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Morphology of fluvial networks on Titan: Evidence for structural control ☆

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ABSTRACT

Although Titan's surface shows clear evidence of erosional modification, such as fluvial incision, evidence for tectonism has been less apparent. On Earth, fluvial networks with strongly preferred orientations are often associated with structural features, such as faults or joints, that influence flow or erodibility. We delineated and classified the morphologies of fluvial drainages on Titan and discovered evidence of structural control. Fluvial networks were delineated both on synthetic aperture radar (SAR) images covering ~40% of Titan from the Cassini Titan Radar Mapper up through T71 and on visible light images of the Huygens landing site collected by the Descent Imager/Spectral Radiometer (DISR). The delineated networks were assigned to one of three morphologic classes—dendritic, parallel or rectangular—using a quantitative terrestrial drainage pattern classification algorithm modified for use with Titan data. We validated our modified algorithm by applying it to synthetic fluvial networks produced by a landscape evolution model with no structural control of drainage orientations, and confirmed that only a small fraction of the networks are falsely identified as structurally controlled. As a second validation, we confirmed that our modified algorithm correctly classifies terrestrial networks that are classified in multiple previous works as rectangular. Application of this modified algorithm to our Titan networks results in a classification of rectangular for one-half of the SAR and DISR networks. A review of the geological context of the four terrestrial rectangular networks indicates that tensional stresses formed the structures controlling those terrestrial drainages. Based on the similar brittle response of rock and cryogenic ice to stress, we infer that structures formed under tension are the most likely cause of the rectangular Titan networks delineated here. The distribution of these rectangular networks suggests that tensional stresses on Titan may have been widespread.

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1. Introduction

Like Earth, Titan has a thick, nitrogen-rich atmosphere that participates in an active volatile cycle and produces a range of processes that modify the surface. Clouds of methane, which constitutes ~5% of Titan's troposphere, have been observed to form and dissipate over various regions of Titan, implying rainfall (e.g., Griffith et al., 2000; Porco et al., 2005; Lunine and Atreya, 2008; Atreya et al., 2009; Turtle et al., 2011). Rain has also been inferred from in situ observations near Titan's equator (Tomasko et al., 2005). As a result of this precipitation and associated surface runoff, fluvial networks, thought to be carved into the water ice bedrock (Collins, 2005; Perron et al., 2006) and/or formed by flow across radar-dark plains, are widely distributed (Fig. 1) (Jaumann et al., 2008, 2009; Lorenz et al., 2008; Baugh, 2008; Burr et al., 2009; LeGall et al., 2010; Cartwright et al., 2011; Black et al., 2012; Langhans et al., 2012). Fluvial incision resulting from sapping by subsurface liquid has been suggested to have operated on small networks with stubby tributaries in the northeast wall of Menrva crater (Baugh, 2008) and at the Huygens landing site (Tomasko et al., 2005), although terrestrial analog work implicates the strong role of overland flow in forming such networks (Lamb et al., 2006, 2008; Burr et al., 2012). In the polar regions, the fluvial networks commonly empty into lakes potentially filled with liquid hydrocarbons and nitrogen (Stofan et al., 2007; Mitri et al., 2007; Hayes et al., 2008). In tropical regions, dark dune fields provide evidence that aeolian processes are also an active resurfacing agent (Barnes et al., 2008; Radebaugh et al., 2008). These atmospheric, fluvial, lacustrine, and aeolian features attest to exogenic modification of Titan's surface. That this activity was recent or is on-going is

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supported by Titan's low crater density (Lorenz et al., 2007; Wall et al., 2009; Wood et al., 2010; Neish and Lorenz, 2012).

In contrast to these obvious effects of atmospheric and surficial processes, evidence for internally driven modification of Titan's surface by tectonism or cryovolcanism is ambiguous. Hypothesized cryovolcanic features such as Ganesa Macula, interpreted as a dome, and Winia Fluctus, interpreted as a flow (Sotin et al., 2005; Lopes et al., 2007; Wall et al., 2009), have been questioned or reinterpreted (Moore and Pappalardo, 2011). A few observations suggest that tectonism may have modified Titan's landscape. Linear mountains and valleys inferred in the Xanadu region have been attributed to regional extension, and nearby lineaments have been interpreted as systems of conjugate faults (Radebaugh et al., 2011), but an impact origin for this structure and its lineaments has also been suggested (Brown et al., 2011). Steep breaks in topography close to the Ontario Lacus shoreline may indicate the presence of fault scarps, suggesting that the lake is contained within a graben or rift valley (Wall et al., 2010), but in the low-resolution and noisy Cassini images the geomorphologic identification of these putative tectonic features is inconclusive. Radar bright regions interpreted as eroded mountain chains (Radebaugh et al., 2007) represent no more than ~10% of Titan's surface based on mapping through T30 (Lopes et al., 2010), and the source and sign of the tectonic stresses that would have built such features are unclear. These limited observations to date of possible tectonic structures suggest that either Titan does not have active tectonic processes, or that erosion and deposition by rivers and wind effectively mask and erase their effects (Collins et al., 2010), preventing a critical analysis. A comparison of Titan fluvial network shapes with landscape evolution models suggests either recent resurfacing or slow fluvial incision rates on Titan (Black et al., 2012).

