An exceptionally high-standing ridge on Enceladus

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Abstract

Cassini stereo-derived topography reveals an exceptionally high-standing, sawtooth-shaped ridge in Enceladus' Samarkand Sulcus. Over a length of ~100 km and of a width of ~10 km, it reaches elevations of up to 1750 m, which makes it the highest ridge observed on Enceladus so far. Flank slopes reach 40°. The morphology of the ridge suggests that it formed by rift flank-uplift caused by extension. However, shear motion has significantly changed the shape, in particular shear related compression is likely to have emplaced the high-standing portions of the ridge. To support the load of the ridge, the effective elastic thickness of the lithosphere at present time must be larger than 1.5 km. Stratigraphically tied to the Samarkand Sulci, the ridge is probably of similar age. If true, and assuming an asteroid-type impact chronology, it may be as old as 3.7 Ga, and assuming a comet-type impact chronology it could only be 20 Ma.

1. Introduction

During Cassini's 228th orbit around Saturn the on-board camera imaged a prominent ridge in Enceladus' Samarkand Sulcus (Fig. 1). First seen in 1 km/pxl Voyager images, the ridge appeared as a positive relief feature up to 1.5 km high [1] and bounded by grooves, which led to the suggestion that it originated from extension [2]. However, this view changed with evidence provided by higher resolution Cassini orbit 003 images (130 m/pxl). From their analysis it was concluded that the ridge formed primarily by compression [3,4].

The new images from orbit 228 are of highest resolution (down to 63 m/pxl) and, most importantly, include stereo coverage of the surface which provides previously unavailable 3D information (Fig. 1). (i) We show that these data are most consistent with the ridge having formed in result of rift flank-uplift caused by extension. (ii) We compare the ridge with other ridges on Enceladus to demonstrate its exceptional height, (Fig. 2), (iii) We consider the ridge as a probe of lithospheric thickness and calculate a lower limit of the effective elastic thickness. (iv) We scrutinize the dark spots on the sun-facing eastern side of the ridge whose nature is still unclear. (v) We used crater size-frequency counts to constrain the age of the ridge [5].

2. Observations

(1) The ridge observed here is morphologically similar to a ridge observed in Enceladus' Harran Sulcus (comp. Fig. 2b and 2e). But there are specific differences. This ridge consists of a lower part and an upper part (Fig. 2a, sections A-B and C-E, respectively)), which stands 600 m higher on average. The upper part itself consists of sections C-D and D-E, respectively, with section C-D being angled slightly off section D-E (Fig. 2a, DEM).

(2) The morphology of the upper part suggests that it experienced substantial uplift (Fig. 2b, p2-p7), which appears to be related to the presence of faults at the western edge (Fig. 3). As a result, ramps and a trapezoidal-like shape developed, and individual km-scale ridges protrude from the flank (Fig. 2b).

(3) Ramps and a trapezoidal-like shape with correlation to faults are also observed at the lower part of the ridge (Fig. 2b, p9 and p10; Fig. 3 left, white arrows).

(4) On its eastern side, the ridge is bounded by a pronounced V-shaped trough. The trough runs roughly straight from south to north and is similarly pronounced all the way along the ridge (Fig. 2a).

