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Geomorphologic mapping of the Menrva region of Titan using *Cassini* RADAR data

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ABSTRACT

We made a detailed geomorphologic map of the Menrva region of Titan, using *Cassini* RADAR data as our map base. Using similar techniques and approaches *that* were applied to mapping *Magellan* radar images of Venus, and earlier, more generalized Titan maps, we were able to define and characterize 10 radar morphologic units, along with inferred dunes and fluvial channels, from the RADAR data. Structural features, such as scarps, ridges, and lineaments were also identified. Using principles of superposition, cross-cutting, and embayment relations we created a sequence of map units for this region. We interpret Menrva to be a 440 km wide degraded impact basin, in agreement with earlier studies by Elachi et al. (Elachi, C. et al. [2006]. Nature 441, 709–713) and Wood et al. (Wood, C.A., Lorenz, R., Kirk, R., Lopes, R., Mitchell, K., Stofan, E., and the Cassini RADAR Team [2010]. Icarus 206, 334–344), and identify it as the oldest feature in the map region. Exogenic processes including hydrocarbon fluid channelization forming the Elivagar Flumina channel network and dune fields resulting from aeolian activity are the current geologic processes dominating our map area, and these processes have contributed to the erosion of the crater's ejecta field. There is evidence of multiple episodes of channel formation, erosion and burial by aeolian deposits, as observed elsewhere on Titan by e.g., Barnes et al. (Barnes, J.W. et al. [2005]. Icarus 195, 400–414). Channel outflow regions have morphologies suggestive of streams formed by flash floods, and dune fields are small and restricted rather than forming large dune seas, consistent with a desert-like environment for this region with low supply of hydrocarbon particles, also consistent with other studies by e.g., Lorenz et al. (Lorenz, R.D. et al. [2008a]. Planet. Space Sci. 56, 1132–1144). There is no evidence of cryovolcanism or non-impact-related tectonic activity in the Menrva region, although this region is too small to infer anything about the roles of these processes elsewhere on Titan. This work suggests detailed geomorphologic mapping can confidently be applied to *Cassini* RADAR data, and we suggest that more extensive mapping should be done using RADAR, ISS, and VIMS data geographically distributed across Titan to assess its usefulness for a future combined RADAR–ISS–VIMS-based global geologic map.

1. Introduction

The *Cassini* spacecraft has revealed the surface of Titan in great detail, and studies by the *Cassini* science team are being done to identify the processes that formed and continue to shape Titan's surface (e.g., Barnes et al., 2005, 2007a,b, 2008; Brown et al., 2008; Elachi et al., 2005, 2006; Lunine et al., 2008; McCord et al., 2008; Porco et al., 2005; Lorenz and Radebaugh, 2009; Nelson et al., 2009; Lopes et al., 2010; Wood et al., 2010). In particular, the *Cassini* RADAR experiment (Elachi et al., 2004) has provided detail on surface morphology over regional scales (tens to hundreds of kilometers), enabling the recognition of surface features produced by specific geologic processes. These include fields of longitudinal dunes composed of sand-sized hydrocarbon particles (Lorenz et al., 2006; Radebaugh et al., 2008; Lorenz and Radebaugh, 2009), impact craters (Stofan et al., 2006; Elachi et al., 2006; Wood et al., 2010), river channels (Elachi et al., 2005, 2006; Lorenz et al., 2008a), lakes (Lunine et al., 2006; Stofan et al., 2007), potentially active cryovolcanic edifices (Sotin et al., 2005; Stofan et al., 2006; Lopes et al., 2007; Wall et al., 2009), and mountains and tectonic features (Stofan et al., 2006; Radebaugh et al., 2007). To date there is a technique that has not yet been extensively applied to the *Cassini* data, i.e., planetary geomorphologic mapping (cf., Stofan et al., 2006; Lopes et al., 2007, 2010; Lunine et al., 2008). Geologic and geomorphologic mapping is a critical tool that is required to relate spacecraft observations to the geologic history of planetary bodies, the results of which can provide crucial information to refine models of surface and interior processes. For Titan, the systematic characterization of surface features in specific regions and their distribution in time and space is essential for identifying any

