GEOLOGICAL PROCESSES ON TITAN DRIVEN BY LOW THERMAL CONDUCTIVITY VOLATILE-RICH DEPOSITS: IMPLICATIONS FOR AMMONIA-WATER CRYOVOLCANISM.

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Introduction: Differences in thermal conductivities exhibited by materials comprising the crust of volatile-rich bodies in the outer solar system may play an important role in controlling the heat flow within and beneath crustal volatile deposits. Such materials, which include non-water ices, clathrate hydrates, salt hydrates, hydrocarbons, just to mention a few, have thermal conductivities 2 to 20 times lower when compared to ice 1h as well as silicates [1, 2]. Consequently, as described below, they may be responsible for driving a number of geological processes. Titan is one of the icy satellites whose crust is thought to contain a large variety of volatile solids and therefore is a premiere candidate to be affected geologically by differences in thermal properties of its crustal components. Recently, modeling of the thermal environment beneath and adjacent to hydrocarbon dunes overlying a water-ice crust has shown that the self-insulating effect of the benzene-like dunes can yield thermal anomalies sufficient to drive melting [3]. Such mechanisms may be responsible for other geological processes occurring in Titan's crust. Here, we are interested in understanding how the difference in thermal conductivity between water-ice, ammonia hydrate ice and benzene may affect the cryovolcanic processes hypothesized to occur on Titan. Cryovolcanism on Titan has been proposed long before the Cassini spacecraft reached Saturn [4] and it is conceived to be one of the major mechanisms by which the satellite replenishes the atmospheric methane lost through photolysis. The analysis of SAR data has identified several possible areas of crovolcanic activity [5]. Here, we model the conduction-driven, steady-state thermal distribution beneath the Sotra Facula, a compelling candidate for cryovolcanim [6]. Finite Element-based Modeling shows that if a thick ammonia hydrate-rich crust was emplaced locally due to cryovolcanism, temperatures in a steady-state conductive regime could reach the peritectic melting point of the ammonia-water system if the ammonia hydrate crust is ≥15 km thick.

Sotra Facula Subsurface Thermal Modeling: Figure 1 shows Cassini SAR images (T25 and T28) of the region near Sotra Facula (subcircular 60-km radius feature located 40 W and 15 S with lobate flow extending toward northeast). Recent SAR-derived topographic data show that the construct exhibits a peak higher than 1000 m and an adjacent 1500 m deep pit which is suspected to be the locale from which the flow originated [5]. Topographic and geomorphologic analysis indicated that Sotra Facula as an excellent candidate for cryovolcanism. We have modeled the subsurface thermal environment beneath the Sotra cryovolcanic construct and determined that the difference in thermal conductivity between the hypothesized ammonia hydrate-rich cryovolcanic ice and the surrounding water-ice crust may be causing a thermal anomaly large enough to drive geological processes related to cryovolcanism.

Figure 1: SAR image of the Sotra Facula cryovolcanic region (40 W and 15 S)

Figure 2 shows the key geometrical parameters used in the simulation. We considered a 2-D SW-NE topographic transect of the Sotra Facula edifice and devised a subsurface scenario comprising four major regions including 1) an ammonia hydrate-rich cryovolcano; 2) a water-ice crust and 3) two 500 m-thick hydrocarbons sand dunes covering the adjacent region. We assumed that the fundamental mode of heat transport is conduction; intergranular gas convection and radiation are ignored. Application of energy conservation coupled with Fourier's heat law yield the well-known heat equation which must be locally satisfied by the temperature distribution. For 2-D steady state models, the temperature distribution must, in any given region, satisfy the Laplace equation:

$$k_i(T)\nabla^2 T_i(x,y) = Q_i(x,y)$$
$$(x,y) \in \Omega_i \, , i = 1,2,\ldots$$

$T_i(x,y)$ is the desired temperature distribution in the region Ω_i (i varies depending on the model geometry).

The proposed models have a 4-region configuration. $Q_i(x, y)$ (in W/m^3) is the source density in the i-th region, $k_i(T)$ (in W/mK) is the thermal conductivity of the i-th region. The model regions are assumed to be ammonia hydrate ice, water ice and/or frozen hydrocarbons. The thermal conductivity depends on temperature [8] so the problem is inherently nonlinear.

Appropriate boundary conditions are imposed. On the surface we set a fixed temperature (Dirichelet boundary condition), which for Titan is assumed to be 94 K. At the interface between regions, continuity of temperature and flux is satisfied.

Heat flux coming from the interior is imposed as the bottom boundary condition (Neumann boundary condition). We have assumed that radiogenic heat is produced beneath the model domain and flows upward.

The multi-region nonlinear Laplace equation for complicated geometries generally cannot be solved in terms of elementary functions. Finite Element Method (FEM), coupled with non-linear, iterative techniques have been used to provide accurate numerical solutions.