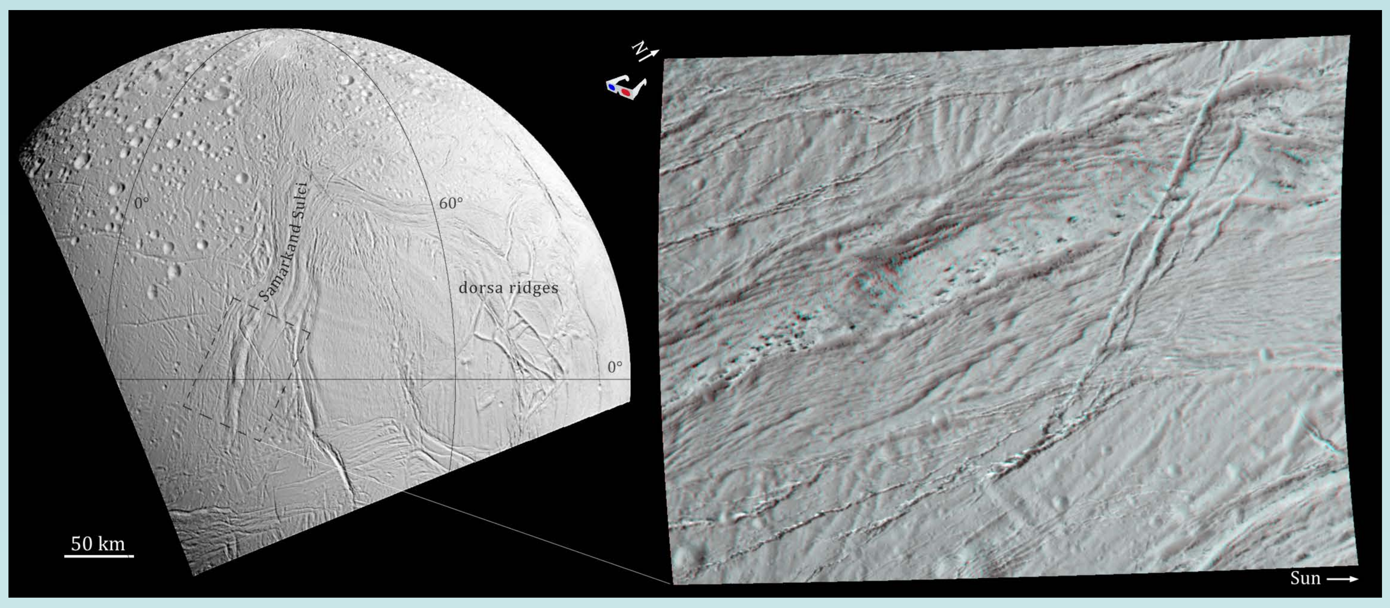

Fig. 1: Location of the ridge and anaglyph image showing a 3D display.

