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Origin of ice diapirism, true polar wander, subsurface ocean, and tiger stripes of Enceladus driven by compositional convection

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ABSTRACT

We consider the scenario in which the presence of ammonia in the bulk composition of Enceladus plays a pivotal role in its thermochemical evolution. Because ammonia reduces the melting temperature of the ice shell by 100 K below that of pure water ice, small amounts of tidal dissipation can power an "ammonia feedback" mechanism that leads to secondary differentiation of Enceladus within the ice shell. This leads to compositionally distinct zones at the base of the ice shell arranged such that a layer of lower density (and compositionally buoyant) pure water ice underlies the undifferentiated ammonia-dihydrate ice layer above. We then consider a large scale instability arising from the pure water ice layer, and use a numerical model to explore the dynamics of compositional convection within the ice shell of Enceladus. The instability of the layer can easily account for a diapir that is hemispherical in scale. As it rises to the surface, it co-advects the warm internal temperatures towards the outer layers of the satellite. This advected heat facilitates the generation of a subsurface ocean within the ice shell of Enceladus. This scenario can simultaneously account for the origin of asymmetry in surface deformation observed on Enceladus as well as two global features inferred to exist: a large density anomaly within the interior and a subsurface ocean underneath the south polar region.

1. Introduction

1.1. Global scale features

1.1.1. Tiger stripes and the south polar thermal anomaly

Cassini observations of the small, icy saturnian satellite Enceladus (radius 252 km) revealed the south polar region is both geologically young and cryovolcanically active. The south pole is heavily tectonically deformed, including a series of four sub-parallel, ~130 km long tectonic fractures (so-called "tiger stripes"; Porco et al., 2006). The discovery that the south polar region has a significant thermal anomaly was quite surprising. In fact, the area surrounding the tiger stripes is observed to have temperatures between 150–180 K which is ~40–80 K higher than the background surface. It is now understood that tidally-driven lateral fault motion along the tiger stripe fractures is capable of generating sufficient heat to explain the thermal anomaly (Nimmo et al., 2007).

1.1.2. A proposed true polar wander event

It has been hypothesized that the position of the tiger stripes at the south pole was caused by a true polar wander (TPW) event having situated them in that location (Nimmo and Pappalardo, 2006). In order for TPW to occur, the mass distribution of the interior (and the inertial tensor that describes it) needs to change enough that the maximum axis of inertia is no longer aligned with the spin axis. Generation of a large density anomaly, in either the silicate core or the ice mantle, can provide the necessary conditions for inducing true polar wander. Whilst the size and location of the density anomaly remain unconstrained, an anomaly of lower density material underlying the south pole region has been proposed (Nimmo and Pappalardo, 2006). Whether the reorientation was a single event or occurred multiple times, and when these events may have occurred, is also unknown.

1.1.3. Driving mechanism for diapirism in the Enceladus' interior

The typical processes by which density anomalies arise within a planetary interior include differentiation or convective motions. In order for true polar wander to be driven by a density anomaly in the core, the core must be viscously coupled to the ice shell. This essentially precludes any type of low viscosity zone at the core mantle boundary during the time of reorientation. In either case (core or ice shell), a large volume of different density material needs to be generated and it is not known through what mecha-

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nism this has occurred. Thermal or compositional convection are the most viable options, however it is not clear how the necessary conditions to allow convection can be achieved. Furthermore, the mechanism must be capable of developing a long-wavelength (hemispherical) upwelling instability. There is some suggestion that thermal effects alone cannot generate interior density structures capable of driving large reorientations (i.e. 90 degrees) and that additional compositional effects may play a role (Roberts and Nimmo, 2008a).

1.1.4. *Inadequate energy sources available for driving interior dynamics*

Energy sources available to produce a large diapir may be either external (impact heating) or internal (radioactive decay and/or tidal heating). Estimates of the present day tidal heating rate that assume Enceladus is a solid body are insufficient to have driven thermal convection in the past (Barr and McKinnon, 2007). The possibility exists that tidal heating was larger in the past, but there are good arguments (see Section 3) to believe that is not the case. Therein lies the conundrum: either (1) the estimates of ice viscosity at appropriate conditions are greatly overestimated and thereby the power requirements for thermal convection are substantially lower than presently believed, (2) the estimates of the past or present heating rates are greatly underestimated OR (3) some other mechanism of heat transfer besides thermal convection is responsible for driving dynamics in the interior.

