IMPACT CRATERING ON TITAN: HYDROCARBONS VERSUS WATER. J. Lunine[1], N. Artemieva[2], and G. Tobie[3]. [1]Department of Physics, Univ. Rome Tor Vergata, jlunine@roma2.infn.it; [2]Planetary Science Institute, Tucson, AZ 85719, artemeva@psi.edu; [3]Laboratoire de Planetologie et Geodynamique, UMR-CNRS 6112, Universite de Nantes, gabriel.tobie@univ-nantes.fr.

Introduction: Saturn's largest moon Titan should have a layer 200-500 meters thick of ethane averaged over the surface of the planet if methane photolysis has proceeded in a continuous fashion over geologic time [1]. The Cassini-Huygens observations militate against the presence of exposures of liquid hydrocarbons extensive enough to constitute the expected reservoir [2]. In this paper we explore the hypothesis that high velocity cometary impacts have removed the reservoir.

Numerical model and initial conditions: To model high-velocity impacts on Titan we use the 3D hydrocode SOVA [3] complemented by the ANEOS equation of state for ice-water [4,5].

Target: The internal structure of Titan after accretion and subsequent core formation consists of an inner silicate core, a lower mantle of high-pressure ices, an upper mantle of water with a small amount (a few percent) of ammonia and a relatively rigid crust. Until 0.5-1 Gyr ago, this crust was largely methane clathrate hydrate with low thermal conductivity and high rigidity, and therefore was quite thin, 10-20 km [6]. Later, ice I began to form at the base of the methane clathrate layer, thickening the crust to its present-day value of about 50 km. The crustal thickening is consistent with the dearth of craters on Titan that yields an age for the surface between 0.2-1 Gyr [7,8], because the thin crust would have been unable to support crater topography down to sizes of 5-10 km, at which atmospheric screening in turn would eliminate smaller craters [9]. Thus, we consider two alternative crustal thicknesses of 10 and 50 km respectively, underlain by a liquid water mantle. In both cases the mantle has a temperature of 270 K, and the temperature gradient in the ice corresponds to an assumed constant surface temperature of 94 K.

Projectiles: Comets are the main source of high-velocity impacts on Titan. The simulations model spherical comets made of ice without porosity, striking Titan's surface at 45° (an average impact angle for the isotropic flux). Impact velocities may vary from 3 km/s (Hyperion family comets) to a maximum of 15 km/s (Jupiter family comets) with an average velocity of ~11 km/s. Porosity in the projectile may change substantially the fate of the projectile itself (its melting, vaporization, ejection, and deposition), but not the cratering or ice-breach effects: a comet of 50% porosity is equivalent to a 1.3x smaller non-porous comet.

Crustal breach: Our preliminary modeling [10] of impact into the thick crust of 50 km showed that the projectile diameter should be at least half of the crust thickness to expose fresh water (i.e. to breach the crust). Thinner 10-km crust is easily breached by 2-km-diameter comets – see Fig.1.

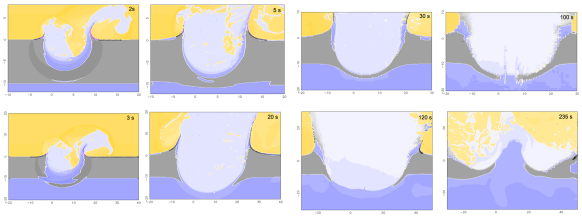

Fig.1. Snapshots of a 11 km/s cometary impact into 10-km-thick crust (grey). Upper plates (2-km-diameter comet): the crust survives the compression stage (2 s and 5 s) and the transient cavity is formed within the ice (30s); however, during the modification (100 s) the crust is broken. Bottom plates (5-km-diameter comet): 3 s after the impact the crust is molten and broken; two minutes later the transient crater reaches its maximum diameter; later the gravitational collapse causes a large rise of liquid water (blue), but no global flooding.

Discussion: There are three ways to mix water with hydrocarbons to form clathrates: 1) ethane near an impact site (directly beneath the impact point) is pushed down and mixed with abundant mantle water; 2) ejected water and hydrocarbons are mixed in the plume and ejecta curtains; 3) deposited water (analogous to terrestrial ejecta blankets) interacts with local hydrocarbons. The last two scenarios result in the deposition of a layer of ethane-rich clathrate onto the surface. As the ethane-rich layer has a density equivalent to liquid water, much larger than the underlying ice/methane clathrate crust, a crustal overturn can occur. Impacts themselves by intensively fracturing the crust may favor the gravitational destabilization of the upper crust and the recycling of ethane-rich clathrate in the interior.