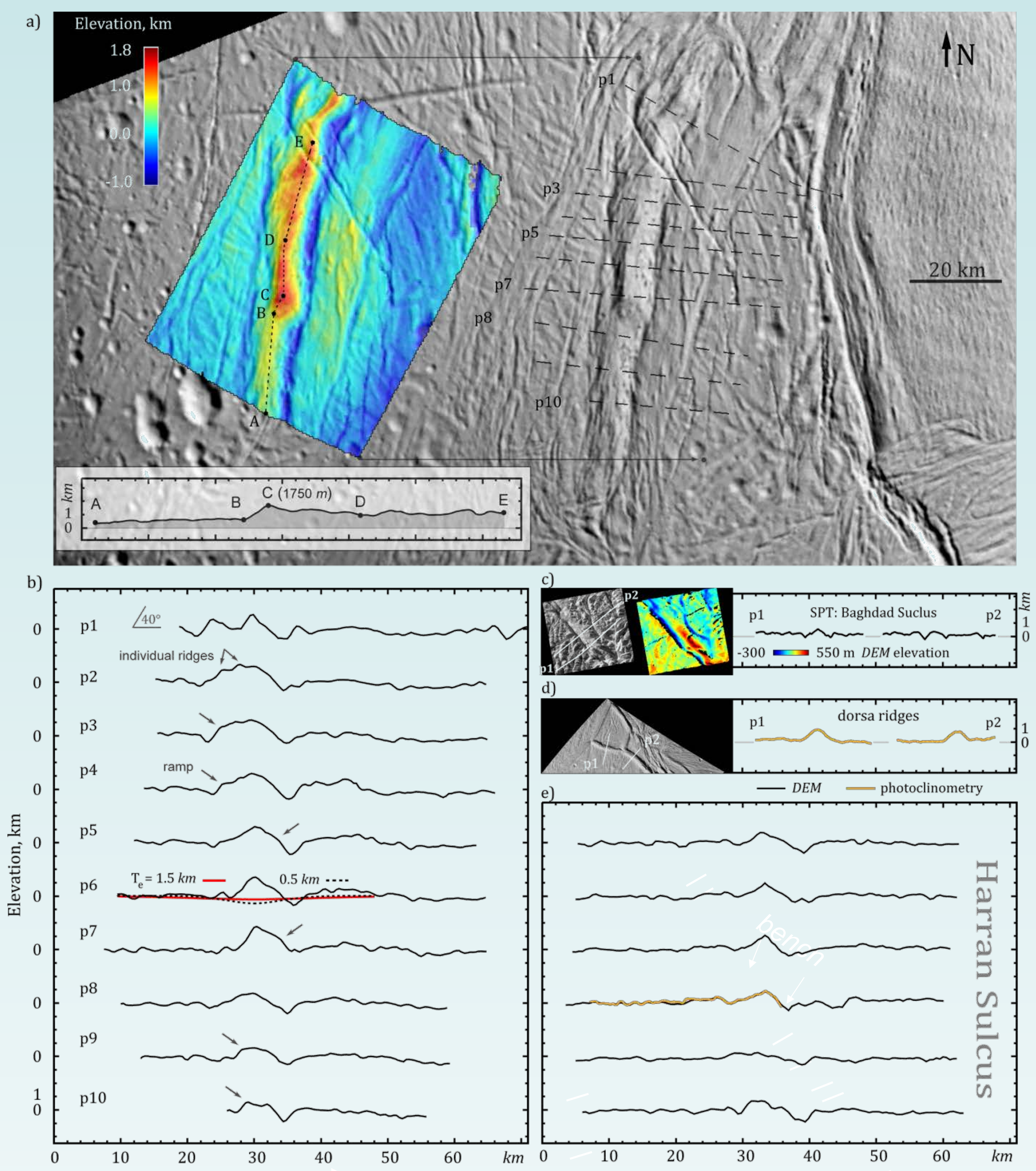

Fig. 2. (a) Color-coded Digital Elevation Model (horiz. res. 400-900 m, vertical point accuracies < 30 m) and along-ridge profile. (b) DEM-derived profiles as indicated in a). p6, red and dotted line: flexural model profiles derived from a line load model. (c) Ridges in the South Polar Terrains with elevations of a few hundred meters [6]. (d) Dorsa ridges on the trailing hemisphere (Fig. 1) [4] with elevations reaching 900 m. (e) DEM-derived profiles in Harran Sulcus [7]. Photoclinometry profile (orange) shown in comparison with DEM data to verify the applied photometric model.

