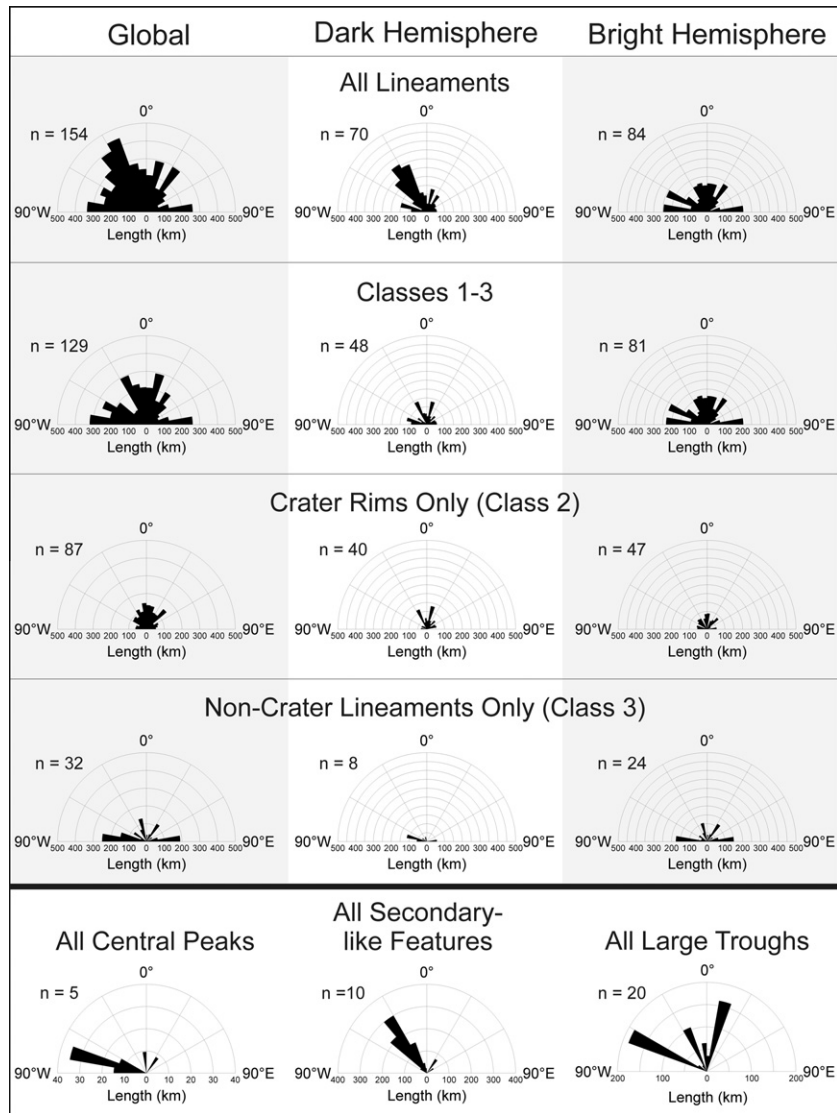


Fig. 7. Lineament azimuth distributions weighted by length. Row 1 from left to right: all lineament types on both hemispheres (classes 1–5), all lineaments on the dark, leading hemisphere, and all lineaments on the bright, trailing hemisphere. Row 2: subset of classes 1–3, which includes large troughs, crater rim segments and non-crater lineaments (excluding potential secondaries and linear central peaks). Row 3: Only crater rimwall segments. Row 4: Only non-crater lineaments. Row 5, from left to right: all linear central peaks on both hemispheres (class 3), all secondary features, which were only identified on the leading hemisphere (class 5), and all large troughs, which are found only on the trailing hemisphere (class 1). These distributions exhibit widely ranging feature azimuths, and do not show an obvious connection with despinning. Note changes in scale between rows 1–4 and row 5. See Sections 3 and 4.

predicted for shear faulting by despinning theory. Subsets of lineaments in latitudinal zones were also investigated (Fig. 8). A plot of all lineaments poleward of latitudes $\pm 50^\circ$, which contains classes 2–4, yields no indication of an E–W trending component (extensional or otherwise). This is also obvious from the map (Fig. 7), and we note that horizontal stress differences due to despinning are minimized in the polar regions.

The largest predicted equatorial zone in which N–S thrust faults might form is between $\pm 25^\circ$ latitude (Fig. 1c) and N–S thrusts would be favored over an even greater range of lithosphere thicknesses if mixed-mode faulting (Simpson, 1997) were considered. A plot of all classes 1–3 lineaments in just this zone does not show N–S lineaments primarily, and we see no morphologic evidence for contraction either. Instead, features near the equator, such as the large troughs, appear extensional. Extensional features do not support a lineament origin by either compressive or strike-slip faulting, and so when found between -45° S and 45° N latitude are not consistent with despinning regardless of lithospheric thickness.

