Heat Loss During Cryomagmatic Transport on Europa

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Introduction

Jupiter's moon Europa has a relatively young surface (60-90 Myr on average)[1-2], 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 cryomagmatic processes. The success of cryomagma transport through Europa's crust depends critically on the ascent rate relative to the rate of solidification. The final transport distance of cryomagmas is thus governed by initial melt volume, 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 [3]. Cryomagma transport may be further facilitated if diapirs travel along pre-heated ascent paths.

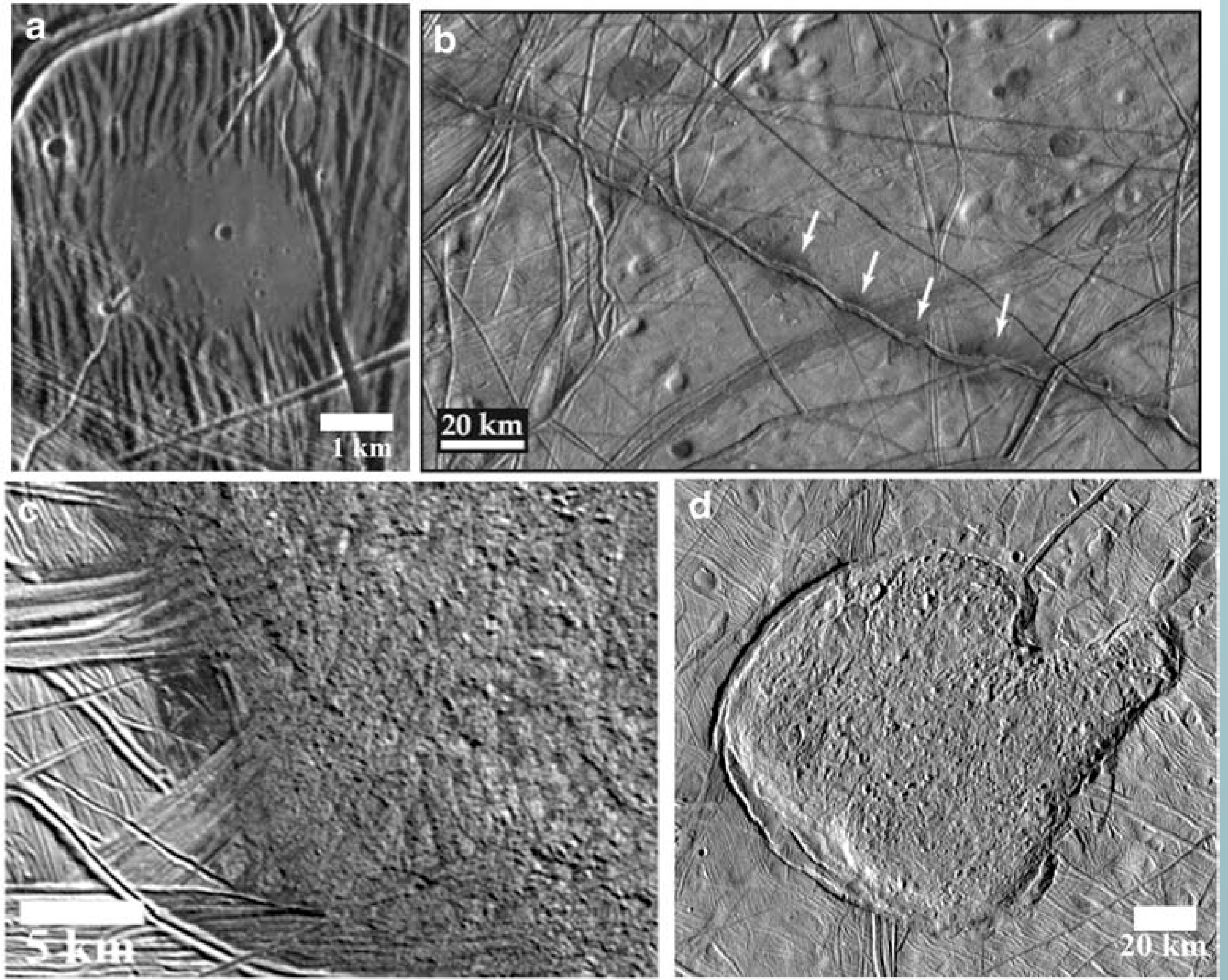


Figure 1. Putative cryovolcanic features on Europa include (a) a smooth circular feature located near the equator [4-5]; (b) dark deposits along Rhadamanthys Linea [5-6]; (c) putative flows at the edge of Thrace Macula [7]; (d) Murias Chaos (The Mitten) [5,8]. Images from Quick and Marsh (2016).

