HOLD ON TO YOUR VOLATILES - EARLY PRESERVATION IN EVOLVING ICY PLANETESIMALS.

G. Sarid and S. T. Stewart, Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, MA 02138, USA.

Introduction. The outer Solar System hosts a vast population of small icy bodies, considered to be primitive remnants from the planet formation epoch [1]. Early thermal and collisional processes affected such planetesimals to varying degrees depending on the time scale and dynamics of early planet growth. Hence, key information about early planet formation processes in proto-planetary disks are recorded in icy-rocky bodies, ranging from comets to dwarf planets.

Recent observations have revealed that many large (>~1000 km in diameter) trans-Neptunian objects (TNOs) exhibit features of crystalline water ice in their surface spectra [2]. Some may even exhibit amorphous ice features [3]. In addition, some of these objects show distinct spectral features of more volatile ices, such as methane and ethane [4, 5] or hydrated ammonia [6, 7].

We present calculations of the early evolution of icy-rocky planetesimals formed beyond the water ice snow line. Such objects should also contain non-negligible fractions of other volatile compounds. The volatile composition and interior structure of these objects may change considerably due to internal heating and/or collisional modification prior to settling in their current (relatively quiescent) dynamical niches. Some volatiles may survive throughout, but the combined thermal and collisional histories may impose an additional composition gradient to that inherent from the disk's physico-chemical evolution. This could be used to test planet formation scenarios in the outer solar system.

Numerical Approach. We regard a planetesimal as a cometary-like porous aggregate of various volatile compounds (as ices or trapped gases) and refractory silicate-mineral solid grains [8]. This initial mix (either homogeneous or following some prescribed heterogeneity) is evolved under the influence of combined energy sources, such as crystallization (amorphous to crystalline water ice transition), radioactive decay (both short-lived and long-lived radionuclides), and reduced insolation. Equilibrium chemical compositions for these objects are taken from existing simulations of chemical and dynamical evolution of disk material [9]. These key volatile species (e.g., H_2O, CO, CO_2, NH_3, CH_4 and CH_3OH) are also the most commonly observed in comets [10], which are remnants of the early planetesimal population.

The early presence of volatile species in the interior can affect the overall heat balance and accompanied phase transitions [11, 12]. Another important effect of volatiles, mostly water ice, is how shock-induced melting and vaporization can affect fragmentation and cratering, during massive collision events [13, 14].

Thermal and chemical internal evolution is examined self-consistently, as the abundances and locations of all species evolve, and we record mass ratios, temperatures, pressures and porosity variations [12, 15]. The equations that govern thermal processing of ices and multi-phase gas flow in a porous medium are those of mass and energy balance, coupled with a hydrostatic scheme, for a 1-D spherical grid of the interior and a quasi-3D calculation of the surface [16].

To explore the effects of collisions on the internal distributions of volatiles, we conduct 3D numerical simulations of collisions between porous icy bodies using the CTH shock physics code [17]. The spatially heterogeneous effects of shock-induced heating, pore compaction, and bulk brecciation and redistribution of materials are used to estimate the post-impact re-equilibration of internal volatiles following collisions between similarly-sized bodies.

In this preliminary work, we focus on understanding the effects of different collision regimes (e.g., merging, disruption, hit-and-run, and graze-and-merge) on early volatile preservation. These regimes include potential moon-forming collisions between large TNOs. In the future, such results can be used to estimate the cumulative effects of multiple impacts.

Results. We show that under certain conditions, layers of crystalline water ice, amorphous water ice and more volatile ices can co-exist, for a prolonged duration in large TNOs. This is shown in Figure 1, where we plot the end-state of a ~1 Gyr evolution run for Makemake, a TNO dwarf planet (~1500 km in diameter). The intermittent layers of ices, which are a part of an overall semi-stratified internal structure, may also exist at a relative depth of a few percent of the object’s radius. These characteristic length scales are comparable to the surface roughness that was found for Ceres [18], a possibly volatile-rich dwarf planet, which may resemble other large TNOs (but residing in the asteroid main belt).

The dynamic pressures encountered during large TNO collisions are sufficient to compact initial pore spaces. An example calculation of the peak pressures experienced during a typical collision between large

TNOs is shown in Figure 2. Pore compaction is achieved near the impact site in this grazing impact. The subsequent merging of the bodies leaves a heterogeneous pattern of compacted and heated material. These processes lead to variations in areas of enhanced or supressed volatile sublimation and degassing through the sub-surface layers.

We stress that the final distribution of material is strongly influence by the inclusion of strength in the simulation; hydrodynamic simulations of similar impacts have artificially enhanced mixing of materials. We will also consider the differences in volatile evolution for initially homogeneous and initially stratified bodies.