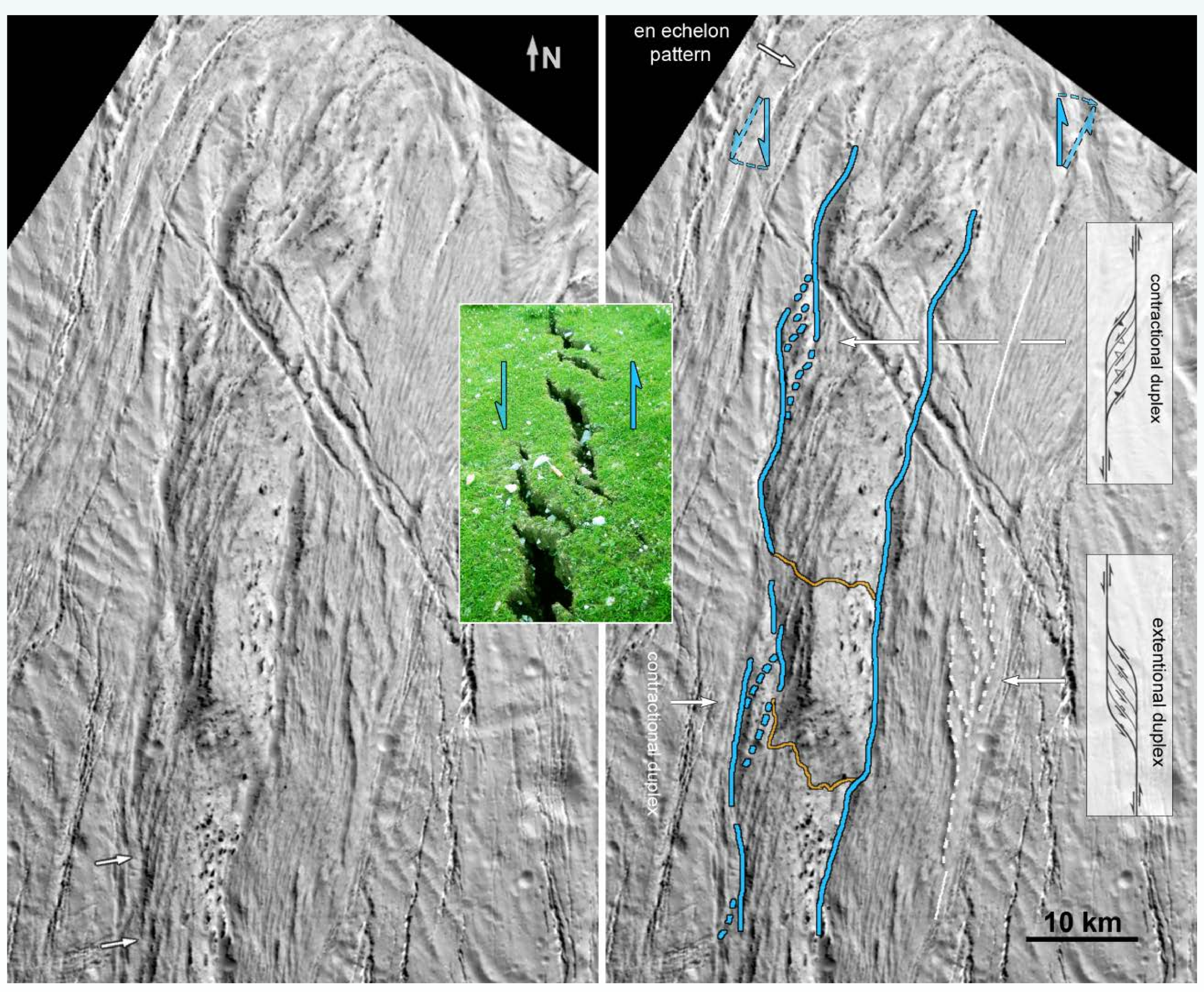

Fig. 3, Sketch map of fault structures (blue) at the boundaries of the ridge. Orange lines mark structural boundaries identified on the basis of the anaglyph image (Fig. 1). White dashed lines map fault structures in the adjoining band. (Center inset) Photograph of en echelon tensional cracks formed during an earthquake in the central Tibetan plateau in 2010 (courtesy of Aiming Lin). These cracks are right-stepping and sigmoidal in planar view, similar to the cracks observed here, and result from left-lateral strike-slip motion [8].

(*observations continued*)

An exception is the transition zone B-C between the upper and lower part where the trough has an obvious narrowing (Fig. 2a; 2b, p7). On its western side, the ridge is bounded by right-stepping sigmoidal faults [4] and associated duplex structures (Fig. 3).

(5) While the west facing flank has a grooved appearance with a grain similar to that of the surrounding band to the east, the east facing flank has not. This flank exhibits in particular a pattern of dark patches spotted in some places and with a linear shape in other places (Fig. 1, anaglyph). The linear forms are aligned with the grooves on the western flank and appear to be fragments of ridges protruding from the flank.

(6) The ridge reaches elevations of 1750 m above the surroundings and is thus higher than all other ridges measured on Enceladus so far (Fig. 2 b-e).

3. Lithospheric Thickness

The upper part of the ridge stands on average 1.3 km above the surroundings and thus poses a considerable load on the ice shell of Enceladus. To simplify the problem we neglect the horizontal extension of the ridge and consider a line load model [9]. Fig. 2b shows deflection profiles for different elastic thicknesses T_e. These demonstrate that for T_e < 1.5 km the lithosphere would experience downward bending by more than 200 m, which would be revealed by our DEM data but which is not observed (Fig. 2b: p5, p6, p7). Thus T_e must be ≥ 1.5 km.

4. Discussion and Conclusion

Our observations are most consistent with the following formational scenario: The region occupied by the ridge today was initially part of the eastern grooved band, which formed by extension. In a late stage of band formation (or thereafter), strain focused in the center of the band and created a deep fault and finally a trough. In result, ductile ice at depth rose isostatically towards the surface thus flexing the lithosphere and creating the saw-tooth shape of the ridge, and with it its two facies. Subsequently sinistral shear motion, as suggested by the similarity of the observed fault pattern with earth observations (Fig. 3), in concert with right-stepping faults and associated compression has modified the shape. This includes the formation of exceptionally high terrain portions, ramps, duplex structures, the narrowing of the eastern trough, and the small-scale fragments sticking out of eastern flank. The latter cause shadows in sunlight which explains a previously puzzling pattern of dark spots. Consistent with that: image-brightness profiles across the spots show the same constant brightness value in the core of their shadows.

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