Silicate Magmas vs. Cryomagmas

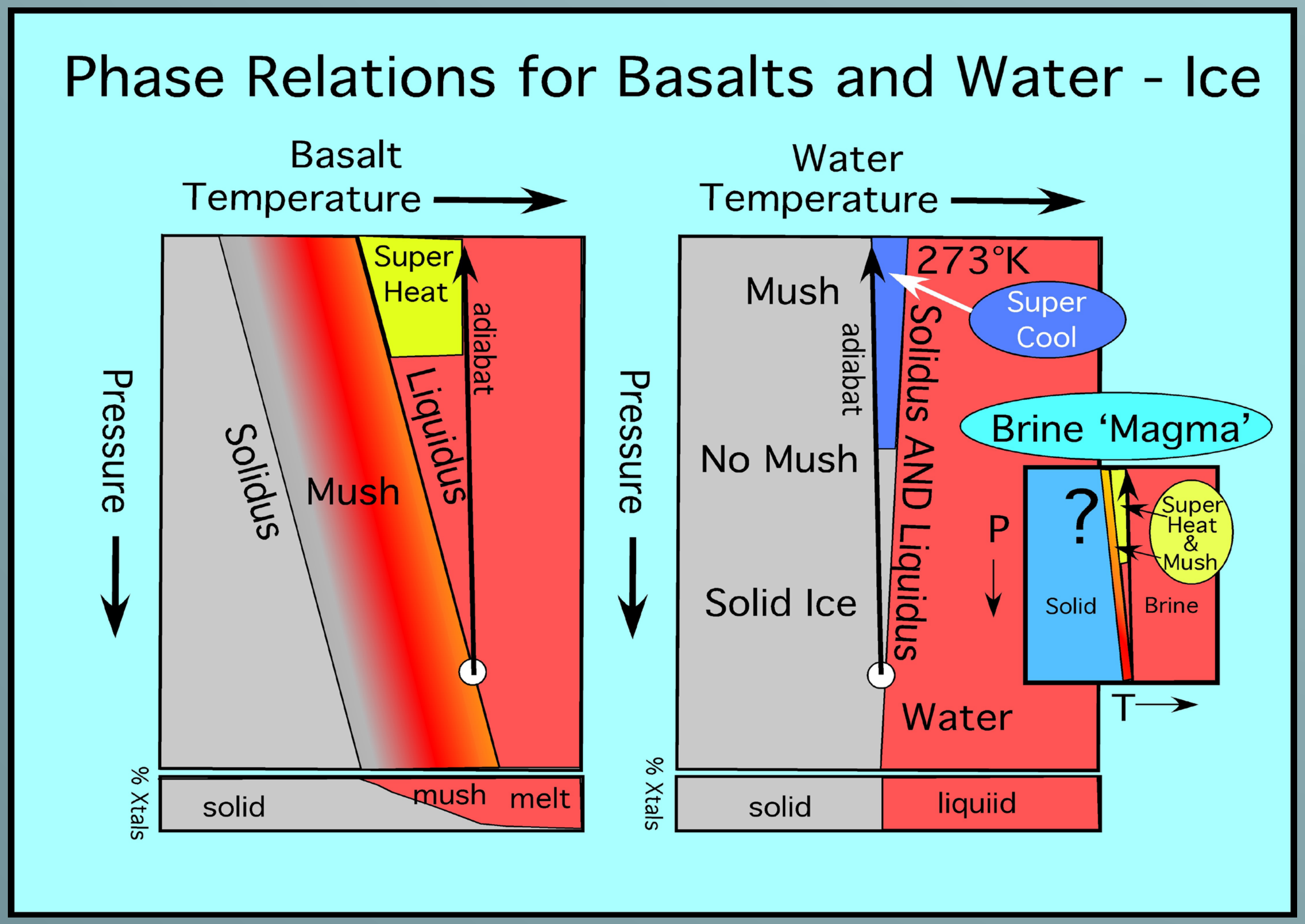


Figure 2. Comparison of melting and transport processes of silicate magmas with those of aqueous cryomagmas. Note that the addition of salts or other low-eutectic impurities may allow for the formation of a mush zone of partial melt for cryomagmas. After Quick and Marsh (2016)

Silicate Magmas:

- Become superheated during ascent to the surface
- Are multicomponent systems. Melting therefore takes place at various temperatures and pressures. This results in a "mush zone" of partial melt between the liquidus and solidus. In addition to pure liquid melt, this "mush" of melt and crystals may also extrude onto the surface
- Are typically less dense than the country rock through which they must ascend

Cryomagmas:

- Will tend to supercool en route to the surface
- Contain no "mush zone" of partial melt
- Water and other briny solutions are negatively buoyant with respect to the surrounding ice they must traverse
- However: warm ice (diapirs) will be positively buoyant, and the addition of low-eutectic contaminants (e.g., salts and/or mineral acids) to fluids moving in dikes and conduits may allow for the presence of a partial melt zone

Cooling Model

The objective of our modeling is to place constraints, dependent upon heat transfer, on the conditions under which warm cryomagmas may arrive at Europa's surface, thereby initiating cryovolcanism. In order to meet this objective, we must determine the amount of cooling that takes place in cryomagmas as they traverse Europa's crust en route to the surface. Cryomagmas may arrive at the surface via diapiric ascent, dike propagation, or ascent in vertical conduits. Here, we focus on heat transfer during diapiric ascent. Diapirs have been approximated as spheres of warm ice that arrive at the base of the stagnant lid with initial temperatures T_o = 269 K. We have also assumed a geothermal gradient, m = 9.7 K/km in the icy crust (Fig. 3). Finally, we consider both heat flux from the surrounding ice (i.e. country ice) and the associated ascent rate to be constant as the diapir traverses the stagnant lid. With these constraints in mind, we use the methods of [9], and Eq. (1) to obtain cooling curves representative of cryomagma temperature as a function of depth, z, in the crust. As displayed in Table 1, associated ascent velocities for each cooling curve have been calculated using Eq. (2).

