Earth and Planetary Science Letters 389 (2014) 43–51

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The ridges of Europa: Extensions of adjacent topography onto their flanks

Richard Greenberg[a,*], Peter B. Sak[b]

[a] Lunar and Planetary Laboratory, University of Arizona, 1629 East University Blvd., Tucson, AZ 85721, United States
[b] Department of Earth Sciences, Dickinson College, Carlisle, PA 17013, United States

ARTICLE INFO

Article history:
Received 11 January 2013
Received in revised form 26 November 2013
Accepted 9 December 2013
Available online 7 January 2014
Editor: C. Sotin

Keywords:
Europa
ice
planetary satellites
tectonics
comparative planetology

ABSTRACT

The surface of Europa displays numerous generations of intersecting arrays of linear ridges. At some locations along these ridges, older ridges on adjacent terrain appear to extend up the flank of a more recent ridge. It has thus been suggested that the ridges may have formed by upturning of that adjacent terrain. However, the newer ridges generally appear to be material deposited over the older terrain. Here we consider how the morphology of the overprinted topography may have been inherited by the more recent ridges. An analogous process occurs along some sediment-starved convergent plate boundaries on Earth, where the poorly consolidated material of a frontal prism of an overriding plate is pushed over preexisting ridges and seamounts on the downgoing plate. The overriding plate inherits the morphology of the downgoing plate even though the actual extension of that topography has been underthrust and buried. A well-studied example lies offshore of Costa Rica where the Caribbean plate overrides the Cocos plate. Experiments show other mechanisms as well: mass-wasting down a flank can result in extensions of adjacent ridges thanks to the geometry imposed by a constant angle of repose; in addition, more pronounced extensions of the older ridges result if the new ridge grows as it is bulldozed from behind (i.e., from the central groove of a double ridge on Europa). The shapes of the ridge extensions are distinctly different in these two cases. If tidal pumping extrudes material to the surface at the center of a double ridge, it might drive the latter mechanism. The ridge extensions observed on the flanks of more recent ridges may provide a crucial diagnostic of dominant ridge-building mechanisms when and if additional images are obtained at high resolution from future exploration. In additional to their morphology, the distribution of ridge extensions at only isolated locales may also provide constraints on ridge formation processes and their diversity.

1. Introduction and background

The ubiquitous double ridges on Europa represent one of the most characteristic types of feature on the ice surface (e.g., Lucchitta and Soderblom, 1982; Belton et al., 1996; Greeley et al., 1998). In places, the double ridges cross over one another and are so numerous and densely distributed that they cover large portions of the surface where no other geomorphic features are visible (e.g. Fig. 1). Those double ridges that have not been cut by more recent surface disruption or by tectonic displacement can extend for thousands of kilometers, often as part of interwoven complexes of ridges. In general, the larger ridges are ∼2 km wide with ∼200 m of relief (e.g. Greeley et al., 1998).

Many major ridges follow courses that correlate with tidal stress on the ice crust, suggesting that they line both margins of cracks in the surface, consistent with their ubiquitous doubled nature. Global-scale ridges roughly correlate with tidal stress on the ice crust, generally striking perpendicular to the direction of maximum tensile stress (σ_3), so ridges likely line both margins of mode I (tensile) fractures (e.g. Greenberg et al., 1998). Numerous double ridges follow cycloidal paths (i.e., chains of arcs) across the surface, a distinctive pattern that can be explained by propagation of tensile cracks as the tidal stress field changes through time (Hoppa et al., 1999a; Marshall and Kattenhorn, 2005; Hurford et al., 2007). In some cases the initial fracture associated with a subsequent double ridge may have involved other stress modes as well, but most models assume that ridges are predominantly tensile features (Kattenhorn and Hurford, 2009).

After the initial formation of a tensile crack in the crust, subsequent tidal working will tend to open and close the crack, with a period equal to the 85 hour orbital period. Greenberg et al. (1998) proposed that ridges could form if a crack extends through the crust and down to the liquid water ocean below. In that model the periodic working of the crack pumps up ocean water and squeezes newly frozen, crushed ice to the surface where it lines both sides of the crack.

---

* Corresponding author. Tel.: +1 520 621 6940; fax: +1 520 621 9692.
E-mail address: greenberg@lpl.arizona.edu (R. Greenberg).