4. Discussion

4.1. Interpretation of lineament data

No subsets of the data show a correlation with despinning stresses as classically derived (Melosh, 1977). If the $\pm 40^\circ$ from north orientation concentration of classes 1–3 features is meaningful, it could indicate that the maximum principal compressive stress direction (σ_1) was N–S, with conjugate shears forming at acute angles to this direction (for ice friction as measured by Beeman et al. (1988)). This result is opposite of that predicted by models for despinning, in which the most compressive stress is E–W (Melosh, 1977), with conjugate shears expected at acute angles to the E–W direction. Despinning models for uniformly thick lithospheres predict the azimuthal stress ($\sigma_{\phi\phi}$) is always greater, or more compressive, than the meridional stress ($\sigma_{\theta\theta}$) (as can be seen in Fig. 1). Superposition of stresses from global expansion can result in an expanded normal faulting province, but these faults (or even joints formed by surface tension) would still be predicted to be E–W,

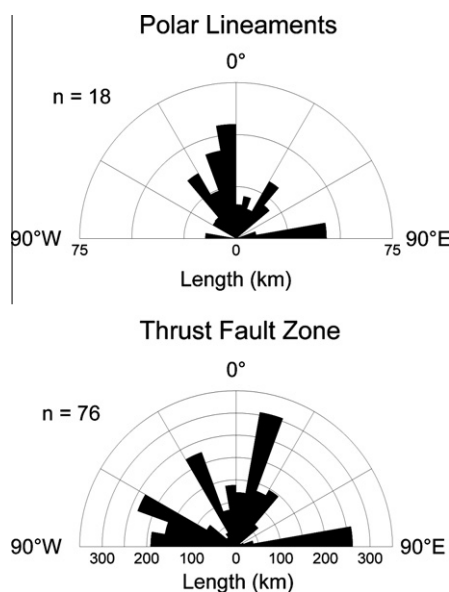


Fig. 8. (a) Rose diagram for polar lineaments only (poleward of $\pm 50^\circ$). These lineaments include features from classes 2–4. (b) Rose diagram for the largest possible equatorial thrust fault zone of $\pm 25^\circ$ latitude (see Fig. 1c), which corresponds to a lithosphere thickness to satellite radius ratio of ~ 0.35 . Classes 1–3 are plotted.

not N–S (for further discussion of these topics see Melosh (1977)). Global contraction would result in an expanded equatorial thrust fault zone, features that are predicted to trend N–S, but the morphologies of the features (for classes 1 and 3) are not consistent with contraction (i.e., they do not appear to be thrust faults and do not resemble features like lobate scarps on Mercury).

The angle between the fault plane and σ_1 is of course dependent on the coefficient of friction of the material, but we stress that the differences between ice and rock are not great enough to produce wildly different conjugate shear angles. Values of the coefficient of friction for ice under confining pressures ≤ 5 MPa range from 0.55 to 0.69 (Beeman et al., 1988), compared with 0.85 for rock (Byerlee, 1978). Laboratory experiments show the most favorable orientation for slip is $\sim 30^\circ$ from σ_1 (Beeman et al., 1988). A smaller coefficient of friction would result in larger angles between σ_1 and the conjugate shear plane, and friction coefficients as low as 0.2 (appropriate for ice at higher confining pressures, ≥ 10 MPa) would only result in conjugate shears at $\pm 40^\circ$ to σ_1 (Beeman et al., 1988). Five-to-ten MPa corresponds to depths of approximately 20–40 km on Iapetus. Faults that originate at or propagate to greater pressures (depths) than 5–10 MPa should experience lower friction (Beeman et al., 1988). Strike-slip faults that originate at these depths may propagate to the surface and present at these angles. Nevertheless, the classical prediction from despinning theory is still for faults to form, from the equator to mid latitudes, at more-or-less acute angles to E–W. Consideration of a thinner (insolation-controlled) lithosphere at the equator does not change this conclusion (Beuthe, 2010). And we can make a stronger statement: no combination of despinning, global contraction, or thinner equatorial lithosphere predicts shear failure at acute angles to the N–S direction.

Thus, the concentration of lineament orientations between $\pm 40^\circ$ from N does not support a despinning origin. A preference for a more N–S orientation could be construed to be consistent with *respinning* stresses, however, provided there was an even earlier, *less oblate* Iapetus, plus some plausible respinning mechanism. Certainly, tides from Saturn will not have this effect. Ip (2006) proposed a collapsed ring remnant origin for the Iapetus ridge, and in this case, infalling ring material would act to spin up the satellite. For a ring mass of $\sim 0.1\%$ of the mass of Iapetus orbiting at the Roche limit, however, the corresponding angular momentum gain would only be $\sim 1\%$ of that of Iapetus rotating with a 16.5 hr period. Recently an elaboration of Ip's collapsed ring hypothesis has been proposed. Walsh et al. (2011) offer that the ring-forming impact itself may have spun up Iapetus to an ~ 16 h rotation rate. Although it is not necessary that a mid-sized icy satellite achieve a more rapid primordial spin through a single discrete "giant" impact (as opposed to the integrated effect of more modest impacts), if the shape response of Iapetus to the angular momentum input was sufficiently delayed, a tectonic respinning signature is not inconceivable. One would then have to ask which should be more apparent, tectonic effects due to respinning or those caused by the initial impact, and indeed if there is any trace on Iapetus' surface of the original impact structure (cf. Dombard et al., 2010).