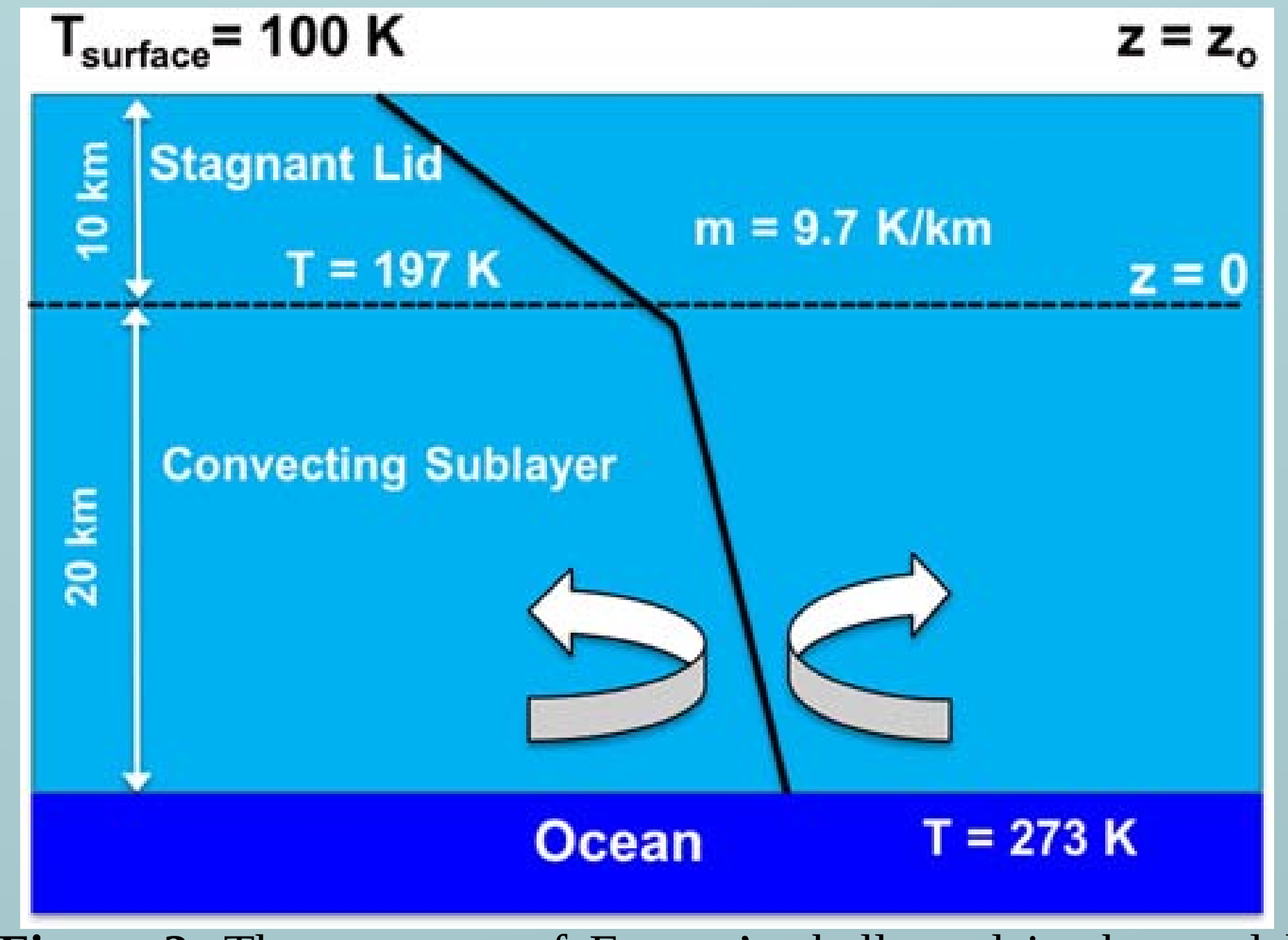


Figure 3. The structure of Europa's shell used in the model presented here. The shell consists of an approximately 10 km thick stagnant conducting lid atop a 20 km thick convecting sublayer. Adapted from [10] with temperature values from [11].

Governing Equations

$$T(t) = T_o - mz + mz\left[\frac{1-e^{-Jt_o{}^{z}/z_o}}{Jt_o{}^{z}/z_o}\right] \quad (1)$$

$$\upsilon \cong \frac{500}{r_s^3 (Jt_o)^2}\, m^4/s \quad (2)$$

Both the temperature and velocity of the diapir as it ascends to the surface are heavily dependent upon the constant, dimensionless parameter Jt_o. Note that $Jt_o = t_{ascent}/t_{transfer}$ is simply the ratio between total ascent time and the time it takes for the diapir to solidify. Small *Jto* values represent rapidly ascending diapirs that lose only small amounts of heat en route to the surface. See Fig. 4 and Table 1.