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evolution in geologic processes working on the surface. It is possible that detailed mapping over geographically distributed regions could reveal to what extent (if any) Titan's current geologic activity is influenced by *endogenic* processes (i.e., cryovolcanism and tectonism: e.g., Lopes et al., 2007; Wall et al., 2009) versus *exogenic* processes (i.e., its hydrocarbon cycle and aeolian processes: e.g., Moore and Pappalardo (2008). It is also desirable to investigate whether application of planetary mapping techniques to *Cassini* RADAR images can provide a relative stratigraphic timescale on which processes have affected parts of Titan's surface.

The purpose of this paper is to report results from a "proof-of-concept" exercise in which we applied geomorphologic mapping techniques to a portion of *Cassini* RADAR strip T3, covering the Menrva region of Titan, to make a detailed geologic map. The goal was to test whether geologic mapping techniques as applied to the *Cassini* RADAR images can be used to identify and determine the relative roles of the various geologic processes that have formed this part of Titan's surface. This was done by mapping the distributions of process-related material units, determining their stratigraphic relations, and producing a complete geomorphologic map of this region.

2. Methodology

We used *Cassini* RADAR data in Synthetic Aperture Radar (SAR) mode (wavelength = 2.17 cm, 13.78 GHz) from the Titan T3 flyby, with a spatial resolution of 350 m to >1 km, as the base for our map. The T3 strip covers $\sim 1.8 \times 10^6$ km^2 (Elachi et al., 2006) with a varying 200–300 km wide swath beginning near $\sim$0°N, 130°W, extending to $\sim$20°N, 10°W, and located northeast of the optically bright Xanadu region. We applied standard techniques for planetary mapping (Shoemaker and Hackman, 1962; McCauley, 1967; Wilhelms, 1972, 1990; Tanaka et al., 1994; Hansen, 2000). The advantage of geologic mapping over photogeology alone is that it reduces the complexity of heterogeneous planetary surfaces into comprehensible proportions, in which discrete material units are defined and characterized based upon specific physical attributes related to the geologic processes that produced them. The distributions of these units are then mapped, along with structural features, in order to identify the relative roles of impact cratering, volcanic, tectonic and gradational processes in shaping their surfaces, and when they were active. Because Titan's thick atmosphere screens out small impactors, it is difficult to use impact crater statistical techniques to age date material units (cf., Lorenz et al., 2007). In this paper, we used the principles of superposition and cross-cutting, and embayment relations, to place units in stratigraphic order in a detailed, localized map of the Menrva region, building upon the more regional mapping by Stofan et al. (2006) and the global survey of unit types by Lopes et al. (2010).

2.1. Uncertainties and assumptions

As was learned from mapping geology using *Magellan* radar images, great care must be taken to consider the complexities of mapping using radar data (Ford et al., 1993; Hansen, 2000). This is especially true for applying mapping techniques for an icy satellite like Titan. First, geologic units are visible only if their radar backscatter characteristics are different from surrounding units. This may not always be the case, particularly in lava flow fields or plains units. Thus, older and younger units could be mistakenly combined into a single unit. If there are lateral changes in a geologic unit, then its radar signature can also vary, and thus one unit could be mistakenly mapped as two or more units. Furthermore, structures are more easily identified when they are oriented normal to the radar-look direction (Stofan et al., 1989). Nevertheless, despite these challenges, useful geologic maps of complex regions on Venus have been made using *Magellan* SAR data (e.g., Hansen, 2000; Stofan and Guest, 2003; Stofan and Brian, 2005), and previous work (Elachi et al., 2005; Stofan et al., 2006; Lopes et al., 2007, 2010) suggests that useful maps could be made for Titan as well.