An alternative, but one that might have the same effect as true respinning, might be the proposed pore collapse and buckling model of Sandwell and Schubert (2010). The degree-2 buckling proposed in this model to account for Iapetus' present oblate shape would have the same geometric effect as respinning. The Sandwell and Schubert model does not conserve volume, however (the buckling is triggered by pore collapse in the interior), and thus Iapetus is subject to very strong global compression as well. The predicted fault patterns at mid-to-low latitudes would be thrust (compressive) faults striking E–W on average, and this would remain true even if the equatorial lithosphere were thinner (Beuthe, 2010). This pattern is not seen. Ultimately, it may simply be that the fault and

joint structures in Iapetus' upper lithosphere reflect other stress sources than those due to despinning or respinning, sources such as thermoelastic stresses, discrete impact effects, or global volume changes.

4.2. Lithospheric thickness and failure

Do we have any independent limits on Iapetus lithospheric thickness? Certainly, if Iapetus spun down from an ~16 h period, it would have had to maintain its shape. And of course, Iapetus may have spun down from a somewhat shorter spin period to the point where it was frozen in its present 16.5 h shape. Using Love number theory, the flattening f of a hydrostatic body can be written as

$$f = h_2^s \frac{\omega^2 a^3}{2GM}, \quad (1)$$

where h_2^s is the secular degree-2 displacement Love number, ω and a are (as before) the angular rotation rate and mean radius, respectively, G the gravitational constant, and M is the mass of the body. For a homogeneous, elastic (but incompressible) body of density ρ and shear modulus (rigidity) μ ,

$$h_2^s = \frac{5}{2} \left(1 + \frac{19\mu}{2\rho ga} \right)^{-1}, \quad (2)$$

a very well known result (e.g., Munk and MacDonald, 1960). This result can be extended to a compressible elastic sphere. Hurford et al. (2006) give flattening curves (their Fig. 5) as a function of $\rho ga/\mu$ and μ/λ , where λ is the first elastic Lamé coefficient ($\equiv 2\mu\nu/(1-2\nu)$) = 6.5 GPa for ice, where ν is Poisson's ratio). For Iapetus, the compressible flattening is only a few percent larger than the incompressible value (Eq. (2)). This is the maximum effect of compressibility on the flattening expected; for a two-layer model, in which an elastic lithosphere of thickness H overlies an inviscid interior or "core," the effect of compressibility on the flattening is smaller still, and vanishes as $H/a \rightarrow 0$ (Melosh, 1977).

Therefore, for Iapetus flattening estimates we can ignore compressibility effects, and write a more general relationship for a uniform density, two-layer model:

$$h_2^s = \frac{5}{2} \left(1 + f(H/a) \frac{19\mu}{2\rho ga} \right)^{-1}, \quad (3)$$

where $f(H/a)$ is a function whose limit is simply 1 as $H/a \rightarrow 1$ and of order H/a as $H/a \rightarrow 0$. In the thin lithosphere limit, the second term in the parenthesis of Eq. (3) is of order $100(H/a)$, which illustrates how resistant Iapetus would be to adjusting its flattening unless its elastic lithosphere were quite small ($H/a \ll 1$). In Fig. 9 we show the final flattening, $f = f_i + \Delta f$, predicted for various initial spin periods ranging from 10 h to 16.5 h as a function of lithosphere thickness, based on Melosh (1977). For this range of spin periods, the linear relationship between flattening f and ω^2 in Eq. (1) holds, more-or-less; for more rapid rotations, the hydrostatic relation (Eq. (1)) becomes increasingly inaccurate. The minimum primordial spin period that Iapetus could have ever experienced, and still be consistent with its present shape, is near 6 h, at the transition from a biaxial to triaxial equilibrium figure (see Weidenschilling, 1981). That is, whatever its primordial spin state, we have no evidence for a fossil triaxial figure.

