THE EARLY HISTORY OF ENCELADUS: SETTING THE SCENE FOR TODAY'S ACTIVITY.

D. L. Matson[1], J. C. Castillo-Rogez[1], S. D. Vance[2], A. G. Davies[1], Torrence V. Johnson[1], [1]Jet Propulsion Laboratory, California Institute of Technology, M/S 230-260 4800 Oak Grove Drive, Pasadena, CA, 91109, E-mail: Julie.C.Castillo@jpl.nasa.gov, [2]Department of Earth and Space Sciences, Box 351310, Seattle, WA 98195.

Introduction: Several scenarios have been proposed to explain the thermal state of Enceladus as inferred from Cassini observations. These models focus on how the South Pole thermal anomaly developed and how it can sustain a heat output of 3 to 7 GW. Some models propose that this thermal anomaly was triggered by - and still involves - the presence of a thermal anomaly in the rocky core [1, 2]. In those models, significant heat flow from the core drives a hotspot in the outer icy shell of the satellite.

Another constraint on the thermal state reached by Enceladus's core during its evolution comes from the South Pole geyser's composition. Matson *et al.* [3] have suggested that the observed molecular nitrogen comes from the decomposition of ammonia at temperatures of about 850 K (between 575 K and 850 K if catalysts are involved). These temperatures can be realized during hydrothermal activity at the interface between a hot core and liquid water.

What conditions in Enceladus's early history could have led to the formation of a core that became sufficiently hot in the long run to power a hotspot located within the ice, driving hydrothermal circulation? The implication is that the satellite differentiated, and that the core became consolidated enough to prevent cooling from deep hydrothermal circulation. The latter situation is not obvious, as the maximum pressure inside Enceladus is less than 40 MPa. This pressure is similar to that on Earth's ocean floors. At these pressures, terrestrial rocks, compacted by gravity, retain significant porosity (between 20 and 40% depending on their nature).

We consider different possible scenarios, as functions of the initial conditions (composition, heat budget, etc.), leading to the formation and the long-term evolution of a rocky core inside Enceladus.

Initial conditions and differentiation: Two key parameters play a determining role in the long-term evolution of Enceladus: the extent of freezing point suppression for water by aqueous species such as ammonia, and the time of formation with respect to calcium-aluminum inclusions (CAIs). The latter parameter determines the amount of short-lived radiogenic isotopes (SLRIs), especially ^{26}Al and ^{60}Fe, that accreted in the satellite [4].

If ammonia and SLRIs are not accreted, the interior temperature barely reaches the water ice melting point and differentiation is only partial.

Spectroscopic observations [5] indicate the presence of a few percent ammonia and suggest that ammonia may have accreted in Enceladus. Further evidence comes from the observation of N_2 in Enceladus's geyser, which can be explained by the decomposition of ammonia (discussed above). The mechanisms for differentiation at the ammonia-water eutectic temperature are not well constrained. However, if we assume that conditions allow the separation of the silicate from the ice, then dry silicate sinks to the center. At temperatures below 300 K, the kinetics of serpentinization reactions are extremely slow, and may not react all of the silicate phase over the lifetime of Enceladus. As a result, Enceladus's core is a probably mixture of rock with up to 40% of ice. In the long term, temperatures reach the water ice melting point due to long-lived radiogenic isotope decay (at about 1 By after formation). This affects only the inner 150 km (Figure 1).

If Enceladus formed less than 4 My after CAIs (Figure 2), differentiation and silicate hydration occur rapidly, taking place during the SLRI decay heat pulse. Serpentinization of the whole silicate phase is likely achieved within a few My following formation. The increased rock volume upon serpentinization may eliminate permability in the core. Alternatively, anisotropic expansion may maintain a network of cross-fractures that allow continued fluid circulation [6, 7]. This situation takes place regardless of whether ammonia is present The combined heat produced from silicate hydration (increasing the temperature by 120 K) and ^{60}Fe decay (an increase of up to 400 K) brings the core temperature up to 600 K in less than 10 My.

Long-term evolution of the core. The composition of the core determines its thermal conductivity, with consequences for its long-term thermal evolution. This parameter ranges between 0.5 and 3 W/K/m depending on the nature of the silicate phase [8].

Penetration depth of the hydrothermal flow is a function of permeability, which in turn is influenced by tectonic and micro-mechanical processes [7, 9]. In the long term, the formation of sulfur compounds fills pores and this further inhibits hydrothermal circulation [10]. If the above factors are manifest on Enceladus, this satellite's core can have easily reached temperatures necessary for melting hydrated silicates (*i.e.*, between 1000 and 1150 K).

Laboratory measurements of basalts dissipative properties at frequencies only a couple orders of magnitude greater than Enceladus' tidal forcing frequency yield dissipation factors less than 100 for temperatures greater than 800 K.

