A SOUTH POLAR SEA ON ENCELADUS? G. C. Collins[1] and J. C. Goodman[2], [1]Wheaton College, Norton MA 02766, gcollins@wheatonma.edu; [2]Woods Hole Oceanographic Institution, Woods Hole MA, jgoodman@whoi.edu.

Introduction: The south pole of Enceladus has been the subject of recent attention since the discovery of a large, internally-generated thermal anomaly [1] and plumes of water jetting out of young fractures in the surface [e.g. 2]. These observations imply that there may be internal thermal activity and a source of liquid water near the surface of the south pole. However, the reported shape of Enceladus does not match the equilibrium shape that would be expected for a differentiated body at its current position. Various explanations have been offered to more closely match the shape, including an undifferentiated interior [2], and a faster spin rate in the past [3]. We propose an alternative explanation, that melting beneath the south pole has produced a localized sea of liquid water. We attempt to simultaneously account for the global shape, heat flow, possible differentiated interiors, and the south polar location of the anomaly.

Formation and stablility of a sea: Before considering the implications of a south polar sea, we should first consider whether such a sea is likely to form and be stable over geologic time. The observed heat output from the south pole (3-7 GW) [1] is more than an order of magnitude greater than the energy that radiogenic heating could provide. If the excess energy is deposited more than 20 km below the surface, the timescale of melting the overlying ice is shorter than the timescale to conduct the heat out to the surface. Convection on Enceladus is likely to be sluggish due to the low driving stresses and thick stagnant lid, and it appears that rather thick ice shells are required to initiate convection on Enceladus (~100 km for 1 mm grain size) [4]. Convection is about as efficient at transporting heat as conduction near this critical boundary, so melting will also win out over convection to transport the observed heat flux out of thick ice shells. Thus we should expect, if a 3-7 GW heat source is turned on at the base of the ice shell on Enceladus, the ice will melt in response, until it reaches a conductive equilibrium with a lid several km thick. Once the subsurface ice is melted, does the melt stay trapped as a local sea over the heat source, or does it spread out into a global ocean? We investigated this question using an axisymmetric 2D finite difference model, which solves for thermal conduction and ice flow (using Goldsby and Kohlstedt rheology [5] and a 1 mm grain size). We begin the ice shell model in equilibrium with a radiogenically heated rocky interior, and then turn on a basal 3-7 GW heat source in a Gaussian bump profile 300 km in diameter. After the model begins, it takes several million years to reach an equilibrium conductive ice thickness at the center of the model, and tens of millions of years for the edges of the sea to approach an equilibrium position. Inflow of ice along the walls of the sea is significant, but it does not broaden the width of the sea by more than 10% over models without ice flow. Ice that flows up the wall of the sea is melted, and replaced by water that freezes to the bottom edge of the wall. Because the ice is melted in place, there is no lateral basal pressure difference to drive the liquid out of the sea; all escape of water to the sides must be balanced by inward flow of ice. Since this inward flow is slower than the melting and freezing timescales, the shape of the sea is dominated by the shape of the heating profile, so localized heating will produce a localized sea that is stable as long as the heating lasts.

Effect of melting on global shape: By melting the ice shell in place, isostatic compensation will form a pit over the heat source. The depth of the pit will depend on the ice shell thickness and power output, but for the observed power and reasonable shell thicknesses, the pit will be 2-3 km deep over the center of the heat source. Since the observed thermal anomaly is centered on the south pole, a pit centered there would have an important effect on the measured length of the *c* axis, and thus the best fit ellipsoid for Enceladus.

The observed value of *a* - *c* is about 8 km, and *b* - *c* is about 3 km [2]. These values are close to (but not quite) what would be expected for an undifferentiated interior structure in tidal and rotational equilibrium. If the interior is differentiated, the equilibrium shape becomes more spherical [6], which would make the *a* - *c* and *b* - *c* values much smaller than observed. However, if the length of the *c* axis has been independently modified by formation of a south polar pit, an accurate fit to the observations may be obtained. Importantly, the formation of a pit at the south pole would also produce the same maximum deviations from

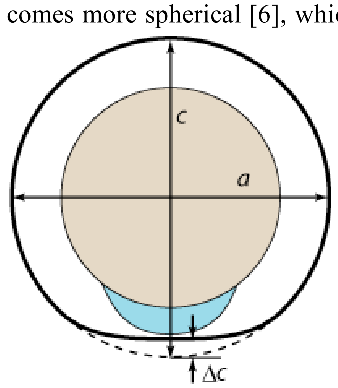

Figure 1. Formation of a sea beneath the south pole of Enceladus can profoundly affect the observed global shape.

an ellipsoid that were reported by Porco et al. [2], with a depression centered on the south pole and a ridge surrounding it at about 50°S latitude.