Taken at face value, Fig. 9 would seem to imply that a primordial Iapetus spinning at a modestly faster rate than 16.5 h (say, under 15.5 h) could have spun down to a 79.3 d period, yet ultimately preserve the biaxial figure appropriate to a body rotating at 16.5 h, as long as the lithosphere was thin enough. The result is unphysical, however, as the calculation in Fig. 9 assumes the lithosphere remains arbitrarily strong. The stresses generated in such thin

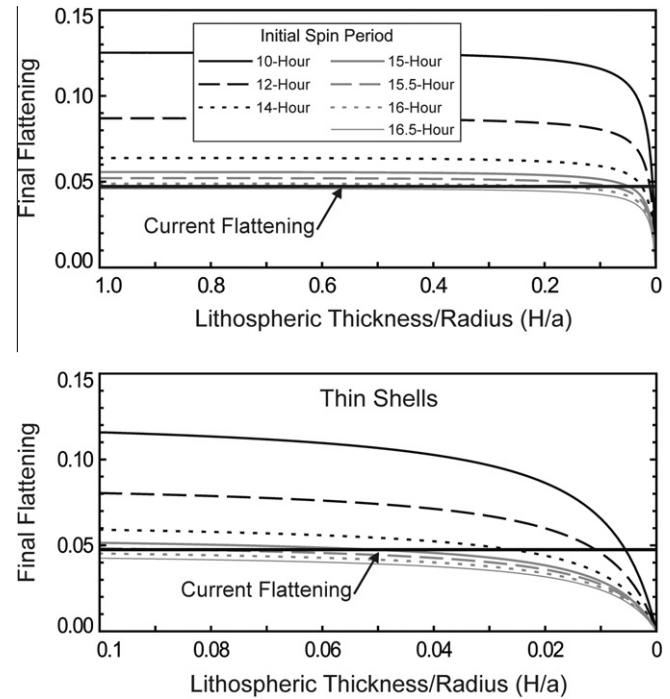


Fig. 9. Final flattening, $f = f_i + \Delta f$, predicted for different initial spin periods, as a function of lithospheric thickness. Hydrostatic initial flattenings, f_i , correspond to initial spin periods from 16.5 h to 10 h, and the final period is 79.3 days in all cases. Iapetus and ice parameters are the same as in Fig. 1 ($\nu = 0.5$); differences between compressible and incompressible flattening adjustments would not be noticeable in this plot. Bottom plot shows lithospheric thicknesses between 0% and 10% of the radius in order to focus on details near the thin lithosphere limit. This plot indicates the thickness of the lithosphere that allows relaxation to a 16.5-h shape for a purely elastic shell overlying an inviscid interior. The final flattening does not change substantially between the elastic spheroid endmember and an $H/a \sim 0.2$. The true thickness would depend on the extent of faulting in the lithosphere, discussed further in the text.

lithospheres would be enormous (e.g., Fig. 1), far greater than the strength of even cold ice. The true limits on Iapetus' primordial lithosphere thickness (that during spindown) and initial rotation rate must come from an assessment of the resulting stresses with respect to the strength profile of lithosphere, which we turn to next.

We evaluate the magnitude of despinning stresses with the *effective shear stress* (the square root of the second invariant of the stress deviator, σ'_{ij}):

$$\tau_{\text{eff}} \equiv \sqrt{J_2} = \sqrt{\frac{1}{2} \sigma'_{ij}^2}, \quad (4)$$

where indices are summed (e.g., Ranalli, 1995). In terms of the despinning geometry,

$$\sqrt{J_2} = \sqrt{\frac{1}{6} [(\sigma_{rr} - \sigma_{\theta\theta})^2 + (\sigma_{rr} - \sigma_{\phi\phi})^2 + (\sigma_{\theta\theta} - \sigma_{\phi\phi})^2]} + \sigma_{r\theta}^2, \quad (5)$$

where σ_{rr} and $\sigma_{r\theta}$ are the radial and shear stresses in the interior of the lithosphere (zero at the surface) (see Jaeger et al., 2007, chapter 2). For illustration, we plot $\sqrt{J_2}$ as function of depth and latitude in Fig. 10 for three lithosphere thicknesses (50 km, 100 km, and 150 km), and all for an initial Iapetian spin period (and corresponding hydrostatic figure) of 16.5 h. For faster initial spins, stresses can be scaled as ω^2 . In each case in Fig. 10 the effective shear stress depends on position within the lithosphere, but for a given lithosphere thickness the overall stress level is similar. For thicker lithospheres, $\sqrt{J_2}$ at depth is notably lower at the poles and greater at the equator (an effect of bending).