For a few melt-percent, the viscosity drops, and the dissipation factor tends toward unity [11, 12]. Significant tidal heating takes place and can maintain a warm core over the long term. Lateral heterogeneities of composition and viscoelastic properties, cooling from hydrothermal circulation, difference in tidal heating between the poles and the equator [13] are likely to give rise to lateral thermal anomalies. Terrestrial analogs (subglacial or suboceanic volcanic activity) indicate that water should remain in the magma due to pressure [14]. However, these terrestrial analogs contain only a few percent water and it is likely that most of the water exsolved during magma production and upwelling. If so, this could give rise to explosive magmatic events [15].

Conclusion: We have shown two types of evolutionary scenarios for Enceladus' core, depending on the initial inventory of SLRI, and, thus, the time of formation of the satellite with respect to the production of CAIs. Because of Enceladus' very low internal pressure, a compact silicate core *per se* can exist only if water is trapped in the structures of the silicate phases so that these minerals reach the close packing limit. In order to form a hot core, models must accrete active SLRIs. Specific properties of hydrated silicate associated with the initial heat "pulse" due to SLRI decay can lead to silicate melting, resulting in volcanism. Tidal heating can maintain partially molten regions over the long term.

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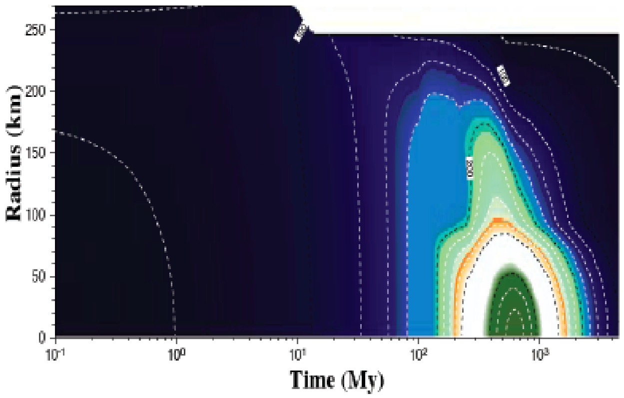
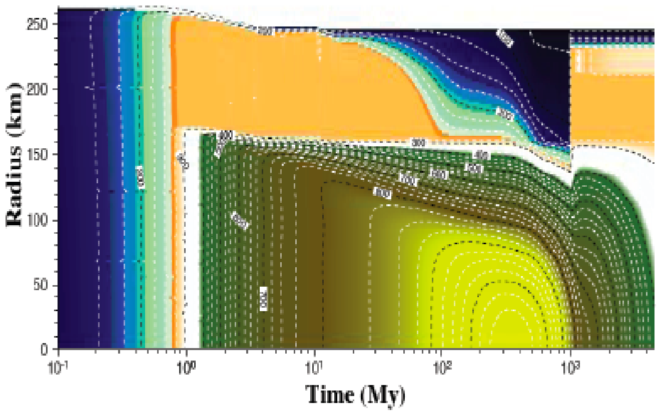
References: [1] Tobie G. et al. (2006) *Eos Trans. AGU*, 87(52), Fall Meet. Suppl., Abstract P13B-0172. [2] Collins G. and Goodman J.C. (2007) *Icarus* in press. [3] Matson D. L. et al. (2007) *Icarus*, *Icarus* 187, 569. [4] Castillo J. C. et al. (2007) *Icarus* in press. [5] Brown R. H. et al. (2006) *Science*, 311, 1425-1428. [6] O'Hanley, D.S. (1992) *Geology*, *20*, 705-708. [7] Vance S. *et al.* (2007) Submitted to *Astrobiology*. [8] Clauser C. and Huenges E. (1995) *Rock Physics and Phase Relations, A Handbook of Physical Constants, AGU Reference Shelf 3.* [9] Vance, S. *et al.* (2007) Submitted to *Icarus*. [8] McKinnon W. B. and Zolensky M. E. (2003) *Astrobiology*, 3, 879-897. [11] James M. R. et al. (2004) *J. Volcan. Geoth. Res*., 3001, 1-15. [12] Matson D. L. et al. (2006) *Bull. Am. Astron. Soc*., 38, 30.01. [13] Tobie G. et al. (2005) *Icarus*, 177, 534-549. [14] Wilson L. and Head J. W. (2001) *LPS* XXXII, Abstract #1013. [15] Wilson L. et al. (1999) *MPS*, 34, 541-557.





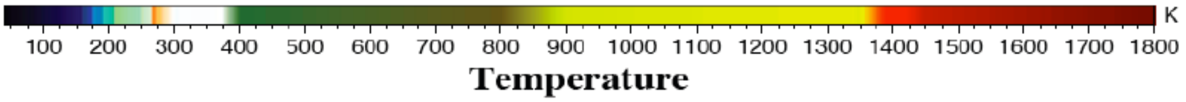


Figure 1. Thermal evolution for a model of Enceladus including a few percent ammonia, formed more than 7 My after CAIs.

Figure 2. A thermal evolution model of Enceladus accreted 4 My after CAIs.