Although fluvial erosion can obscure evidence of tectonically generated landforms, it can also reveal tectonic patterns. Tectonic deformation can generate strongly oriented topographic features that divert surface flows, and fault zones, joints or exposed layering that are more easily erodible. These mechanisms can produce fluvial drainage networks with links oriented in a small number of preferred directions, instead of branching networks in which the orientations of individual links are controlled primarily by the slope direction. An example of the influence of tectonic contraction on drainage may be seen in the Zagros Simply Folded Belt in Iran, where an inferred dendritic pre-fold drainage system was reformed after Mio-Pliocene deformation into a trellis pattern, with the dominant stream azimuths parallel to the NW–SE-trending folds (Burberry et al., 2008). Similarly, in the Nepal Himalaya, large transverse rivers flow longitudinally in alternating directions along mountain fronts north of the Main Boundary thrust, forming a 'gridiron' pattern (Gupta, 1997). In the Argentera Massif (French-Italian Alps), the Pliocene–Pleistocene tectonics have also produced transverse (largely trellis) drainages in some regions, although other regions show dendritic drainages (Ribolini and Spagnolo, 2007). In other collisional settings, such preexisting tectonic influence may be erased by subsequent tectonic modification; for example, a study of correlations between kink-banks and jointing with drainage patterns in the Chamba Nappe of the Himalaya, indicates that the river valleys correspond with orientations with neotectonic joints but not with Precambrian to Upper Paleozoic kink-band structures (Sharma et al., 2003). The influence of tensional tectonic stresses may be seen in southwestern Ontario, where Pleistocene glacial deposits are underlain by Paleozoic bedrock on top of Proterozoic basement. The episodic arching of the basement fractured the strata bedrock into regional joint sets whose orientations correspond both to the buried channels within the bedrock and to the superjacent post-glacial river valleys (Eyles et al., 1997). Complex tectonic histories involving both extension and compression may be inferred with input from drainage analysis; a morphotectonic study of the lower Sangro River valley, central Italy showed that uplift and tilting formed a parallel drainage network during the Middle Pleistocene, after which activity along faults and fractures reorganized drainage into a rectangular network (D'Alessandro et al., 2008).

Our plan view analysis of fluvial drainage networks on Titan indicates biases in substrate erodibility or pre-existing topography, suggesting the influence of tectonic structures on overland flow. For this analysis, we used an empirical terrestrial drainage classification algorithm that has been modified for use with the limited information available from the Cassini–Huygens mission at Titan. This classification algorithm differs from the qualitative classification methods used in previous Titan work in that it makes use of measurable parameters, and it yields somewhat different results as presented here. To validate our modifications to the original classification algorithm and to test the robustness of our results, we applied our modified classification algorithm to both previously classified terrestrial drainages and to fluvial networks generated by a numerical landscape evolution model. For the most common drainage patterns in our Titan data, we explored and discuss the types of stress responsible for such drainage patterns on Earth and the implications for Titan.

2. Background

2.1. Fluvial drainage networks in Cassini–Huygens data

Inferred fluvial features have been detected by three imaging instruments onboard the Cassini spacecraft: the Visual and Infrared Mapping Spectrometer (VIMS), operating at 300–5100 nm (Brown et al., 2004), the Imaging Science Subsystem (ISS), operating over 200–1100 nm (Porco et al., 2005), and the Cassini Titan Radar Mapper (RADAR), emitting at 2.17 cm (Elachi et al., 2005). The datasets for these instruments have a range of spatial resolutions. VIMS and ISS images have surface resolutions that vary with position and emission angle, but are commonly a few kilometers per pixel. The synthetic aperture radar (SAR) data from the RADAR are collected in swaths with the highest resolution (~350 m/pixel) at swath center, corresponding to closest approach, and lower resolution (down to 1.7 km/pixel) at the swath ends. These data constitute the highest resolution dataset available from the Cassini spacecraft. Although they cover less than one-half of the surface to date, compared to near-global coverage by the VIMS and ISS data, the SAR data provide the best resolution for mapping the fluvial networks and sufficient coverage to infer global distributions by network type (Fig. 1). Radar swaths are referred to by their Titan flyby number, T#.

The fluvial networks observed in SAR data can be hundreds of kilometers in length and tens to hundreds of kilometers in width and display a variety of forms (Fig. 2; see also Burr et al., 2012). Initial studies classified the networks on the basis of width and length as well as visual characteristics such as SAR albedo and bright-dark pairing (Lorenz et al., 2008). More recent efforts to map and characterize fluvial networks also used a visual classification scheme (Langhans et al., 2012).

Multiple fluvial networks are also observed in visible light (0.66–1.00 μm) images taken by the Huygens Descent Imager/Spectral Radiometer (DISR) during its descent to the surface of Titan (Tomasko et al., 2005; Soderblom et al., 2007a). The spatial resolutions of DISR images range from 20 to 90 m/pixel for images taken during descent. The networks detected in DISR data (~5–10 km in length, ~100 m in width for individual links; Fig. 3) are significantly smaller than those detected in SAR data and are not discernible in the available overlapping SAR data (Soderblom et al., 2007b).

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