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Formation of ridges on Europa above crystallizing water bodies inside the ice shell

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ABSTRACT

Jupiter's second Galilean satellite, Europa, is a Moon-sized body with an icy shell and global ocean approximately 100 km thick surrounding a rocky interior. Its surface displays extensive tectonic activity in a geologically recent past. Europa's most ubiquitous surface features, double ridges, have a central trough flanked by two raised edifices. Double ridges can extend hundreds of kilometers and appear genetically related to cracks formed in the Europan ice shell. The origin of the raised flanks has been the center of much debate and many models have been proposed. There are also ridges without a central trough, single ridges. These ridges are far less common than their double ridge counterparts. However, there are locations where along-strike changes in ridge type appear to occur. We explore an elastic model in which the ridges form in response to crystallization of a liquid water intrusion. In our model, liquid water fills tension cracks that open in the Europan crust in response to tidal stress or perhaps overpressure of a subsurface ocean. The crack would be long and essentially continuous, similar to dikes on Earth, explaining the remarkable continuity and lack of segmentation of Europan ridges. The freezing of the water would cause a volume expansion, compressing and buckling the adjacent crust. We find that the geometry of the intruding water body controls the shape of the resulting ridges, with single ridges forming above sill-like intrusions and double ridges above dike-like intrusions. In order to match the ridge heights observed for double ridges we would need approximately 1.5 km^2 of water intruded at a shallow depth in the ice shell, potentially over the course of multiple events. Deeper intrusions result in a broader, lower amplitude ridge than shallow intrusions.

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1. Introduction

The most ubiquitous features on Europa are double ridges, which consist of a central trough flanked by two raised edifices (Head et al., 1999; Greeley et al., 2000; Kattenhorn and Hurford, 2007). They are most often long linear features that extend hundreds of kilometers. However, there are also cycloidal ridges that have curved segments joined by together by cusps. Understanding the formation process of ridges can provide constraints on the structure of the ice crust and with it the thermal evolution of the satellite. We show that the morphology of double ridges can be explained by the deformation of the ice crust of Europa over a crystallizing water-filled crack.

Below we summarize ridge morphology and the various models proposed for the origin of ridges. We also motivate the consideration of this model by reviewing the evidence for water bodies inside the crust of Europa. Then we describe the setup of our models and the relation between the geometry of the crystallizing water body and surface features.

2. Water in the Europan ice shell

The presence of a time varying induced magnetic field around Europa (Kivelson et al., 1997) suggests that the ~100 km thick global H_2O layer of Europa (Anderson et al., 1998) is composed of a briny global ocean covered with an ice shell estimated to be between 1 and 30 km thick (Cassen and Reynolds, 1979; Pappalardo et al., 1998; Collins et al., 2000; Figueredo and Greeley, 2004). It is the presence of this ocean that, among other things, makes Europa such an important planetary body to understand, as liquid water is believed to be necessary to support life (e.g. Reynolds et al., 1983; Chyba and Phillips, 2002). An abundance of liquid water also creates a unique geologic setting, especially for magmatic and volcanic processes.

Albedo changes and a reddish coloration, observed in images from *Voyager* and *Galileo* missions, are associated with many surface features including ridges, lenticulae, chaos terrain and

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bands (e.g., Greeley et al., 1998). A change in surface properties suggests a change in surface composition from relatively pure water ice. The precise composition of the impurities that create the red coloration is not known, however. Observations from the Near Infrared Mapping Spectrometer (NIMS) onboard Galileo are compatible with hydrated salts such as magnesium and sodium sulfates (McCord et al., 1998, 1999; Kargel et al., 2000; Prieto-Ballesteros and Kargel, 2005). The reddish coloration on the shell is rarely related to undisrupted regions of ice with relatively no observable features, suggesting that the mechanism(s) responsible for transporting or concentrating the impurities at the surface may also play a role in the formation of the features. McCord et al. (1998) suggests that impurities may be carried by water or slush making its way to the surface. During the crystallization of salt water, brine rejection often observed on Earth causes the ice to contain significantly less impurities than the water from which is crystallized from (e.g. Lake and Lewis, 1970). A similar process active during the freezing of the ice shell on Europa would result in highly concentrated brine that, when it finally crystallizes at the surface, would produce the compositional heterogeneities observed on Europa.

Manga and Wang (2007) determined that cracks can form from a pressurized ocean beneath the shell. As Europa cools and its shell thickens, it would freeze downward. Since water expands when it freezes this would create a force that acts on the surface of the global ocean to pressurize it. Water is mostly incompressible causing it to exert a restoring force back on the base of the ice shell, creating cracks when the strength of the ice is exceeded. Manga and Wang (2007) showed that stress gradients in the shell cause these cracks to penetrate through the entire shell. Water can rise inside the crack to a level of equilibrium inside the shell, which, in the absence of ocean overpressure, would be approximately 90% of the shell thickness. Ocean overpressure pushes water slightly higher than this level but is not sufficient to push water to the surface, causing eruptions (Manga and Wang, 2007). Moreover, ocean overpressure would diminish if water was free to be expelled to the surface, negating any long term effect of ocean pressurization. Nevertheless, cracks would provide a pathway for water to move into the ice shell. Heterogeneities within the ice can further facilitate lateral and vertical movement of water within the ice shell, by depressing the melting temperature of pure ice. Heterogeneities are common in the Earth's crust and are observed in sea ice on Earth (Kusunoki, 1955); while the settings differ, heterogeneities may still be possible in ice on Europa.