1.1.5. *Origin of hemispherical asymmetry*

Another issue which has not been addressed in any detail is the global asymmetry in which large tectonic fractures have developed, namely, that the tiger stripes are unique to the south pole. Reorientation of the satellite's elastic lithosphere due to true polar wander may generate large tectonic stresses, compressive in some areas and extensional in others. Depending on the magnitude of the tidal bulge (flattening), the elastic strength of the lithosphere and the amount of true polar wander, tectonic stresses of order ~10 MPa may be generated (Melosh, 1980). This magnitude of stress is consistent with the observed faulting and deformation pattern of the tiger stripes (Nimmo and Pappalardo, 2006). Therefore, the origin of the tiger stripes may likely be a consequence of reorientation and correspond to one of several possible global fracture patterns. However, in all cases the faulting patterns are global in extent and uniformly distributed across the surface (Melosh, 1980), which then raises the question as to why the deformation is confined to the south polar region. Using the methodology of Melosh (1980) and extending it for analytically calculating distortions of a tri-axial body (Matsuyama and Nimmo, 2008), it may be possible to demonstrate whether the pattern of deformation induced by a reorientation of the planet will result in one similar to the tiger stripes. Presently, the observed pattern of deformation appears to be more consistent with the stress fields and tectonic patterns predicted from a 90 degree rotation (Melosh, 1980; Matsuyama and Nimmo, 2008) than the 30 degree rotation as suggested (Nimmo and Pappalardo, 2006). There is also speculation that ancient polar terrains have been observed at an equatorial location (Helfenstein et al., 2006) which is consistent with a 90 degree reorientation. It is not clear how stresses generated by a global-scale event would be localized to only a small fraction of the planet's surface or why the tectonic stress patterns predicted by reorientation are not observed on the remainder of the satellite.

1.1.6. *Origin and persistence of a subsurface ocean*

A subsurface ocean is proposed to exist based on observations of Enceladus' shape (Collins and Goodman, 2007). The shear heating model (Nimmo et al., 2007) requires that the surface is decoupled from the interior by a subsurface ocean in order to sustain lateral shear velocities of sufficient magnitude to generate the observed heat flow. However, neither the depth or lateral extent of the ocean are constrained by the shear heating model (depth is independent of the model particulars), but it must be at least as large as the south polar region (and possibly global in extent). Key considerations include the age and volume of the ocean within the ice shell, as well as the energy source for increasing a significant volume to its melting temperature. Further, if the ocean has not originated in the geologically recent past, how has a liquid ocean persisted over geologic time (Tobie et al., 2008; Roberts and Nimmo, 2008b) without refreezing?

1.1.7. *Relation of the south pole's geyser and plume ejecta material to the subsurface composition*

Gas content measurements of a south polar geyser reveal a composition of nearly pure water vapor (Porco et al., 2006). A geyser content of pure water is puzzling, as liquid water requires temperatures of at least 273 K, almost 100 degrees above the highest surface temperatures inferred by infrared observations (Spencer et al., 2006). The source of the vapor production is purported to be sublimation caused by shear heating within the tiger stripes (Nimmo et al., 2007), escaping from cracks reopened by tidal stresses (Hurford et al., 2007b). Additionally, the surface appears to be pure water ice as low ridges that flank each side of the tiger stripes display compositionally distinct crystalline water ice (Porco et al., 2006). How then, can observations of pure water ice on the surface and pure water vapor in the plume be reconciled with a subsurface ocean if it is too cold for liquid water to exist (even at depths down to 100 km)?

1.2. *Considerations for Enceladus' thermal evolution*

The previous sections describe several aspects of Enceladus, some have been directly observed, some indirectly observed, and some exist merely by inference based on hypotheses and we have summarized these in Table 1. The main goal is to attempt to reconcile how these features and supposed events can fit together into a single, self-consistent thermal evolution.

Large tectonic stresses, and their associated fractures, are typically the surface expressions of heat transfer inside a planet or Moon. Plate tectonics is the unique manifestation of thermal convection for Earth, whilst Venus and most other large moons and planets evolve in the stagnant lid regime (Solomatov and Moresi, 1996; Reese et al., 1998). In contrast a small, icy satellite, such as Enceladus, is unlikely to achieve supercritical thermal convection given relevant estimates of tidal heating and likely interior properties (Barr and McKinnon, 2007). So while the shear heating model (Nimmo and Pappalardo, 2006) can account for the enigmatic, south polar thermal anomaly, the origins of nearly all other global scale features of Enceladus remain unresolved (Tobie et al., 2008).

We first carefully review the available energy sources which can be compared with requirements of driving convective motions. We next review mechanisms of differentiation, present evidence for the presence of ammonia in Enceladus' interior and discuss the implications that such a composition would have on differentiation. We then explore the scenario of how chemical differentiation of the ice shell may lead to the formation of a low density diapir. We present some numerical models of a thermochemical diapir in which most of the buoyancy is compositional. We show that it is capable of providing a density anomaly sufficient to drive polar wander, as well as plausibly deliver enough heat to produce a regional subsurface ocean. We propose a new conceptual model of thermochemical evolution and discuss how it is able to provide a physical mechanism for linking the origin of the diapir, the subsurface ocean, and the tiger stripes. Finally, we conclude with a discussion of the possible scenarios that may arise from this