Clathrate stability problem: The mixing of the ethane with the exposed water-ammonia liquid involves large temperature differences. The water-ammonia ocean is at a temperature of 270 K while the ethane liquid and the surrounding environment was originally at 94 K. Fig. 2 shows the distribution of post-impact

temperature near the impact site. The water-ammonia plume cools rapidly to ocean temperature of 270 K where freezing begins. Liquid and gaseous ethane in contact with the forming ice may then form clathrate hydrate, although the extent to which this happens is difficult to predict because of the large temperature differences in various components within the impact site. Ethane clathrate is denser than the surrounding ice mantle, and then could be advected toward the underlying ocean through convective processes, while remaining stable. The result of the breach is trapping of ethane in water ice, possibly as clathrate, even if much of the underlying crust is methane clathrate. Ethane is much preferred as a guest molecule in the clathrate hydrate structure than is methane; for example, in a gas mixture of 0.1% ethane and 99.9% methane, 30% of the clathrate cages will be occupied by ethane [11]. Thus, as atmospheric photochemistry converts methane to ethane and progressively enriches the surface and crustal environment in the latter at the expense of the former, clathrate hydrate formed as a result of interaction with "fresh" liquid water or water ice should contain vastly more ethane than methane.

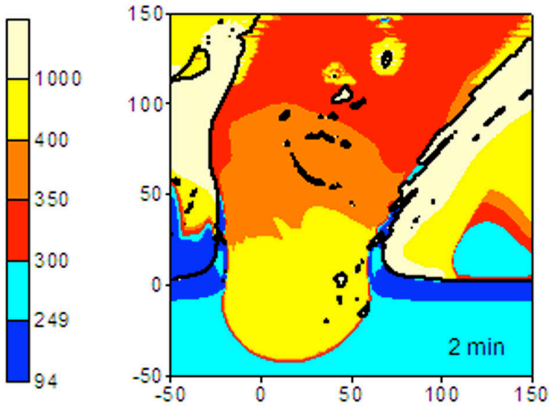

Fig.2. Temperatures in the plume after impact of a 5-km-diameter comet (cf. bottom plates of Fig.1).

The much higher volatility of liquid methane than ethane means that the impact process will end by driving liquids to the ethane-rich endmember through a kind of fractional distillation. The atmosphere is nearly fully saturated in ethane, though not in methane, since the vapor pressure over pure ethane liquid is 2 x 10^{-4} that over liquid methane at 94K. After a large impact, vaporized ethane rains out nearly completely.

Global effects of impacts. The probability of cometary impact events on Jupiter [12] may be extrapolated to Saturnian system, including Titan. This yields 35 events/Gyr with a projectile diameter of >5 km (fresh water exposure within the impact site), 6 events with a projectile diameter of >10 km (water interaction with hydrocarbons within ejecta blanket area), and at least one event with D>20 km (water "ejecta blankets" are thicker than 10 m at the distance of 1000 km, i.e. an affected area ~ a few percent of Titan's surface). Considering the area affected directly by each impact, the input from various events sorted by size is comparable (smaller events affect smaller area, but occur more frequently). At least 10^5 km^2 of Titan's surface was subjected to a direct impact (with total removal of hydrocarbons) and 10 times larger area was influenced indirectly (ejecta deposits, gravity-driven tectonics, etc). Taking into account higher impact fluxes early in Titan's history [13,14] the number of "moderate" impacts could be dozens, with a few global events (>30-km-diameter projectile).

Conclusions: All impactors that survive the entry through Titan's thick atmosphere breach the thin crust dominant on Titan for much of its history, and expose surface deposits of hydrocarbons—including ethane—to the liquid mantle. The surface exposition of fresh liquid water and water ice may result in the clathration of ethane in and around the impact site. As ethane-rich clathrates have a density larger than water ice or methane clathrates, crustal overturn may occur. In this way, 75-95% of the ethane produced over Titan's history could have been sequestered in the deep interior.

The amount of water ice required to accommodate all the ethane produced up to 0.5-1 Gyr ago is small: 0.3% of the total amount of water in the liquid water-ammonia mantle. The global liquid layer of ethane formed after the crust thickening is somewhere between 20-50 m in depth; we expect that this relatively small amount of ethane is contained within the crust in pore spaces and fractures, possibly as clathrate hydrate [11] and in the high latitude lakes and seas [15].

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