http://dx.doi.org/10.1016/j.epsl.2013.12.009

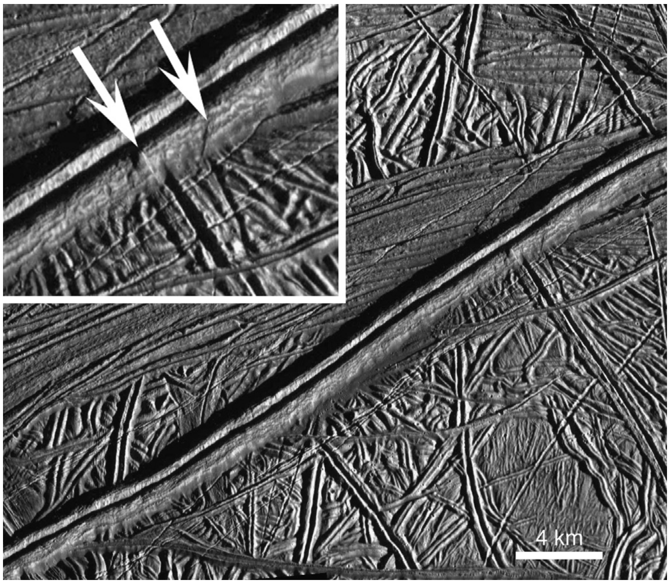

Fig. 1. A ∼45-km-long section of a large double ridge crossing a region of densely ridged terrain, just north of Conamara Chaos on Europa, imaged at very high resolution (21 m/pixel) during orbit E6 of the Galileo spacecraft. In general the outer flanks of the large ridge appear to be material emplaced over the surrounding terrain. In only a couple of places, features on the flank appear to be aligned with ridges in the surrounding terrain: One site about 1/4 of the way along the ridge from the right is enlarged in the inset at upper left; the other is along the lower-left-most 8 km. The arrows show two features on the flank identified as extensions of features on the adjacent terrain by Head et al. (1999), where they are displayed twice (their Figs. 3c and 4a).

An alternative model, proposed by Head et al. (1999), assumes that the cracks penetrate only through the uppermost brittle-elastic portion of the ice crust, while between the bottom of the cracks and the subjacent liquid ocean lies a thick (∼20 km or more) layer of viscous ice. In that model a linear diapir of upwelling ice in the viscous layer uplifts the edges of a crack creating the ridges, such that the outer slopes of the double ridges represent portions of the preexisting surface that were tilted outward during their formation.

That interpretation of double ridges as upturned lips of surface cracks is based on the observation of preexisting topographic lineaments that appear to continue from the surrounding surface up the outer slopes of some ridges. Evidence for this model was found in a particular study area (Fig. 1) just north of Conamara Chaos, where high-resolution images had been obtained by the Galileo spacecraft during orbit E6. This area contains a 45-km-long portion of one prominent double ridge that crosses terrain densely packed with smaller ridges. Of the many background ridges that intersect the main ridge, Head et al. (1999) reportedly traced over half of them at least halfway up the flank, although only six of these were identified and these all lie within a 6-km-long segment of the newer ridge.

These six lineaments on the flank of the more recent ridge could be interpreted as degraded, partial extensions of ridges on the adjacent terrain. However, only two of the six extend most of the way up the flank (Fig. 1). Moreover, one of these two examples (rightmost arrow in Fig. 1) is not actually aligned with the adjacent lineament. In part, perhaps, because the ridge described by Head et al. shows few compelling examples of older ridges running up its flank, the phenomenon has not been considered to be a significant or general characteristic of Europan ridges (Kattenhorn and Hurford, 2009).

That issue aside, other problems with this model have prevented its wide acceptance. Most importantly, no explicit mechanism was proposed to form diapirs that are linear and uniform along hundreds of kilometers. Moreover, the qualitative appearance of the ridges suggests to us material piled over the older terrain.

Fig. 2. A set of lineaments (AFRs) on the flank of a ridge near the south pole aligned with ridges in the surrounding terrain (Greenberg, 2005). This image is from the high-resolution south-pole sequence taken during Galileo orbit E17. Similar alignments seem unusually common in this region (Riley et al., 2006). This image shows an area 9 km wide. (At this site, the main ridge with the AFRs on its flank is part of a ridge pair that has been partially disrupted by subsequent cracking with incipient ridge formation.)

While there are good reasons to question the linear-diapir model, our examination of high-resolution images of Europa shows numerous examples of linear features on ridge flanks that are aligned as apparent continuations of older ridges on the adjacent terrain, in fact many more than those noted by Head et al. (1999). These features, which for conciseness we call “aligned flank ridges (AFRs)”, are clearly present along significant lengths of particular ridges.

Here (in Section 2) we present the results of a search for AFRs. Then we consider evidence that material pushed over older terrain, in a manner possibly analogous to what occurs in ridge formation on Europa, can inherit the topography of a buried surface: As discussed in Section 3, analogous features on Earth, specifically in the outer forearcs of many sediment-starved convergent margins where bathymetric highs (ridges, plateaus, and seamounts) on the underthrusting plate are transmitted through the thin, weak leading edges of the upper plate and expressed as highs which have similar dimensions to the features on the underriding plate Although most aspects of subduction-zone mechanisms are very different from what might occur at a ridge on Europa, the common aspect is a layer of weak material overlying preexisting morphology. In addition, qualitative laboratory-scale experiments demonstrate ways that aligned flank ridges can form on a ridge of unconsolidated material (Section 4). Finally, in Section 5 we discuss possible implications for ridge formation on Europa, and suggest that, as a diagnostic of this crucial process, investigation of aligned flank ridges should be an important objective of future spacecraft missions.

2. Observations of aligned flank ridges

Only a small portion of Europa’s surface has been imaged at a resolution adequate to resolve any AFRs. About 10% of Europa’s surface has been imaged at ∼200 m/pixel, mostly in the Regional Mapping sequences of the Galileo mission. At this resolution, even the flanks of the largest ridges are at most one or two pixels wide. In some locations on these images there is a hint of correlation with the surrounding terrain, but the resolution is inadequate for definitive identification. AFRs have been clearly visible only on images with resolutions better than ∼40 m/pixel, which are available only for a few selected locations, due the severe constraints of the Galileo spacecraft’s downlink data rate.

In addition to the ridge considered by Head et al. (1999) (Fig. 1), Greenberg (2005) noted an even stronger correlation of AFRs with adjacent terrain in high-resolution images (40 m/pixel) near Europa’s south pole (Fig. 2) (see also Riley et al., 2006).