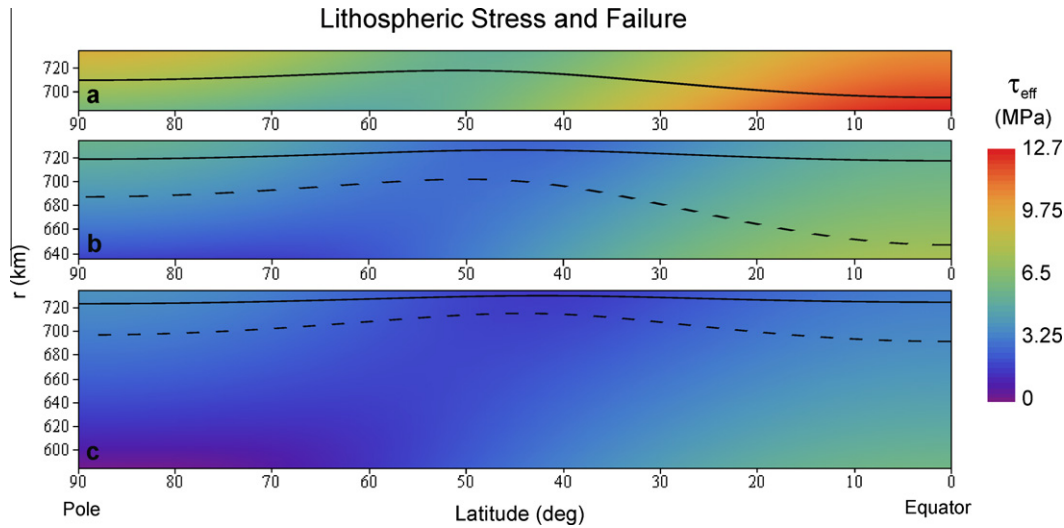


Fig. 10. Effective shear stress (τ_{eff} , or square root of the second invariant of the stress deviator, $\sqrt{J_2}$) plotted for three Iapetus lithosphere thicknesses: (a) a 50 km, (b) 100 km, and (c) 150 km. Iapetus is assumed to be compressible ($\nu = 0.325$; Petrenko and Whitworth, 1999) and initially rotating with a 16.5 h period. The magnitude of the effective shear stress experienced at different locations in the lithosphere can be compared with the shear strength profile in Fig. 11 to predict whether failure will occur, depending on the tectonic regime. The solid line indicates the depth to which failure in compression is likely (thrust faulting), and the dashed line indicates the depth to which failure in extension is likely (normal faults and graben). Out of these three cases, only the 50 km lithosphere experiences significant failure, indicating that Iapetus would likely need a lithosphere thicker than 50 km to support its observed biaxial shape.

The strength profile of the lithosphere depends on the nature of the stresses developed within it, but here we examine Mohr–Coulomb failure for the classic limiting cases of uniform horizontal extension and compression. We follow the development of Beeman et al. (1988), but for low mean stress (pressure) adopt their experimentally determined relation between shear (τ) and normal stress (σ_n) constrained to pass through the origin, $\tau = 0.69\sigma_n$. We do this because (1) Beeman et al. (1988) state that the apparent finite cohesion of their saw-cut ice samples may be an artifact of their indium jacketing; (2) the lithosphere of Iapetus is almost assuredly deeply impact fractured, if not a reworked megaregolith; and (3) this relation is most comparable to the equivalent for rock, Byerlee's rule, $\tau = 0.85\sigma_n$.

Given this proviso, the maximum supportable differential stress ($\Delta\sigma_f$) at depth in the lithosphere is given for the horizontal compression case by

$$\Delta\sigma_f = 2.63\sigma_{rr} \quad \sigma_{rr} \leq 9.5 \text{ MPa} \quad (6a)$$

$$= 20.2 \text{ MPa} + 0.49\sigma_{rr} \quad \sigma_{rr} > 9.5 \text{ MPa}, \quad (6b)$$

and for the horizontal extension case by

$$\Delta\sigma_f = 0.72\sigma_{rr} \quad \sigma_{rr} \leq 35 \text{ MPa} \quad (7a)$$

$$= 3.6 \text{ MPa} + 0.33\sigma_{rr} \quad \sigma_{rr} > 35 \text{ MPa}, \quad (7b)$$

and σ_{rr} is assumed to be hydrostatic ($=\rho gz$, where z is depth). These strength limits are illustrated in Fig. 11, where $\Delta\sigma_f/2$, the maximum supportable shear stress, or “shear strength,” is plotted. The shear strength in compression is much greater than that in extension, as is well-known. Shear strength in pure shear ($\sigma_{\theta\theta} = -\sigma_{\phi\phi}$) is an intermediate case (not plotted).

Comparing the strength profiles (Fig. 11) to the stresses at depth (Fig. 10) can provide a gauge of where failure is possible in the lithosphere. The effective shear stress ($\sqrt{J_2}$) corresponding to the shear strength (sliding friction) limits in Fig. 11, assuming an initial hydrostatic state and $\sigma_{\theta\theta} = \sigma_{\phi\phi}$, is simply given by $\Delta\sigma_f/\sqrt{3}$, which is essentially the same as the shear strength implied by Eqs. (6) and (7), $\Delta\sigma_f/2$ (and which is plotted in Fig. 11). For pure shear the correspondence is exact. In Fig. 10, the effective shear stress contour $\sqrt{J_2}$ that equals $\Delta\sigma_f/2$ in compression from Fig. 11 is shown as a solid line, and as a dashed line for the extension case. These are plotted as a guide to the eye, but the depth of brittle failure depends on

