SLOW FLOW: THE MIGRATION OF AMMONIA-RICH MELT THROUGH AN ICE SHELL AND IMPLICATIONS FOR CRYOVOLCANISM ON TRITON. N. P. Hammond¹,2, E. M. Parmentier¹ and A. C. Barr¹,3 ¹Centre for Planetary Sciences, Department of Physics and Environmental Sciences, University of Toronto Scarborough, 1265 Military Trail, Toronto, ON, M1C 1A4 Canada (noah.hammond@utoronto.ca). ²Department of Earth Environmental and Planetary Sciences, Brown University, 324 Brook St., Providence RI, 02912, ³Planetary Science Institute, 1700 E. Ft. Lowell, Suite 106, Tucson AZ, 85719.

Abstract: Regions of partial melt within the ice shells of icy satellites could play an important role in their geologic and thermal evolution. Here we model the flow of ammonia-rich melt through the ice shell and examine the evolution of partially molten regions [1]. We apply our model to the early evolution of Neptune’s moon Triton. We focus on a time when the ice shell is gradually thickening to understand whether ammonia-rich fluids might freeze into the ice shell as it cools.

We find that low-temperature ammonia-rich melts migrate orders of magnitude slower than pure water melts, and that ammonia can become frozen into the top 5 – 10 km of the ice shell. The trapping of ammonia-ice near the surface could enable cryovolcanism by creating density instabilities and the potential for low-temperature eutectic melts to be generated by future heating events.

Introduction: Near-surface melts are suggested to play a role in geologic resurfacing on several icy satellites and Kuiper belt objects [2,3,4]. Understanding the dynamics of how melt is generated and migrates through the ice shell is crucial to explaining observations of near-surface water and potential cryovolcanic features [c.f. 5,6,7].

The presence of chemical impurities in the ice shell could strongly influence the dynamics of melt generation and evolution by lowering the temperature for the onset of melting, called the solidus temperature, $T_s$. Ammonia, in particular, can lower the solidus temperature to $T_s = 176.15$ K [8]. Ammonia also reduces the temperature for complete melting, called the liquidus temperature, $T_l$, which depends strongly on the mass-concentration of ammonia, $X_{NH_3}$. At temperature between the liquidus and solidus, only a fraction of solids will melt [8].

Figure 1 shows an example of the melt fraction with depth in a 10 km thick ice shell, with a linear-temperature profile and an ammonia concentration $X_{NH_3} = 10\%$ that is constant with depth. A large partially molten region exists at depths between 4 and 9 km. However, liquids and solids in this region will segregate; negatively buoyant ammonia-rich melt will migrate toward the subsurface ocean while ice crystals will rise. Where the melt fraction is greater than ~50%, water ice crystals will be suspended in the melt and will quickly float upwards [c.f. 9].

Where the melt fraction is less than ~50%, water ice will form a porous solid-network. Melt segregation in this region will occur by porous flow accompanied by compaction of the solid matrix [10]. The ammonia-rich melt cannot migrate out of this region until the surrounding solid matrix is squeezed shut. The melt migration rate therefore depends on the compaction viscosity of the solids, $\xi_c$, which is strongly temperature-dependent [11]. Melt present near the eutectic temperature of $T_e = 176$ K will thus migrate orders of magnitude slower than pure water melts at 273 K.

Melt Migration Model: We wish to understand the dynamics of ammonia-rich melt migration. Additionally, it is important to understand whether ammonia might freeze into the ice shell while it is cooling and thickening. If ammonia-rich melt is trapped at the solidus boundary, solid ammonia-dihydrate ice could form as the ice shell progressively cools.

To address these questions, we constructed a coupled thermal evolution-melt migration model. We simultaneously solve for melt-migration and ice shell thermal evolution in a thickening ice shell, using a one-dimensional finite difference code. Our numerical
model, described in detail in [1], solves for the conservation of mass, energy, momentum and composition.

We focus on a time when the ice shell is initially very thin and cools by conduction. We assume an initial ice shell thickness of 1 km above a subsurface ocean with an ammonia concentration of $\chi_{NH_3} = 10\%$. In the example shown below we use physical parameters appropriate for Neptune’s moon Triton, with a surface temperature of 40 K [12]. Triton may have been intensely tidally heated as it was captured into orbit around Neptune, melting much of its ice shell [13]. Therefore, our simulations that focus on cooling from an initially warm state are appropriate for Triton’s early history, just after its orbital eccentricity has decayed.

**Results:** Figure 2 shows the melt fraction and ammonia concentration in the ice shell as it thickens from 1 km to 20 km over a period of ~10 Myr. When the ice shell is thickening rapidly, the ice shell is cooling faster than ammonia-rich melt can migrate out, and a significant amount of ammonia becomes frozen into the ice shell. As the ice shell thickening rate slows down, the cooling rate becomes slower than the migration rate of ammonia-rich melt and more ammonia can escape the ice shell and concentrate in the ocean.

We find ammonia can freeze into the top 5 to 10 km of the ice shell at concentrations between 0.5-10%. Below this depth, the ice shell is nearly-pure water ice. Low-temperature ammonia-rich melts migrate orders of magnitude slower than pure water melts, since the compaction viscosity of ice near the eutectic temperature is $\sim 10^{20}$ Pa s, (limiting the rate at which melt can be squeezed out).

**Discussion:** The freezing of ammonia into the upper 5 to 10 km of the ice shell is significant; Solid ammonia ice is denser than the underlying water ice, setting up a potential gravitational instability, which could perhaps play a role in the formation of the geologically young cantaloupe terrain on Triton [12].

An important general conclusion is that volatiles such as ammonia can become frozen into the near-surface during ice shell formation. If the near-surface is ever reheated by tidal heating or convective plumes, near-surface eutectic melts could be generated. These melts would then migrate toward the ocean much slower than pure water melts. The slower migration rate would allow more melt to build up near the surface, and perhaps cause near-surface melts to play a more significant role in geologic resurfacing.

Near-surface melt bodies that migrate down slowly would be more susceptible to freeze out and overpressurization [2,5], which could drive melt toward the surface. Future work will focus on applying our model- ing to brines and expanding our melt-migration and thermal evolution models to two and three-dimensional codes.