The clearest evidence of cracks at the surface of Europa is in the form of long, continuous fractures that take on a cycloidal trajectory. The depth to which cracks extend may be debated (Hoppa et al., 1999; Lee et al., 2005), but their abundance is irrefutable. Pressurized water near a crack may be injected into it, following the pre-existing trajectory of that crack. Depending on the stress conditions near an intrusion and the extent of pressurization of the reservoir injecting water into the cracks, freezing has the ability to aid in the perpetuation of a crack. The models described below presuppose the presence of a liquid water body inside the ice shell. Determining the source and migration of this water body is beyond the scope of this model. Instead, the observed correlation between ridges and albedo changes provides motivation to investigate the formation of ridge-like features above a confined crystallization of body of water.

3. Morphology of double ridges and proposed formation models

Coulter (2009) and Coulter et al. (2009) describe the characteristic dimensions of ridges on Europa. Ridge height ranges from tens of meters to 400 m and ridge width is usually less than 3 km. A maximum ratio of ridge height to width was observed, suggesting that ridges cannot be wide and tall. However, a few ridges have widths just over 4 km but a relief not exceeding 400 m. The outer sides of double ridges have slopes measured to be less than 28°, implying that ridges are not formed principally by surface processes such as mass wasting.

Previous workers (Head et al., 1999; Greeley et al., 2000) have differentiated between several ridge types, including single ridges, double ridges, complex ridges and cycloidal ridges. All of these ridges are nearly linear in map view, with the exception of cycloidal ridges, which have characteristic arcuate segments joined together by cusps (Fig. 1). Although each of these ridge types is clearly distinguishable from the others at regional scale, ridge morphology is remarkably similar for all these ridge types when viewed at a scale of a only a few km (Fig. 1).

Cycloidal ridges have double ridge morphology (Fig. 1) but appear as linked arcuate segments rather than continuous, linear features. The formation of cycloids is often considered separate from ridges because this unique trajectory is well predicted by models of crack propagation in a rotating diurnal stress field (Hoppa et al., 1999; Hurford et al., 2007a, 2007b; Rhoden et al., 2010, 2012). However, the fine scale morphology of cycloidal ridges is similar to that of linear ridges. Cycloids also can transition along strike to quasi-linear trajectories, similar to double ridges. Therefore, any model that proposes to explain ridge morphology must also be applicable to cycloids.

Complex ridges are often composed of several ridges that run parallel or anastomose to one another. It has been suggested that these features are formed by the successive build-up of double ridges (Figueredo and Greeley, 2004). It is not hard to imagine that complex ridges are gradually formed by several ridge building events because the individual morphology of these ridge pairs is remarkably similar to double ridges (Fig. 1). Fig. 2 shows some ridge morphologies, indicated by roman numerals, and along strike transitions, indicated by circles. Boxes C, D and E illustrate the fine scale morphology changes of ridges from boxes A and B. There are double ridges (I) with narrow summital troughs (Ib); single ridges (II) and complex ridge (III) with variants. The range of morphologies for complex ridges extends beyond parallel and anastomosing, to ridges flanked by narrow troughs (IIIb) and ridges with a modified summital trough, which could be expressed as subparallel ridges (IIIa) or a flat floor (IIIc), possibly hummocky. These modified troughs may indicate that volcanic processes play a central role in ridge development (Fagents, 2003).

Along-strike transitions between different ridge morphologies and cracks are not uncommon. Fig. 2 shows some of the transitions identified and indicated by circles in a region centered at 77°W, 45°S. The similarities in small-scale ridge morphologies (Fig. 1) and along strike transitions between ridge types (Fig. 2) motivates us to look for a unifying process that can be active in the formation of all the ridge types described.

Single ridges are also observed on Europa. Figueredo and Greeley (2004) observed that single ridges are usually associated with chaotic terrain and suggests they may be a part of the formation mechanism for chaotic terrain. The fact that these ridges cut across chaotic terrain and are often slightly more sinuous than double ridges in their trajectory (Figueredo and Greeley, 2004) supports their distinct classification. However, single ridges are also found outside of chaos terrain (Fig. 2). Also, we cannot rule out that single ridges may be double ridges that are just below the resolution of the images so that the central trough cannot be recognized. If they are not single ridges they must be double ridges with narrower troughs, indicating some change in morphology and near surface conditions. In the absence of higher resolution images we assume that these are indeed single ridges.

Many models of ridge formation have been proposed including tidal working, cryovolcanism, and shear heating. Greenberg et al.

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