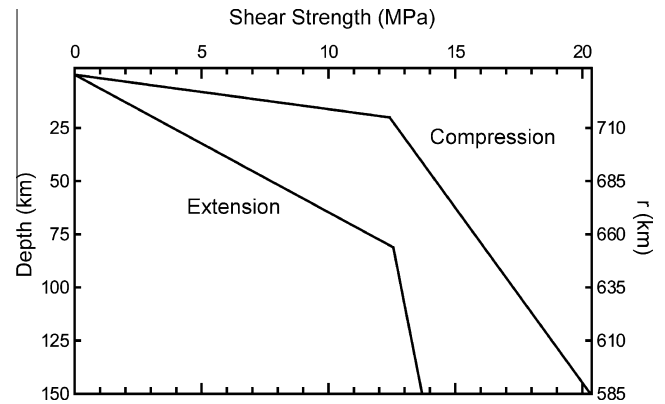


Fig. 11. Shear strength (maximum supportable differential stress divided by 2) as a function of depth in Iapetus' lithosphere for the endmember cases of uniform horizontal compression and uniform horizontal extension (Beeman et al., 1988).

the tectonic regime, which in turn depends on latitude and longitude. For example, at latitudes where normal faults are expected (towards the poles), $\sqrt{J_2}$ should exceed $\Delta\sigma_f/2$ in extension at depths shallower than the dashed contour, but not at greater depths. Conversely, in tectonic provinces where both surface stresses are compressional, brittle failure might be expected up to the depth of solid contour. Finally, if strike-slip is predicted, brittle failure should extend to a depth intermediate to the two contours. We can now apply these interpretations to the stresses in our despun Iapetus lithospheres.

For a 150-km-thick lithosphere (Fig. 10c), the shear stress levels exceed that necessary for failure only at the very top of the lithosphere, regardless of tectonic regime or province. Most of the lithosphere cannot fail brittlely, and the amount of flattening thus realized (from Fig. 9) is negligible. For the 100-km-thick lithosphere (Fig. 10b), the portion of the lithosphere in failure extends to greater depths from the surface, and especially so near the poles where both tectonic despinning stresses would be extensional (Eq. (7a)). Nonetheless, most of the lithosphere is not in failure, and this remainder should be more than thick enough to largely (though not completely) suppress any flattening adjustment. In the case

of the 50-km-thick lithosphere, stress levels are now much higher, and the strength of the lithosphere markedly reduced. Comparing Fig. 10a with Fig. 11, most of the lithosphere has failed, especially where extensional stresses are involved. Moreover, as lithospheric failure spreads deeper, the remaining elastic portion must “pick up the slack,” further increasing shear stress levels, at least until the lithosphere fails (faults) completely, releasing much of the accumulated elastic strain.

A detailed model of lithospheric failure during despinning is not the principal purpose of this paper and would require numerical evaluation to be accurate, but the results presented here suggest that the elastic lithosphere of Iapetus was *no less than* 50-km thick during and after despinning, given that 16.5 h was likely the *minimum* primordial spin rate. Otherwise, Iapetus could not present the biaxial figure it has today. Even a 100-km-thick lithosphere may not be quite enough, considering the depth of despinning-driven faulting, stress concentration in the remaining elastic portion, and the fact that the primordial spin rate must have been higher than 16.5 h (implying higher stresses) to account for some flattening relaxation (Fig. 9). We note that the lithosphere need not have been several 100-km thick (Castillo-Rogez et al., 2007; Beuthe, 2010), though on the basis of shape preservation alone it certainly could have been.

Leaving aside Iapetus' fossil bulge, the lack of an explicit tectonic signature of despinning is itself suggestive of a much thicker lithosphere during and after despinning and thus an initial spin period close to 16 h (Beuthe, 2010). The heavily cratered and thus ancient surface of Iapetus may not, in the end, preserve much of this signature. Near-surface shear stresses of a few MPa (e.g., Fig. 10b) imply elastic strains of order 0.1–0.2%: even faults 10s of km deep may only have initially resulted in offsets of several 10s of meters. The surface expressions of most such faults may have long since been erased, leaving only a poorly expressed lineament grid as a palimpsest. Ultimately, it is Iapetus' nonhydrostatic figure that provides the evidence for Iapetus' primordial spin and the best constraint on its lithospheric evolution.

4.3. The equatorial ridge

No discussion of Iapetus' tectonics is complete without consideration of the equatorial ridge, although we argue here that the ridge is unlikely to be tectonic. The ridge, in terms of its N–S topographic symmetry, does not resemble a lobate scarp (as on Mercury) or the surface expression of some other asymmetric thrust fault. In terms a tectonic analogue, the best morphological match is provided by the high-relief ridges on Mercury (and some extent on Mars). These long, relatively broad landforms transition to lobate scarps on Mercury and thus are judged to be contractional features (Watters and Nimmo, 2010; Watters et al., 2009). Though high-relief ridges can be linear over several 100 km length (e.g., Watters et al., 2009), none match the length of equatorial ridge of Iapetus (which essentially circles the satellite). It is in fact rare to find a tectonic feature on any planet or satellite that maintains such a constant strike. The closest on the icy satellites are the great-circle lineaments of Europa (Kattenhorn and Hurford, 2009). These latter are thought to be extensional and/or strike slip ridge features formed in a simple tidal stress environment and, apparently, within a mechanically simple and intact or annealed (as opposed to heterogeneous and broken up or fractured) and relatively thin, ice lithosphere. Whereas the driving stresses on Iapetus are also likely to be geometrically simple, its lithosphere was doubtless deeply fractured, if not shattered, by the early impact pummeling the satellite clearly took. There is no evidence for endogenic rejuvenation on Iapetus, thermal or otherwise.

