Fire and Ice on Triton: models for Cryovolcanism and Glaciology

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The majority of features on Triton's surface can be interpreted as cryovolcanic in origin based on morphology and distribution (1,2). Several important facets of the physical and chemical nature of the extrusive activity can be addressed on the basis of the morphology, remote chemical sensing, comparisons with terrestrial volcanological phenomena, and estimates of bulk composition.

**Bulk Composition and Interior Structure.** The density of Triton is 2.07 g/cm³, near that nominally predicted for objects formed in the solar nebula, as contrasted with objects formed in local planetary nebulae which would have densities near 1.3, like the smaller saturnian satellites. Solar nebular objects consist primarily of water ice and (presumably) carbonaceous chondritic rock, but are somewhat poorer in H₂O ice than planetary nebular objects because carbon is primarily in the form of CO (and nitrogen is in the form of N₂, which absorbs a lot of oxygen that would otherwise form H₂O). In planetary nebular objects, carbon is primarily in the form of CH₄ and nitrogen is in ammonia. Triton is not a purely a solar or planetary object since both nitrogen, associated with solar nebular materials, and methane, usually associated with planetary nebular materials, have been detected in Triton's atmosphere. Neither ammonia nor CO have been directly detected, but the presence of their respective nebular counterparts, methane and N₂, in the atmosphere suggests both may be present (there is indirect evidence for ammonia, see below). The high density of Triton precludes significant incorporation of the pure ices of CO, N₂, or CH₄ (which would yield a density near 1.2), but all of these ices could have been incorporated in minor amounts in Triton during accretion as trapped molecules in a dominant water-ice clathrate or as ammonia hydrate.

H₂O has not been detected on Triton, though it implies the presence of water ice. Observed vertical topography of cliffs, ridges, knobs, and depressions in all of Triton's surface units except the polar and smooth "lake" materials is typically hundreds of meters up to near 800 meters. Impact craters are preserved in the smooth materials, ranging in depths from hundreds of meters to near 1.5 km. Based on the measured rheological properties, such topography could only be preserved for a few years if the crust and smooth materials were composed primarily of solid methane, even at Triton's frigid temperatures. Only bumps and ledges a few meters high could be preserved for millions or billions of years if methane were the primary crustal material. Measurements of the viscosity of pure solid ammonia indicate ammonia to be even "softer" than methane at Triton surface conditions, in spite of ammonia's significantly higher melting point. The rheology of solid N₂ and CO have not been measured, but estimates of their creep properties based on isomechanical scaling (3) with other molecular ices (H₂, neon, argon, krypton, CH₄, NH₃, CO₂, and H₂O) indicates that they should be two to three orders of magnitude softer than methane under similar conditions. Of the likely crustal ices, only water ice or water-dominated ammonia-water ice can preserve the observed topography, thus H₂O must be the primary component of both the crustal materials and the smooth "lake" deposits.

The extensive resurfacing on Triton implies that its interior is largely differentiated. The resurfacing by water ice implies that ice did not dominate Triton's interior convective heat transport, allowing temperatures to rise sufficiently to melt and drive out interstitial ices. Once begun, differentiation would tend to fall into a positive feedback loop: removing ice from the core would raise the effective viscosity, which would force the temperature up, which would tend to remove more ice, etc., driving the differentiation to near completion. This must be tested by further modeling, however. Differentiation of Triton's interior is likely to have happened relatively late in the satellite's history, possibly around the time of a giant impact over a rocky core about 1000 km in radius. (There is probably a thin layer of mixed rock-ice at the boundary.) This assumes a rock density of 3.6 g/cm³ and an ice density of 0.92 g/cm³; various assumptions about the hydration state of the rock do not greatly affect this result. The pressure at the bottom of the ice layer is about 1 kb, thus no ice II or higher density phases were present in this model when the ice mantle formed, though a thin layer of ice II may have formed later as the satellite cooled off. The computed thickness of any ice II layer is strongly dependent on the adopted phase boundary between ice I h and ice II, which is poorly at temperatures relevant to Triton's upper crust. The central pressure for this model is about 19 kb and the corresponding mass fraction of rock is about 0.72. The heat driving the differentiation may be due to radioactive heating or a Goldreich-type tidal heating event(4). In either case, differentiation would have begun near the center, first driving out any pure deposits of the light ices CO, N₂, or CH₄, then any ammonia in an ammonia-water melt, then the rest of the light ices and water ice as the clathrate melted. The sequence of melting would have repeated as melting progressed outward. The materials comprising the observed cryovolcanism probably came from the outermost (and last) layer of mixed ices and rock to melt, after the bulk of the ice crust had formed. Thus the observed cryovolcanism may have involved all of molecular ices. Interestingly, the rock core itself is large enough to have undergone some melting of interior rocks, possibly leading to localized rock volcanism at the ice/rock interface. Since the ice crust is relatively thin, the surface may be affected by such an episode.

Speculatively, the large "lakes" may represent local remelting of the ice crust over a rock volcanism zone.