We will discuss the survival of species more volatile than water, as a function of their initial phases, objects size and density (porosity), and the relative timing of collisional and thermo-chemical evolution. For example, larger and denser objects internally heated by radionuclides can have volatiles initially survive close to the surface, only to be lost as they are destabilized by a collision (leading to migration inward or sublimation from the body). In some cases, deeply buried material, which is thermally altered or devolatilized, may survive non-destructive collisions.

Acknowledgements. This work is supported by NASA Outer Planets Research Grants NNX09AP27G and NNX12AK25G.

References. [1] Stern S. A. (2003) *Nature*, *424*, 6949, 639-642. [2] Barkume K. M. et al. (2008) *AJ*, *135*, 55-67. [3] Pinilla-Alonso N. et al. (2009) *A&A*, *496*, 547-556. [4] Licandro J. et al. (2006) *A&A*, *445*, L35-L38. [5] Schaller E. L. and Brown M. E. (2007) *ApJ*, *670*, L49-L51. [6] Cook J. C. et al. (2007) *ApJ*, *663*, 1406-1419. [7] Barucci M. A. et al. (2008) *A&A*, *479*, L13-L16. [8] Weidenschilling S. J. (2004) *Comets II*, U. Arizona Press, 97-104. [9] Bond J. C. et al. (2010) *ApJ*, *715*, 1050-1070. [10] Bockelee-Morvan D. et al. (2004) *Comets II*, U. Arizona Press, 391-423. [11] Desch S. J. et al. (2009) *Icarus*, *202*, 694-714. [12] Prialnik D. et al. (2008) *SSRv*, *138*, 147-164. [13] Leinhardt, Z. M., et al. (2008) *The Solar System Beyond Neptune*, U. Arizona Press, 195-211. [14] Kraus R. G., Senft L. E. and Stewart S. T. (2011) *Icarus*, *214*, 724-738. [15] Sarid G. and Prialnik D. (2009) *MAPS*, *44*, 1905-1916. [16] Prialnik D. et al. *Comets II*, U. Arizona Press, 359-387. [17] McGlaun, J.M., et al. (1990) *Int. J. Impact Eng. 10*, 351-360. [18] Li J.-Y. et al. (2006) *Icarus*, *182*, 143-160. [19] Leinhardt, Z. M. et al. (2010) *ApJ*, *714*, 1789-1799.

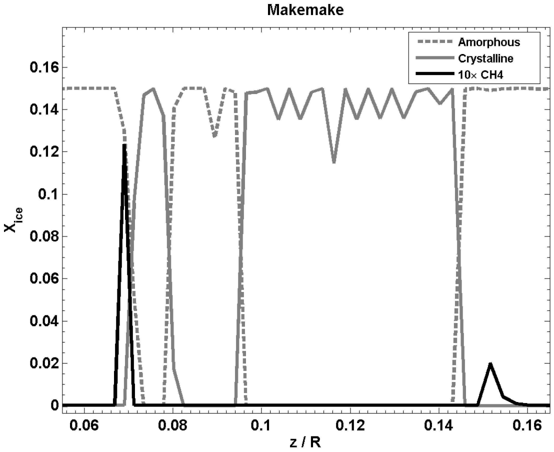

Figure 1. A snapshot of internal structure at the end of a long-term simulation run for (136472) Makemake. Stratified ice structure is shown as mass fraction of ices vs. relative depth, below the surface (z/R=0). We focused here on the region around the maximum abundance of methane ice.

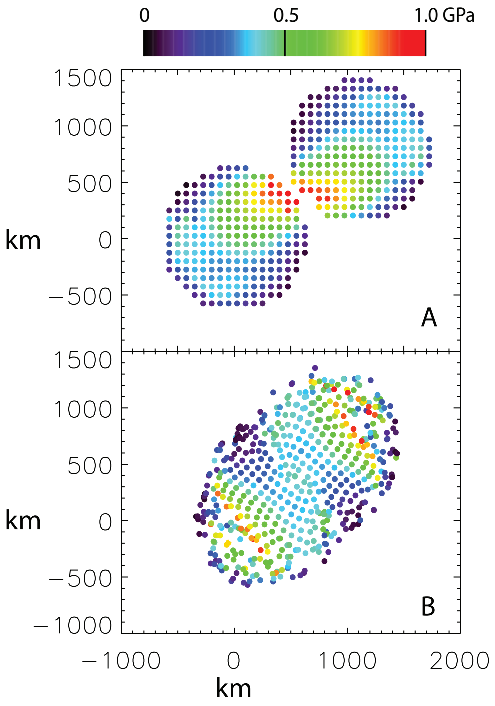

Figure 2. Example peak pessures recorded by Lagrangian tracer particles for the graze-and-merge collision proposed for the formation of the dwarf planet Haumea (simulation from Fig. 4 in [19] with strength). (A) Peak shock pressures in the midplane of initial configurations for two 1300-km diameter ice/rock bodies colliding at an 800 m/s mutual escape velocity. (B) Peak shock pressures for material shown in their final locations in the midplane of the merged body.