Even more problematic for any tectonic origin model is that the ridge lies *precisely* on Iapetus' equator. Compressional stress due to

despinning does maximize at the equator (Fig. 1; Melosh, 1977) and the maximum compressive principal stress direction can be switched from E–W to N–S if the equatorial lithosphere is sufficiently thin compared to the global average and a sufficient amount of global contraction also occurs (Beuthe, 2010). However, even if a fault could localize initially somewhere along the equator, what fracture or fault (or system thereof) could hew so closely to a fixed latitude (of zero) as it propagated? Real fractures/faults and fracture/fault systems veer and kink, they splay and anastomose, and parallel and subsidiary fractures and/or faults almost certainly develop. On Iapetus, there are no parallel or sub-parallel ridges or thrust scarps north or south of the ridge that we can see in the available imagery. As noted earlier we do see a set of parallel E–W lineaments between 220 and 350 km north of the ridge (18° to 26°N), and in what could be a mostly compressional tectonics province for lithospheres >150-km thick (Figs. 4 and 6). These lineaments express as a set of relatively narrow, somewhat discontinuous troughs, but their specific tectonic origin is otherwise enigmatic.

In our view, the sum of these geometric considerations preclude any endogenic tectonic (or volcanic, for that matter) origin for the equatorial ridge. The only ridge origin scenarios that make physical sense (to us) so far invoke the gravitational potential minimum at the equator of an oblate body as the localizing mechanism. These include, but are not limited to, the collapsed ring hypothesis of Ip (2006), as noted in Section 4 (e.g., Dombard et al., 2010). Further discussion along these lines is beyond the scope of this paper.

5. Conclusions

The global distribution of linear features on Iapetus does not show an obvious connection to despinning. The morphology of the features varies but we see no specific evidence of contraction (thrust faults) or strike-slip offsets, the two types of faults predicted to form in equatorial to mid-latitude regions from despinning. Our discussion of the stresses and faulting in Iapetus' lithosphere shows that the lithosphere would need to be at least 50 km thick (and probably greater) for Iapetus to be (and have been) “frozen” in its current biaxial shape. In addition, the relatively low effective shear stresses that would occur in a lithosphere 100 km or thicker would not result in large strains or considerable offsets if faults occurred. Thus, if Iapetus did have a tectonic signature from despinning it may have been largely obscured over time. Finally, we consider it highly unlikely that the equatorial ridge is a tectonic or volcanic feature, as it is such a large, continuous feature

Table 2
Typographical corrections for Melosh (1977).

Equation number in Melosh (1977)	Amended equation
4	$m = \frac{\omega^2 a^3}{GM}$
A24	$p_m(\text{core}') - p_c(\text{core}') = (\mu\kappa/6)\eta(\eta - 1)\phi^2(f_i - f'_i)(1 - 3\cos 2\lambda)$
A25	$= -(1/6)(f - f')(1 - 3\cos 2\lambda)a$ $= (\alpha_1 + \alpha_2 a^2 + \alpha_3 a^{-3} + \alpha_4 a^{-5})(1 - 3\cos 2\lambda)a$
A26	$f - f' = -6(\alpha_1 + \alpha_2 a^2 + \alpha_3 a^{-3} + \alpha_4 a^{-5})$
A27	$= -(1/6)(f_i - f'_i)(1 - 3\cos 2\lambda)b$ $= (\alpha_1 + \alpha_2 b^2 + \alpha_3 b^{-3} + \alpha_4 b^{-5})(1 - 3\cos 2\lambda)b$
A28	$f_i - f'_i = -6(\alpha_1 + \alpha_2 b^2 + \alpha_3 b^{-3} + \alpha_4 b^{-5})$
A29	$[M_{ij}] \begin{bmatrix} \alpha_1 \\ \alpha_2 a^2 \\ \alpha_3 a^{-3} \\ \alpha_4 a^{-5} \end{bmatrix} = \begin{bmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \end{bmatrix}$
Table A1.B	The inhomogenous α and β should all be multiplied by 4
Table A1.I	Matrix same as A29

