COMPARATIVE SEDIMENT TRANSPORT BY FLOWING LIQUID ON EARTH, MARS, AND TITAN: SYNTHESIS OF THEORY AND OBSERVATIONS. D. M. Burr[1], [1]Carl Sagan Center, SETI Institute (515 N Whisman Rd, Mountain View, CA 94041 USA, dburr@seti.org).

Introduction: On three bodies in our solar system, sediment is known to be or have been moved by flowing liquid. Silicate sediment is or has been moved by flowing water on Earth and Mars, and organic sediment and ice-rich sediment is or has been moved by flowing methane-nitrogen on Titan. Understanding the process of liquid sediment transport informs myriad investigations, such as interpreting the history of water on Mars' surface (which processes may be on-going today [1]) and constraining the age of Titan's lightly cratered surface [e.g., 2]. This abstract will discuss 1-D modeling comparing liquid sediment transport on Earth, Mars, and Titan, some implications of that modeling, and a survey of published observations pertinent to this topic. This work pertains to liquid flowing uni-directionally under the force of gravity, and is not directly relevant to liquid moved by other driving forces (e.g., tides).

Modeling: Comparative modeling was accomplished for these three bodies through use of hydraulic formulae for entrainment thresholds ("Shields' curve"). Two different empirical ratio values were then used to determine the settling velocity cutoffs for the three modes of sediment transport (i.e., bedload, suspended load, and washload). Finally, these settling velocity curves were converted into minimum flow depth curves for each category of sediment transport (Fig. 1). (See [3] for details of this modeling).

Implications: This modeling provides some implications, which can be used in geological interpretation.

Movement. The theory confirms previous calculations [4] that sediment is more likely to be moved (i.e., at lower flow velocity [4] or depth [3]) on Mars than on Earth. It also indicates that, in comparison to Mars and Earth, water-ice sediment on Titan is even more likely to be moved. In contrast, organic sediment on Titan is the least likely of all to be moved. This difference is because of the ~1.5 times greater density of organic than water-ice sediment used in the model [3].

The geological expression of these tendencies, however, depends critically on both the global slope and sediment size distributions. The global distribution of slopes for Titan is not known. Regarding the sediment size distributions, Hugyens data show water-ice sediment ranging from 15 cm down to 3 mm (the imager resolution limit) in diameter, whereas aggregate organic particles in the atmosphere have an approximate modeled diameter of >1 μm [5]. Thus, even with flocculation or other aggregation on the surface, organic sediment is orders of magnitude smaller than water-ice sediment. The shape of the curves in Fig. 1 indicate that, as a consequence, organic sediment should move at orders of magnitude shallower flow.

Deposition. Deposition of sediment from flowing liquid creates distinct, recognizable bedforms such as subaqueous dunes or bars [e.g., 6, Table 4.10]. In contrast, deposition from standing liquid does not create distinct bedforms, although it creates other, more dispersive deposits (e.g., varves). The Hjulström curve [e.g., 6] shows that, for larger grain sizes, the likelihood of sediment movement correlates with the likelihood of deposition. This implies that sediment is less likely to deposit on Mars than on Earth. The Hjulström curve also shows that, for smaller grain sizes, the likelihood of deposition monotonically decreases, such that it becoming anti-correlative. This implies that the much smaller size of organic sediment on Titan should result in a much, *much* lower likelihood to deposit.

Thus, the implications of the theory are 1) that distinct, remotely recognizable, terrestrial-style bedforms are less likely on Mars than on Earth, and 2) that on Titan, terrestrial-style bedforms are comprised primarily of water-ice-rich sediments, and that fluvial bedforms of only organic sediments are non-existent.

Observations:

Observations of bedforms from the literature can be compared with these two theoretical implications.

1) *Mars.* In the Hesperian-aged, circum-Chryse outflow channels, numerous streamlined bars exist. These have been broadly inferred on the basis of high thermal inerial to be erosional [7]. In some Amazonian-aged outflow channels, streamlined bars are scarce [8]. In other Amazonian-aged channels, bar morphology indicates formation by deposition, with bar location and clustering suggesting special circumstances causing that deposition, i.e., hydraulic ponding [9]. Subaqueous dunes in Athabasca Valles [10] are located in this site of inferred hydraulic ponding, and subaqueous dunes in Maja Valles [11] are likewise located at a site conducive to ponding. In the smaller, Noachian-aged outflow channels, bars also appear rare, but those that have been identified in the literature are inferred morphologically to be depositional [e.g., 12, Fig. 15]. This example is located at a channel junction, a location that implies hydraulic processes that would decrease the flow capacity. In summary, Martian outflow channels bars have been broadly inferred to be erosional. Bedforms inferred to be depositional are located in sites of unusual hydraulic processes.