Titan's crust is assumed to have a thermal conductivity similar to ice (varying non-linearly with temperature, 6.25-3.4 W/m^{2}K in the 94-176 K range [1]). The ammonia-rich crust is modeled as ammonia dihydrate which has a thermal conductivity of 1.2 W/m^{2}K and weakly dependent on temperature on the range 94-176 K [7]. The sand dune thermal conductivity is estimated by fitting data for solid benzene (0.84-0.29 W/m^{2}K in the 80-200 K range) [8]. Benzene's thermal conductivity properties are similar to those of solidified heavy and light alkanes, anthracene, asphalt, polyethylene, and other pure and mixed hydrocarbons, which explains its choice considering the available data as well as the likely occurrence of benzene on Titan's surface.

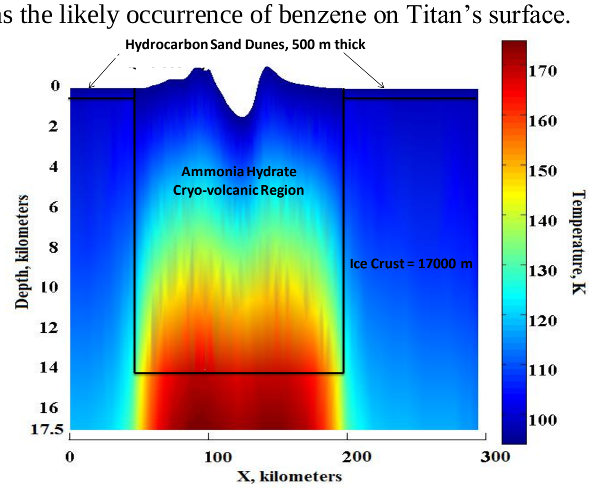

Figure 2: FEM-predicted temperature distribution below Sotra Facula. The model shows warm thermal anomalies within and beneath ammonia dihydrate cryovolcanic construct resting on an ice crust. The surface temperature is set to be 94 K. The heat flux from Titan's interior is estimated to be 0.0063 W/m^2. This is based on Titan's estimated rock mass and a per-unit-mass heat production same as Earth.

Model Interpretation:

These results demonstrate our key point that migration and emplacement of compositionally distinct materials on the surface of and within the crust of Titan will generally cause a perturbation of the thermal conductivity structure and hence, of the thermal structure and heat flow through the crust. This case of construction of a cryomagmatic complex of dominant ammonia dihydrate composition adds to our prior example of migration of thick hydrocarbon dune deposits [3]. Both processes are able to impact the thermal structure of the crust and produce local elevated temperatures within these deposits and in the underlying crust. In the case modeled in Figure 2, temperatures can approach the melting point of ammonia dihydrate so long as the deposits (including the volcanoes and their igneous roots) are ≥15 km thick. Such deposits may be emplaced by a deeper cryovolcanic source.

The crust near the base of the ammonia-water cryomagmatic complex could respond either by deforming ductily and spreading laterally (hence, thinning) as temperatures approach the melting point; or melting could occur and drive additional cryovolcanism. If 10% of the background heat flow goes into the latent heat of fusion of ammonia dihydrate [9], a layer of ammonia hydrate 1 m thick could be melted every 640 years, allowing complete recycling of the cryovolcanic complex every 10^7 years. Alternatively, for the surface topography indicated (Fig. 2), shear stresses are ~1-2 x 10^5 Pa. Lateral creep of the roots might regulate the thickness of the deposit to about 15 km. Extrapolating available ammonia hydrate rheological data [2], we calculate creep rates of 3×10^{-14} s^{-1}, such that topographic creep rooted at depth could be significant for million-year timescales, if the temperatures come close to the melting point. The similarity of timescales and temperatures for significant (a) remelting or (b) creep and lateral spreading suggests that both processes could occur together as a consequence of emplacement of thick cryovolcanic complexes. Migration of surficial hydrocarbon deposits due to eolian [3] or sublimation processes, e.g., hydrocarbon dunes near Sotra Facula, could add further complexity to the thermal development of the crust.

References: [1] Ross, R. G., Kargel, J. S. (1998), Solar System Ices, pp. 33-62. [2] Durham et. al. (2010), Space Science Reviews, 153, 273-298. [3] Furfaro, R. et al. (2009), LPSC abstract #1828. [4] Lorenz, R. D., (1996), Planet. Space Sci., 44, 1021–1028. [5] Lopes, R.M, et. al. (2010), 205, 540–558. [6] Kirk, R.L. et. al. (2010), 2010 Fall AGU meeting. [7] Kargel J.S. (1992), Icarus, 100, 556-574. [8] Purskii, I.O. et. al. (2003) Fizika Nizkikh Temp., 2003, v. 29, Nos. 9/10, p. 1021–1026. [9] Croft et. al., 1988, Icarus 73, 279-293.