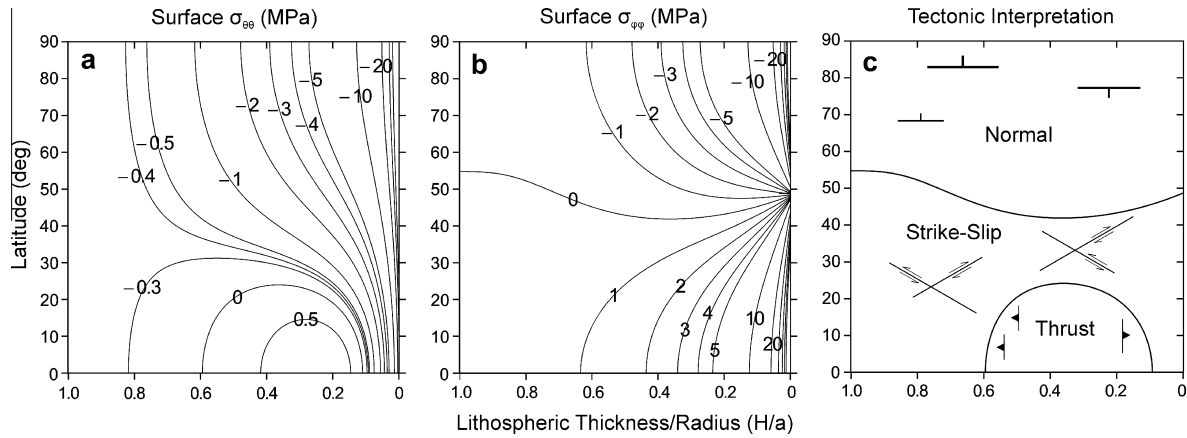


Fig. 12. Surface stresses for a despun, compressible Iapetus. All parameters are the same as in Fig. 1 except $\nu = 0.325$. (a and b) Surface stress as a function of lithospheric thickness and latitude. (c) Tectonic interpretation based on stresses in a and b.

with a constant strike, and has no other nearby lineaments, faults, or other structures associated with it. The ridge is sufficiently unlike other tectonic or volcanic features in the Solar System to suggest alternate hypotheses be seriously considered.

Acknowledgments

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Appendix A. Despinning stress solution

We calculate lithospheric despinning stresses following the appendix of Melosh (1977). Typos in that paper are corrected as shown in Table 2. For definition of terms see Melosh (1977).

We note that substitution of the homogeneous solution flattenings (Melosh equations (A26) and (A28)) into the boundary conditions (his equations (A19) and (A20)) do not give his auxiliary quantities A_2 , B_2 , or K_2 . Use, however, of Melosh's A_2 , B_2 , and K_2 does produce the proper surface flattenings and stresses for our model Iapetus when incompressible (albeit fortuitously, see below), and the proper flattening and stresses in the thin lithosphere limit in the compressible case for Iapetus in particular (Fig. 12). M. Beuthe (personal communication, 2011) suggests an alternate boundary condition between the elastic lithosphere and inviscid core, and derives

$$A_2 = \frac{\kappa}{7} \left(\frac{6-5\nu}{1-\nu} \right) \frac{(1-H/a)^2}{10} (1-\eta) \quad (\text{A.1})$$

$$B_2 = \frac{\kappa}{30} \left[\left(\frac{1-5\nu}{1-\nu} \right) (1-\eta) - 5\eta \right] (1-\eta) \quad (\text{A.2})$$

$$K_2 = \frac{\kappa}{12} \left[\frac{1}{7} \left(\frac{6-5\nu}{1-\nu} \right) \right] (1-H/a)^2 (\Gamma - \Gamma') (1-\eta), \quad (\text{A.3})$$

which yields the correct stresses in the incompressible limit for arbitrary values of η , κ , Γ , and Γ' are defined in Melosh (1977), and η is the density ratio between the inviscid interior and the lithosphere. In our Iapetus models, $\eta = 1$, and both Melosh's A_2 , B_2 , and K_2 and Eqs. (A.1)–(A.3) are thus all identically equal to zero in the incompressible limit. The compressible case corresponding to Fig. 1 is shown in Fig. 12. The stress patterns are quite similar, as

expected, and the flattenings are close (Section 4.2). Stress differences are higher for the incompressible case, however, by up to 10%.

We note that Melosh's derivation assumes an internal gravitational potential (and the pressure derived from the potential) appropriate for a uniform density lithosphere, and so is in this sense approximate for a compressible lithosphere. It is, however, increasingly accurate (for $\eta = 1$) for thinner lithospheres, and can be shown to be exact as $H/a \rightarrow 1$, as long as $\kappa (= \rho g a / \mu$ for $\eta = 1$) is small, which it is for Iapetus. Hence we retain his solution for Fig. 10. Other methods and approaches exist for calculation of lithospheric stresses due to tides and rotations (e.g., Sabadini and Vermeersen, 2004; Wahr et al., 2009; Beuthe, 2010; Matsuyama and Nimmo, 2008, and references therein), but comparison of these approaches and Melosh (1977) is beyond the scope of this work.

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