Model Results

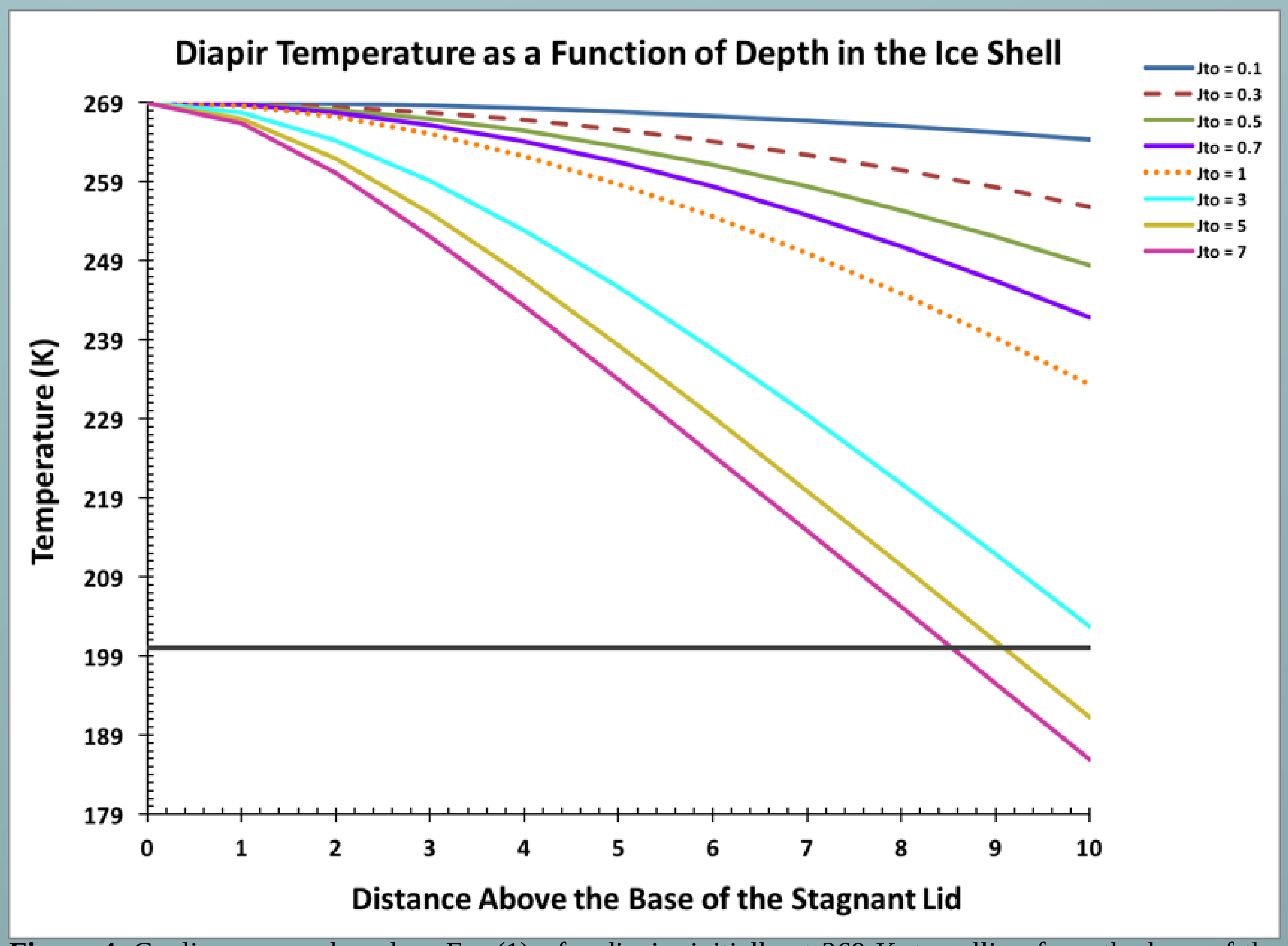


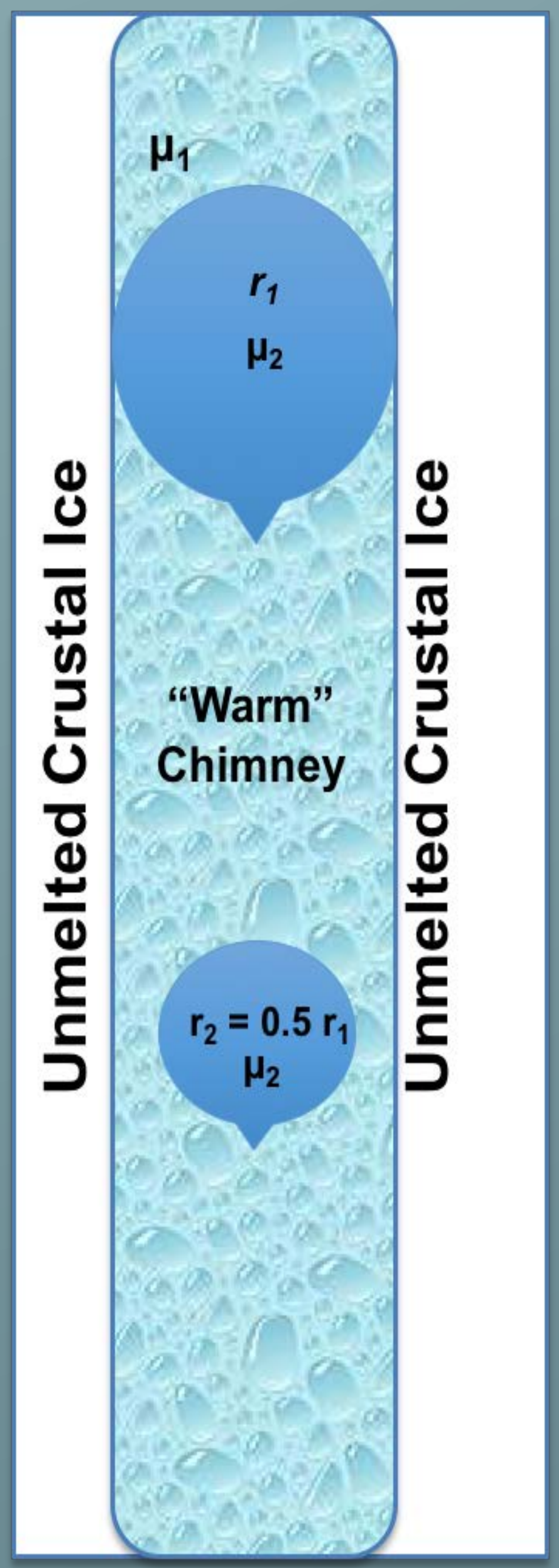
Figure 4. Cooling curves, based on Eq. (1), for diapirs initially at 269 K, travelling from the base of the stagnant lid to the surface. In accordance with (1), the smallest Jt_o values correspond to the quickest ascent rates and highest temperatures upon reaching the surface. The grey line represents the 200 K temperature mark required for cryovolcanism to be incited at the surface by the successful ascent of cryomagma. See also Table 1. From Quick and Marsh (2016).

			***r* = 1 km**	***r* = 5 km**
Jt_o	***T* (K) at *z* = 5 km**	***T* (K) at *z* = 10 km**	**υ (m/s)**	**υ (m/s)**
0.1	268	264	5×10^{-5}	4×10^{-7}
0.2	267	260	1.3×10^{-5}	1×10^{-7}
0.3	266	256	5.6×10^{-6}	4.4×10^{-8}
0.4	264	252	3.3×10^{-6}	2.5×10^{-8}
0.5	263	248	2×10^{-6}	1.6×10^{-8}
0.6	262	245	1.4×10^{-6}	1.1×10^{-8}
0.7	261	242	1×10^{-6}	8.2×10^{-9}
0.8	260	239	7.8×10^{-7}	6.3×10^{-9}
0.9	260	236	6.2×10^{-7}	5×10^{-9}
1	259	233	5×10^{-7}	4×10^{-9}
3	246	203	5.6×10^{-8}	4.4×10^{-10}
5	238	191	2×10^{-8}	1.6×10^{-10}
7	234	186	1×10^{-8}	8.2×10^{-11}

Table 1. Approximate temperatures and ascent rates for diapirs for each Jt_o value investigated. Diapir temperatures 50% of the way to the surface, and at the surface, are displayed in the second and third columns. From Quick and Marsh (2016)

