THEORETICAL CALCULATIONS ON SEDIMENT TRANSPORT ON TITAN, AND THE POSSIBLE PRODUCTION OF STREAMLINED FORMS

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Introduction: The Cassini Imaging Science System (ISS) [1] has been returning images of Titan, along with other Saturnian satellites. Images taken through the 938 nm methane window see down to Titan's surface [1]. One of the purposes of the Cassini mission is to investigate possible fluid cycling on Titan. Lemniscate features shown recently [2] and radar evidence of surface flow [3] prompted us to consider theoretically the creation by methane fluid flow of streamlined forms on Titan. This follows work by other groups [e.g. 4] in theoretical consideration of fluid motion on Titan's surface.

Streamlined forms on terrestrial bodies: Streamlined forms on Earth and Mars are teardrop-shaped features oriented with the wide end pointed into the predominate flow and the tapered end pointed down flow. Under natural conditions, they are created as sediment-laden fluid flows around an obstacle; the sediment in the fluid creates a streamlined shape through erosion of the obstacle and/or deposition in its lee [5]. On Earth, both natural and engineered (e.g., airfoil) streamlined forms, created by or designed for water and air, have a L:W value ~ 3-4; this derives from the countervailing tendencies of the flow fluid to 1) minimize form drag through cross-section minimization and therefore an increase form elongation, and 2) minimize surface drag through surface area minimzation and therefore an increase in form compaction [5]. Streamlined forms were investigated in the Pleistocene-age Channel Scabland catastrophic flood terrain in eastern Washington state [6], and have since been considered one of the primary indicators of catastrophic fluid flow in the outflow channels on Mars [6,7]. Figure 1 shows a grouping of streamlined forms in an outflow channel on Mars [8]. Streamlining also occurs in marine environments behind shipwrecks and other obstacles [9].

Streamlined forms on Titan? The creation of streamlined forms requires sediment transport both to erode preexisting terrain and to deposit material in the lee of the flow obstacle. To test the possibility of streamlined form creation on Titan, we applied hydraulic formulas to establish conditions for sediment transport on Titan.

Sediment transport in terrestrial environments occurs as: 1) bedload (material that moves by sliding, rolling, or saltating on the channel floor), 2) suspended load (material that is transported above the bed by vertical currents in the water), and 3) washload (auto-

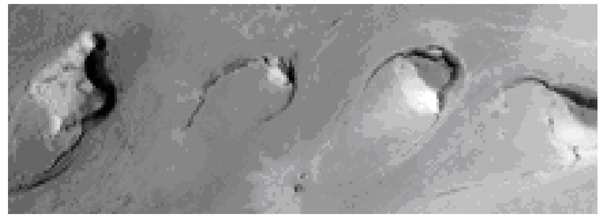

Figure 1: Mosaic of Mars Orbiter Camera images showing 4 streamlined forms in the Athabasca Valles channel. Flow was from upper right to lower left.

suspended load that is uniformly distributed in the water column) [10]. Bedforms such as streamlined forms are created through erosion by the flow and deposition of bedload and suspended load. These categories are distinguished by balancing settling velocity (or terminal velocity), the rate at which a sediment grain settles in a fluid, with the fluid frictional shear velocity. Small or light grains which settle more slowly are more easily kept in suspension by the shear velocity; large or heavy grains, which settle more quickly, move either as bedload or not at all. Threshold values of k, where k is the ratio of settling to frictional velocities, are used to discriminate among these categories [10].

We used the following formulae for terminal velocity of ice grains in methane under laminar (Stokes) and turbulent conditions [11]:

$$V_{lam} = (1/18)[(\sigma-\rho)/\eta](gd^2)$$

$$V_{turb} = [c_D(\sigma-\rho)/\rho](gd)]^{1/2},$$

where d is the particle diameter, σ is the particle density, ρ is the fluid density, η is the fluid dynamic viscosity, g is the acceleration of gravity, and c_D is the drag coefficient (~0.5 for a sphere in turbulent flow, see [7], pg. 266). We used k=0.075 for the onset of washload, k=1.25 for the onset of suspended load [10].

For quartz particles in H_2O flow on Earth, σ=2650 kg/m^3, ρ=1000 kg/m^3, $\eta=1\times10^{-3}$ Pa-s, and g=9.8 m/s^2. For Mars, we consider basalt particles in H_2O flow. In the same units as above, σ_{basalt}=2900, g=3.69; and ρ and η remain unchanged. For Titan, we consider both H_2O ice particles and organic material as the sediment in a CH_4/N_2 fluid flow. In the above units, σ_{ice}=992, $\sigma_{organic}$=1500, ρ=450 , $\eta=2\times10^{-4}$, and g=1.35 [12].

The results of our calculations are shown in Fig. 2. For a given shear velocity, larger grains can be transported on Titan and Mars than on Earth. Thus, in comparison with water flow on Earth and Mars, even slow to moderate CH_4/N_2 flow on Titan may lead to production of streamlined forms. These calculations only apply to the competence of the fluid to transport sediment; the actual transport is limited by the availability of the sediment. In the case of a cohesive substrate, e.g., flow over bedrock, cavitation may be the dominant erosive process [13] and the limiting consideration on sediment transport.

