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Heat transfer of ascending cryomagma on Europa

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ABSTRACT

Jupiter's moon Europa has a relatively young surface (60–90 Myr on average), which may be due in part to cryovolcanic processes. Current models for both effusive and explosive cryovolcanism on Europa may be expanded and enhanced by linking the potential for cryovolcanism at the surface to subsurface cryomagmatism. The success of cryomagma transport through Europa's crust depends critically on the rate of ascent relative to the rate of solidification. The final transport distance of cryomagma is thus governed by initial melt volume, ascent rate, overall ascent distance, transport mechanism (i.e., diapirism, diking, or ascent in cylindrical conduits), and melt temperature and composition. The last two factors are especially critical in determining the budget of expendable energy before complete solidification. Here we use these factors as constraints to explore conditions under which cryomagma may arrive at Europa's surface to facilitate cryovolcanism. We find that 1–5 km radius warm ice diapirs ascending from the base of a 10 km thick stagnant lid can reach the shallow subsurface in a partially molten state. Cryomagma transport may be further facilitated if diapirs travel along pre-heated ascent paths. Under certain conditions, cryolava transported from 10 km depths in tabular dikes or pipe-like conduits may reach the surface at temperatures exceeding 250 K. Ascent rates for these geometries may be high enough that isothermal transport is approached. Cryomagmas containing significant amounts of low eutectic impurities can also be delivered to Europa's surface by propagating dikes or pipe-like conduits.

1. Introduction

The surface of Jupiter's moon Europa is littered with many putative cryovolcanic features (Fig. 1). While several of these features are thought to be evidence of effusive flows (Wilson et al., 1997; Figueredo et al., 2002; Fagents 2003), it is possible that low-albedo deposits that surround lenticulae and lie along lineated features may be cryoclastic mantlings deposited during explosive eruptions (Pappalardo et al., 1999; Fagents et al., 2000; Quick et al., 2013). Moreover, lenticulae, chaotic terrain, and ridge and band formation may be surface manifestations of subsurface cryomagmatic processes associated with diapirism (Pappalardo et al., 1998, 1999; Rathbun et al., 1998; Collins et al., 2000; Fagents et al., 2000; Figueredo et al., 2002; Prockter et al., 2002; Sotin et al., 2002; Fagents, 2003; Tobie et al., 2003; Pappalardo and Barr, 2004; Han and Showman, 2005; Prockter and Schenk, 2005; Schmidt et al., 2011), diking, and sill emplacement (Greenberg et al., 1998; Johnston and Montési, 2014; Michaut and Manga, 2014; Craft et al., in press).

Models for cryovolcanism on Europa (cf. Crawford and Stevenson, 1988; Wilson et al., 1997; Wilson and Head, 1998; Fagents et al., 2000; Fagents, 2003, Quick et al., 2013) can be expanded and enhanced by linking observational evidence for cryovolcanism at the surface to inferred subsurface cryomagmatic processes. Our work attempts to provide this linkage by evaluating the heat transfer associated with specific styles of cryomagma transport in Europa's interior. We aim to place rigorous bounds on the tradeoffs between magma volume, ascent rate, and body geometry to achieve cryovolcanism at the surface. In exploring these limits, constraints are also placed on the physics of possible ascent mechanisms.

1.1. Silicate magma vs. cryomagma

A particularly striking contrast exists between cryovolcanism on icy satellites and terrestrial volcanism. Terrestrial volcanism is distinct in three important ways: first, because silicate magma has an adiabat that is much steeper than its liquidus, which itself *decreases* with decreasing pressure or depth, terrestrial magmas tend to become strongly superheated during ascent (e.g., Marsh, 2007); second, because silicate magmas are multi-component systems, they possess a large crystallization interval between the liquidus and solidus of 200 degrees or more. This interval produces a substantial sub-liquidus corridor or “mush zone”, consisting of a highly mobile mix of melt and crystals, which can extrude onto the surface as lava (Fig. 2a); third, silicate magmas are generally less dense than the country rock through which they must ascend. These three features of silicate magmas ensure that the associated volcanism will be frequent and multifaceted.