Conclusions

On Earth, diapirs establishing an initial path through the brittle crust are likely to travel on the order of 10^{-8} to 10^{-9} m/s, while diapirs ascending paths that have been insulated by the heat of previous generations of diapirs (Fig. 5) are likely to travel at rates between 10^{-7} and 10^{-6} m/s [9, 12]. The visocsity difference between magma and mantle rock on Earth is, at most, about 21 orders of magnitude [13-14]. This is similar to the maximum viscosity difference between warm ice and the coldest part of the Europan lithosphere [15]. Owing to the similar viscosity differences between Earth's mantle rocks and magma, and Europa's brittle lithosphere and warm ice, ascent velocities for Europan diapirs may be comparable to those of terrestrial magmatic diapirs moving through Earth's mantle. The maximum ascent rate attainable for diapirs on Europa may thus also be on the order of 10^{-7}-10^{-6} m/s. According to Eq. (2), this corresponds to $Jt_o \geq 0.3$ for diapirs with 1 km radii, and $Jt_o \geq 0.06$ for diapirs 5 km in radius. From (1), a 1 km radius diapir with Jt_o = 0.3 would reach Europa's surface at T = 256 K (Table 1). Conversely, diapirs that are 5 km in radius with Jt_o = 0.06 would reach the surface at T = 266 K. Hence, if diapirs were able to attain these ascent rates, cryomagma could be successfully brought to Europa's surface to facilitate cryovolcanism.



Future Work

The model presented here is focused on heat transfer associated with cryomagmatic ascent. An extensive treatment of the dynamics of warm ice diapirs ascending through a brittle, stagnant lid must be undertaken to further validate these conclusions. On Earth, it is expected that diapirs must travel ascent paths that have been used for millions of years by their predecessors in order to arrive at the surface before freezing out (Fig. 5) [9,12]. Like terrestrial diapirs, Europan diapirs may be more likely to reach the surface if they ascend paths that have been warmed and softened by the repeated passage of previous generations of diapirs [3,16]. In a next iteration of this model, the dynamics of diapiric ascent through the brittle lithosphere, inclusive of the effects of viscosity changes in the surrounding country ice, will be investigated.

Figure 5. In order to arrive at Europa's surface in a molten state, diapirs may repeatedly traverse the same insulated path through the ice shell [3,16]. Hence, uplifts created via diapirism and areas where cryolavas may have erupted (Fig. 1) could lie atop "hot spots". Stalled diapirs in the shallow subsurface could also act as transient, habitable niches, and may therefore be astrobiologically significant.

References

[1] Zahnle K. et al. (2003) *Icarus, 163*, 263. [2] Bierhaus, E.B. et al. (2009). *Europa*, pp. 161-180. [3] Quick, L. C. & Marsh, B. D. (2016) *J. Volcanol. Geoth. Res, 319*, 66-77. [4] Pappalardo, R.T., et al. (1999) *J. Geophys. Res., 104*, 24015. [5] Fagents, S. A. (2003) *J. Geophys. Res., 108*, 5139. [6] Quick, L. C. et al. (2013) *Planet. Space Sci., 86*, 1-9. [7] Wilson, L., et al. (1997) *J. Geophys. Res., 102*, 9263-9272. [8] Figueredo, P. H. (2002) *J. Geophys. Res., 107*, 5026. [9] Marsh B.D. (1978) *Phil. Trans. R. Soc. Lond. A., 288*, 611-625. [10] McKinnon, W.B. (1999) *Geophys. Res. Lett., 26*, 951. [11] Pappalardo, R. T. et al. (1998) *Nature, 391*, 365. [12] Marsh, B.D. (1982) *Am. J. Sci., 282*, 808-855. [13] Spera, F. J. (2000) *Encyclopedia of Volcanoes*, pp. 171-190. [14] Turcotte, D. L. & Schubert, G. (2002) *Geodynamics*, Ch. 6 & 10. [15] Barr, A.C. & Showman, A.P. (2009) *Europa*, pp. 405-430. [16] Quick, L. C. (2014) *Workshop on the Habitability of Icy Worlds, Abstract #4062*