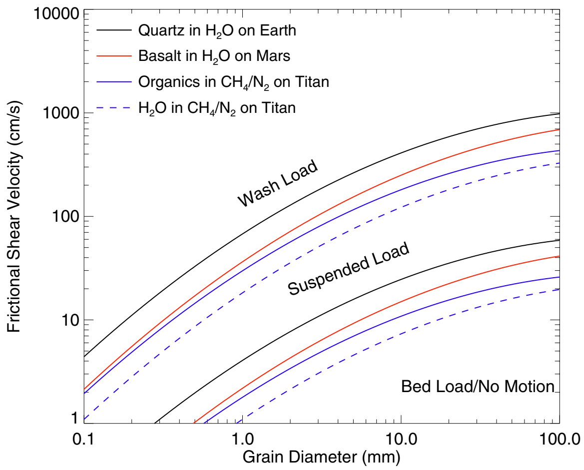

Figure 2. Fields of modes of transport for various materials on Earth, Mars, and Titan.

Are flows of this velocity possible on Titan? For uniform or near-uniform flow, the relation between frictional shear velocity and flow depth is given as: $u_* = (ghS)^{1/2}$, where h is flow depth and S is bed slope. We used this relation to calculate the minimum flow depth required to carry quartz and organic sediment in wash load and suspended load for various slopes.

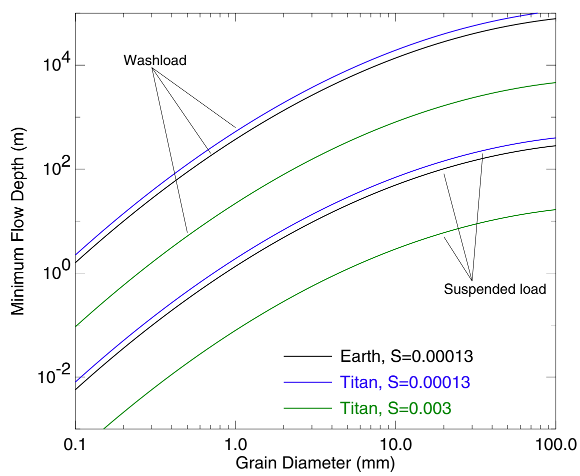

Figure 3. Minimum flow depths required to carry quartz and organic sediment on Earth and Titan, respectively, in wash and suspended load. (S in m/m)

In Fig. 3, the lower slope is characteristic of rivers on Earth and the larger slope is that for Ares Vallis, Mars and the Channeled Scabland flood terrain on Earth. For similar slopes, the minimum flow depth required to carry wash or suspended load is actually quite similar for Earth and Titan (assuming organics as the sediment on Titan). If H_2O ice is the sediment, minimum depths are even lower on Titan.

Flows of the depth required are unlikely on Titan if the weather cycles are regular. Methane rain will typically evaporate before reaching the ground [13] because of the low relative humidity of CH_4; flows of depth > 100m are not expected. If regional slopes are substantially higher than the minimum assumed, however, flows of sufficient depth (and speed) to transport significant amounts of sediment are possible. Additionally or alternatively, streamlining could occur in hydrocarbon oceans due to coastal currents or basin-scale circulation, in a manner analogous to streamlining in marine environments on Earth [e.g., 9,14].

Future work: In future work, we plan to investigate the likelihood of depositional verses erosive processes on Titan, including a distinction between erosion by sediment impact [e.g., 15] versus erosion by cavitation [13]. Having shown the possibility of sediment transport by CH_4/N_2 fluid flow, we hope to use Cassini data (e.g., slopes from the Cassini Radar Altimeter) to explore the possible conditions of that flow in comparison to the required sediment tranport parameters. We will also continue to explore the lemniscate features' morphology, i.e., if streamlined forms, they should stand higher than the surrounding terrain

The streamlined forms on Earth and Mars are located in topographic (confined) channels. Rivers on Titan are 'improbable' [13], but streamlines around shipwrecks [9] show that streamlining also occurs in unconfined flow. Future Cassini data will indicate if the Titanic features are streamlined forms and with what type of flow and material they formed.

References: [1] http://ciclops.lpl.arizona.edu/ [2] McEwen A.S. et al. 2004 *AGU FM*, abstract P41B-01 [3] Elachi C. et al. 2004 *AGI FM*, abstract P41B-02 [4] Ori et al. 1998 *Planet Space Sci* 46(9/10) 1417-1421 [5] Komar P.D. (1983) *Geology* 11, 651-654 [6] Baker V.R. (1982) The Channels of Mars [7] Carr M.H. (1996) Water on Mars [8] Burr D.B. et al (2002) *Icarus* 159, 53-73. [9] Caston G.F. 1979 *Geology* 33, 193-204 [10] Komar P.D. (1980) *Icarus* 42, 317-329. [11] Turcotte, D.L. and G. Schubert (1982) Geodynamics. [12] Lorenz R.D. et al. *EOS* 84(14), 125, 131-132. [13] Lorenz R.D. and Mitton J. Lifting Titan's Veil [14] Stride A.H. 1982 (ed) Offshore Tidal Sands: processes and deposits, see Ch.3 [15] Hancock G.S. et al. 1998 Rivers over Rock, p. 35-60.