**Minor Compositions of the Cryomagmas.** The morphologies of some of the cryovolcanic deposits provide indirect indicators of composition. There is a range of viscosities represented by the cryovolcanic deposits. The smooth material of the "lakes" is very flat (except for a few clusters of depressions that may be due to subsurface drainage) and embays all bordering irregularities without visible topographic "lips" to the limit of resolution. Thus this material had low viscosities at the time of emplacement. Conversely, the high-standing linear ridges and light lobate deposits in the patchy-smooth and hummocky materials appear to be extruded materials hundreds of meters thick, indicating high viscosities at the time of emplacement. Direct estimates of the internal viscosities of the thick flows cannot be made, but where the thicknesses of the edges of the flows imply yield strengths at the time of flow stagnation of the order of a few tens of a bar, in the middle of the observed range of yield strengths for terrestrial lava flows. For
TRITON MODELS. CROFT, S.K.

terrestrial magmas, internal viscosities correlate roughly with yield stresses (the physical relationship is not well understood). Since the mechanics and yield stresses of the flows on Triton (though certainly not the compositions) are apparently similar to those of terrestrial flows, the viscosities of the flows on Triton are probably also similar, of order $10^3$ poise. The viscosities of pure molecular liquids (i.e., pure methane, water, etc.) are very low (order $10^2$ poise). Viscosities high enough to generate very thick deposits have been found only in partially gaseous mixtures of substances: to date only ammonia-water and mixtures of ammonia-water with small amounts of other substances have been confirmed to generate viscosities sufficiently high(5). Thus the ridges and lobate deposits may indicate the presence of small amounts of ammonia mixed in the melts. Crater statistics and superposition indicate that the smooth "lake" materials are generally younger than the ridges and lobate deposits. Thus the more viscous materials may represent early melts containing ammonia, while the late "lakes" materials may be water-rich melts that were generated after the ammonia was exhausted in the melt-generating regions. The composition of the "spots" and the lobate dark deposits are unknown. Their morphologies are different from the other cryovolcanic materials, suggesting a distinct composition. The melts are stratigraphically late, suggesting that they are late, high temperature (200 - 300 K) melts. One possibility for the composition of these deposits are the paraffin-like compounds found in small amounts in carbonaceous materials. Such compounds have appropriate melting points, densities low enough to rise through an ice crust, viscosities high enough to make the lobate forms, and carbon capable of darkening with time to the observed albedos.

Nature of the Volatiles. Several morphologic forms indicate cryoclastic and possibly explosive cryovolcanism (2), which implies the presence of materials much more volatile than H$_2$O. The primary candidates are CH$_4$, CO, and N$_2$. At eruption temperatures characteristic of water-rich cryomagmas (270 K), these gases dissolve at levels similar to 1-10 in terrestrial magmas. Solubility increases with increasing pressure, reaching concentrations of several weight % at one kilobar, the approximate pressure at the presumed last melt zone at the rock/ice interface. Exsolution of the gases at these concentrations upon nearness of the surface will generate particulate ejection velocities of 300 to 500 m/s, just in the range needed to produce cryoclastic ejecta blankets in the observed diameter range of a few hundred kilometers. The liquids of CH$_4$, CO, and N$_2$ are all buoyant in an H$_2$O crust and will exist as liquids at depths of a few to a few tens of kilometers in Triton’s crust for likely thermal gradients. The vapor pressures of N$_2$ and CO at 270 K are 5-10 kb (comparable to steam in terrestrial magmas), sufficient to blast off lids of ice several kilometers thick. Thus liquid water penetrating pods of liquid N$_2$, CH$_4$, or CO at depth would be capable of maar-like explosions, possibly producing features like the dimples of the cantaloupe terrain.

Vent Shape. One of the surprises on Triton was the presence of circular cryovolcanic vents similar to terrestrial vents in addition to the linear vents characteristic of cryovolcanism on the other icy satellites. Mechanism changing the initial linear vents on earth to circular vents include: a) thermal stress driving wall failure, b) volatiles in the wall rocks driving wall failure by vaporization, and c) thermal melting and erosion of the walls. These mechanisms have not yet been thoroughly evaluated for cryovolcanism in an ice crust. Thermal stresses are apparently not important since similar temperature rises would occur during cryovolcanic intrusion on all the icy satellites, whereas circular vents are not common. Volatile expansion may be the case on Triton, but this implies no "volatiles" on the other icy satellites. Thermal erosion may work if Triton's cryomagmas are water-rich while those on the other icy satellites are not. Work on this problem is in progress.

"Glaciers." The rheological differences between water ice and other molecular ices indicate that the roll water ice plays in Triton's geology is thus the roll to the roll of rock on Earth, while the roll of methane and nitrogen ices is similar to the roll of temperate water ice; in other words, layers of methane and nitrogen ices more than a few meters thick on Triton would flow downhill in a glacier-like fashion and collect in low spots. No "glaciers" or glacial features have been seen on Triton. However, the stresses at the bases of layers of methane and nitrogen snow thick enough to flow are very small (of order 10$^{-4}$ bars), hence little mechanical erosion of the kind associated with terrestrial glaciers is expected. Also, fissures and surface deformations associated with the very thin elastic layers (of order a few meters) would be small, probably below the resolution available for Triton, thus "glacial" deposits on Triton would be difficult to recognize. However, many surfaces on Triton are characterized by isolated rugged ridges separated by smooth-floored valleys. The bright material of the polar caps, which are probably "snows" of methane and nitrogen, preferentially occupy low spots near the edge of the polar cap. Such low-lying smooth materials may represent methane and nitrogen ices that have "glacially" onto the topographic lowlands, obscuring any pre-existing roughness.