2) *Titan*. Early Cassini-Huygens data have shown a fluvially complex surface whose interpretation is just

beginning. The channels in the Huygens images indicate significant fluvial erosion [5]. As the channels are incised into inferred water-ice bedrock, they should have produced water-ice sediments, such as are seen at the Huygens landing site [5]. However, no such sediments are visible as bars, dunes, or other distinct, terrestrial-style bedforms within the Huygens channels nor at the channel mouths. The resolution of the images may be (part of) the cause of that non-observance within the channels. However, a bright bar and other subparallel bright streaks are visible 'offshore' of the Huygens 'shoreline' [5, their Fig. 5]. Their bright albedo and static appearance indicates that these features may be water ice sediments. Their plan-view morphology and location proximal to the coastline and fluvial channels suggests transport of water-ice sediment via the channels, dispersive desposition on the low-albedo plain, and subsequently reworking into a coastal marine bedform (e.g., a spit, longshore bar). Such bedforms develop through wave and tidal reworking of beach sediments [e.g., 13]. In summary, bedforms are lacking data of Titan to date. Those forms visible in the Huygens data are not morphologically consistent with fluvial deposits and suggest formation through reworking of more broadly dispersed material.

Synthesis: This synthesis of theoretical modeling and geologic observations indicates that terrestrial-style bedforms are energetically unlikely on Mars [8] and Titan. Their observation indicates unusual hydraulic conditions, and is useful in constraining paleoflow.

Impact/relevance: Previous 1-D hydraulic modelling of Martian outflow channels have used largely present channel topography and assumptions regarding the water elevation (e.g, 'bankfull'), assuptions that have been shown to be likely erroneous [e.g., 14]. For more advanced and multi-dimensional modelling [e.g., 15], bedforms can provide additional constraints. For example, subaqueous dunes occur at Froude numbers less than ~0.7, which provide constrains on model depths and flow velocity [10]. Depositional bars demonstrate a change in channel cross-sectional area and also indicate a decrease of the flow carrying capacity below that necessary to transport sediment of the deposits' inferred grain sizes.

Hypothesis testing: This synthesis is based on theoretical modeling and (especially on Titan) limited observations. It thus provides a hypothesis to be tested with future data of Mars and Titan.

Mars. A meaningful statistical comparison between the distribution of bedforms on Earth and on Mars is not currently possible due to the low resolution and/or poor coverage of Martian data. The 6 m/px resolution imagery of the Mars Reconnaissance Orbiter (MRO) Context Imager (CTX) will provide some additional coverage of Mars' surface [16], including channel beforms. If this hypothesis is correct, those data will confirm a general lack of depositional bedforms except in hydraulically unusual locations. If the hypothesis is incorrect, CTX data will reveal a population of small-scale bedforms not previously imaged.

Titan. Interpretation of Titan data is complicated by the likely discrepancy of production rate and grain size between ice and organic sediments. However, if this hypothesis is correct, further coverage will show a paucity of bright (e.g., water ice) fluvial bedforms, and organic bedforms will continue to be absent.

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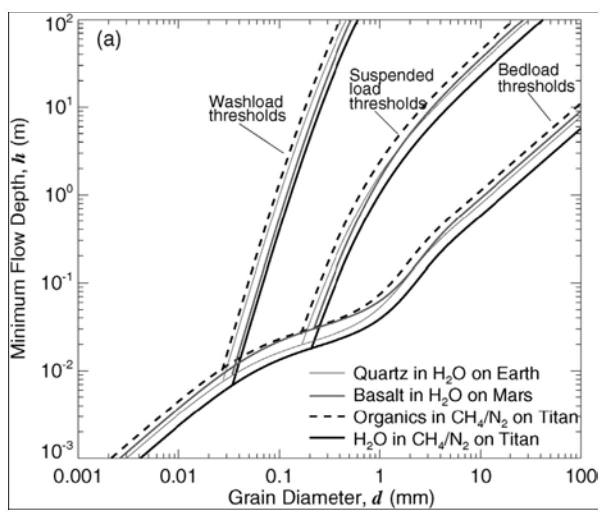

Figure 1: The minimum required flow depth for each mode of sediment transport by grain size [from 3].