Inverse modeling of required heating from observed shape: The shape of Enceladus and the heat output from the south pole are fairly well constrained by observations, but the basal profile of the internal heating and the differentiation state of the interior are unconstrained. Therefore, we take an inverse approach to the problem. Our hypothesis will succeed if we can find a reasonable heating profile which will melt an initially hydrostatic ellipsoid for a differentiated body and produce the observed modern shape. For the observed modern shape, we use the best-fit ellipsoid reported by Porco et al. [2], plus their reported maximum deviations from the ellipsoid at the pole and 50°S. We then construct ellipsoids for differentiated Enceladus structures in hydrostatic equilibrium, and line up their northern hemispheres with the observed northern hemisphere. The increasingly large difference between the surfaces of these ellipsoids as one approaches the south pole represents the volume lost to melting within the ice shell. We then find the basal heating profile that would produce this melt profile.

We have performed this analysis for a wide range of core densities and initial mean radii, and summarize the results on Figure 2. In the dark grey area (low core densities), the model is violated because the required depth of ice melting exceeds the available amount of ice. The white zone between the light grey areas shows models where the total heat source for melting is between 3 and 7 GW. The thin contours show the magnitude of the worst mismatch between the proposed shape and the observed A-C and B-C planes (the A-C plane is not as well constrained observationally).

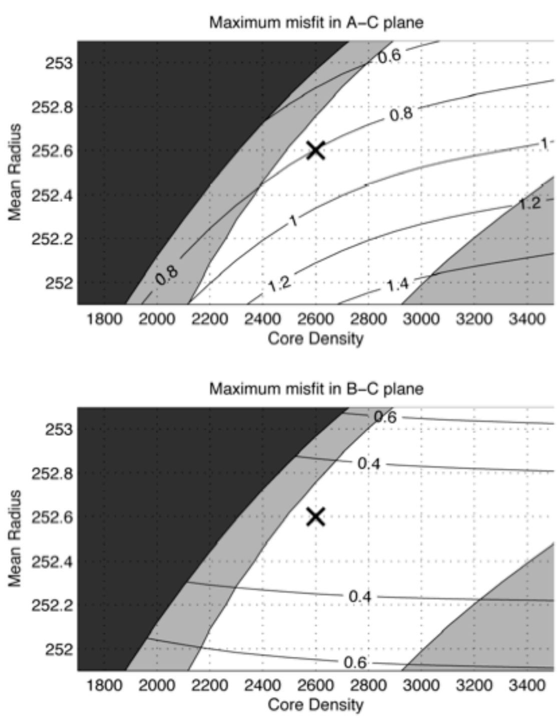

Figure 2. Inverse model fits to observed shape of Enceldus. See text for details.

Our best guess based on this inverse model is shown by the X on Fig. 2, where Enceladus has a core density of 2600 kg m^{-3}, and a pre-melting mean radius of 252.6 km. The shape of the sea resulting from this parameter choice is shown in Fig. 3.

Reorientation of Enceladus: The same mechanism described by Nimmo and Pappalardo [7] to reorient the active region of Enceladus to the south pole also applies to our model. Whereas they relied on a partially uncompensated low-density diapir, we can accomplish the same effect with a completely compensated melt pool (possibly coupled with a diapir in the rocky core). Approximating the shape of the sea shown in Fig. 3 as a set of stacked high-density regions centered on the pole, we estimate a second-degree gravity anomaly of -2.6 mgal at 100 km altitude.

Conclusion: Isolated seas may be stable for long time periods on Enceladus, as long as the heat source lasts. By considering the effect of internal melting, we can reconcile the shape of Enceladus with its anomalous south polar heat flow and a differentiated internal structure. Future attempts to determine the topography and gravity field of the south pole of Enceladus, as well as the satellite's axial moment of interia, are critical for testing this hypothesis for the existence of a sea beneath the south pole.

References: [1] Spencer et al., *Science* 311, 1416-1418, 2006; [2] Porco et al., *Science* 311, 1393-1401, 2006; [3] Schubert et al., *AGU Fall mtg.*, #P31D-06, 2006; [4] Barr and McKinnon, *GRL*, submitted; [5] Goldsby and Kohlstedt, *JGR* 106, 2001; [6] Dermott, *Icarus* 37, 575-586, 1979; [7] Nimmo and Pappalardo, *Nature* 441, 614-616, 2006.

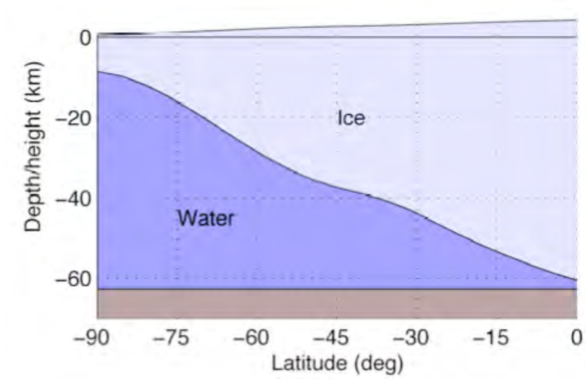

Figure 3. Cross-section of south polar sea from model parameters shown by the X in figure 2.