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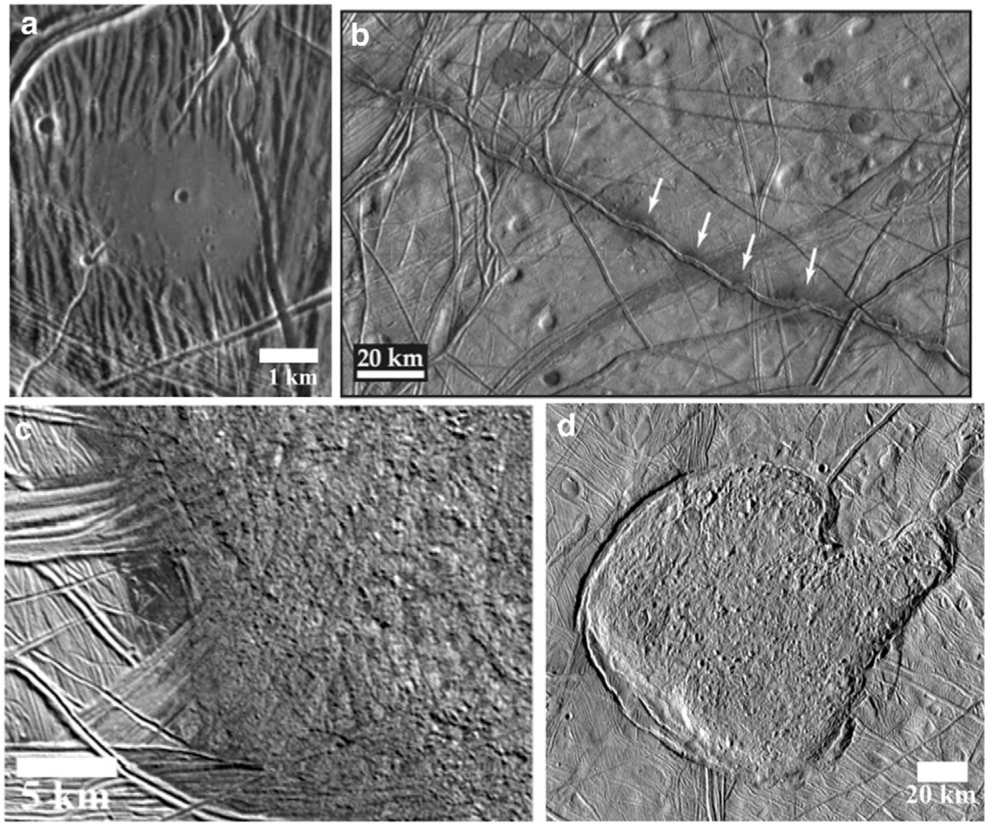

Fig. 1. Putative cryovolcanic features on Europa include (a) a smooth circular feature located near the equator; (b) dark deposits along Rhadamanthys Linea; (c) putative flows at the edge of Thrace Macula; (d) Murias Chaos (The Mitten).

Conversely, for warm ice and/or relatively pure water, which likely serve as magmatic fluids on icy satellites like Europa, there is virtually no solidus–liquidus gap or mush corridor, and the melting point slightly *increases* with decreasing pressure or depth. As a result, ascending cryomagma tends to become supercooled. If the liquidus is crossed, the cryomagma has no pressure–temperature corridor of partial melt available, and further ascent is immediately arrested by quenching (Fig. 2). Furthermore, water and other briny solutions that may serve as cryomagmas are negatively buoyant with respect to the surrounding ice they must traverse. For this reason, these fluids may never rise to the surface except for the case of pressure-driven ascent, or when significant amounts of volatiles are included in solution (Crawford and Stevenson, 1988; Fagents et al., 2000; Muñoz-Iglesias et al., 2014; Neveu et al., 2015). It is therefore essential to determine the heat transfer parameters, transport mechanisms, and ascent rates that will enable cryomagma to: (1) successfully reach Europa's surface and (2) arrive before undergoing thermal death by solidification.

1.2. Briny cryomagmas

Data returned from Galileo's Near-Infrared Mapping Spectrometer (NIMS) revealed the presence of hydrated minerals on Europa's surface. These minerals have been identified as hydrated Mg- and Na-sulfate salts and are mainly found near recently disrupted surface areas and potential sites of extrusion of subsurface materials, i.e., along lineae and near chaotic terrain (McCord et al., 1998, 1999). Linear mixture modeling has confirmed that these species are prevalent in low-albedo surface units on Europa (Dalton et al. 2005; Shirley et al., 2010; Dalton et al., 2012). It is possible that these hydrated minerals originated in the subsurface ocean (Kargel et al., 2000; Spaun & Head, 2001), and previous workers have suggested that they may play a critical role in cryovolcanic processes on Europa and other icy satellites (Kargel, 1991; Hogenboom et al., 1995; Spaun and Head, 2001; Muñoz-Iglesias et al., 2013, 2014). Brown and Hand (2013) have suggested that ocean-derived salts on Europa may be chlorides instead of sulfates. These authors argue that salts such as $MgCl_2$, KCl, and NaCl may be endogenically produced and quite abundant on Europa. If this is indeed the case, then chloride salts could also be constituents of Europan cryomagmas.

Sulfuric acid and its hydrates have also been detected on Europa's surface (Carlson et al., 1999, 2002; Dalton et al., 2005 and references therein). While there is sufficient evidence that these species may have been exogenically emplaced (Carlson et al., 1999; Dalton, 2007; Dalton et al., 2012, 2013), previous work by Kargel et al. (2000) and Pasek and Greenberg (2012) suggests that Europa's ocean could be highly acidic and that sulfuric acid and its hydrates could be endogenic in origin. It has also been suggested that low-albedo spots on Europa's surface could be products of small-scale flooding of sulfuric acid species (Fagents, 2003). Furthermore, it is possible that surface species on Europa may be cycled into the interior by impact gardening (Cooper et al., 2001), crustal cycling (Prockter and Pappalardo, 2000; Prockter et al., 2002; Kattenhorn and Prockter, 2014), and ridge formation (Greenberg, 2010), among other processes. This could allow exogenically produced compounds like sulfuric acid to participate in geophysical processes on the icy moon. Hence even if exogenically emplaced, it is still possible that sulfuric acid species could participate in cryovolcanic processes on Europa. We therefore consider the possibility that Europan cryomagmas could also consist of sulfuric acid hydrates, albeit with the aforementioned caveats for exogenic emplacement.

The addition of any of these components to an H_2O-dominated cryomagma may allow for a 5–75 K separation of the liquidus and solidus and the formation of a cryomagmatic mush zone (Fig. 2b). As previously discussed, and as illustrated in Fig. 2a and b, the formation of this mush zone may be of critical importance when considering