The role of volume scattering must also be considered. Volume scattering occurs when a radar wave enters the surface and is scattered by subsurface inhomogeneities. This scattering allows the escape of a fraction of incident radiation that would otherwise be absorbed if the medium were uniform with depth. Janssen et al. (2009) reported that *Cassini* radiometry data indicates that volume scattering does contribute to radar backscatter, especially in radar-bright regions, thus potentially leading to misinterpretation of the radar signature of a surface. Furthermore, there are additional challenges to consider when mapping radar data of Titan, which is an icy body whose surface is characterized by solid hydrocarbons (dielectric constant $\varepsilon = 2.0$–2.4; Thompson and Squyers, 1990), water ice ($\varepsilon = 3.1$; Thompson and Squyers, 1990), water–ammonia ice ($\varepsilon = 4.5$; Thompson and Squyers, 1990; Lorenz, 1998), or combinations thereof (e.g., Lorenz et al., 2008b). Methane can be trapped in an ice-like solid called clathrate hydrate. The dielectric constant of clathrates is determined by the proportion of ice/methane molecules in the clathrate hydrate structure and could reach about 1.8 (Hobbs, 1974), slightly lower than solid hydrocarbons or ice alone, thus allowing for the possible presence of clathrates on Titan surface (Tobie et al., 2006; Paganelli et al., 2007, 2008). Because the *Cassini* SAR is a single-polarization instrument, the relative contributions to SAR brightness from factors such as topography, surface roughness, material composition, and volume scattering are not well understood. In effect, Titan maps can be considered 'radar property maps', in the same way that many planetary maps are 'geomorphologic maps' rather than true 'geologic maps' in the terrestrial sense (Stofan et al., 2006). This is why we refer to our Menrva map as a geomorphologic map. Nevertheless, despite these challenges, our work presented here along with previous mapping exercises using *Cassini* RADAR data have proven useful in analyzing Titan's surface (e.g., Lopes et al., 2010), and mapping is regarded by many members of the *Cassini* RADAR team as a critical tool to help interpret the *Cassini* data (Stofan et al., 2006).

Our map units were defined and characterized based on qualitative comparison of their radar properties (i.e., radar brightness), their morphologies (shapes, textures, and appearances), and their contact relations with adjacent units. Qualitative descriptors of radar brightness such as "bright", "intermediate", and "dark" relates to roughness at the scale of the *Cassini* SAR (2.17 cm), which we define as "rough", "intermediate", and "smooth", respectively. The map units were grouped into five types: plains units, a highlands unit, units associated with crater materials, units associated with aeolian dunes, and units associated with channels and their outflows.

3. Results

Figs. 1a and 1b present our geomorphologic map for the Menrva region on Titan, as observed by the *Cassini* RADAR experiment during the T3 flyby. Part of the eastern segment of this region, now named Elivagar Flumina (Lorenz et al., 2008a), can be compared with more generalized mapping done by Lopes et al. (2010): Fig. 2. Menrva has been interpreted as a 440 km wide degraded impact basin (e.g., Lopes et al., 2010; Wood et al., 2010), and our mapping is consistent with that interpretation. The 10 map units (plus dunes and channels) that we defined and characterized from this RADAR image are listed in approximate stratigraphic order in a sequence of map units (COMU) in Fig. 3. Table 1 lists the description

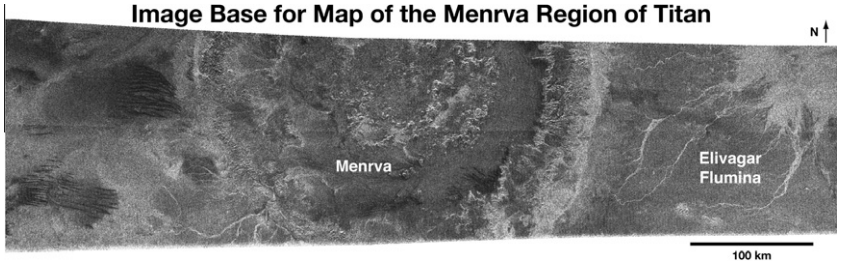

Fig. 1a. *Cassini* RADAR image from the T3 flyby, used as the image base for our geologic map.

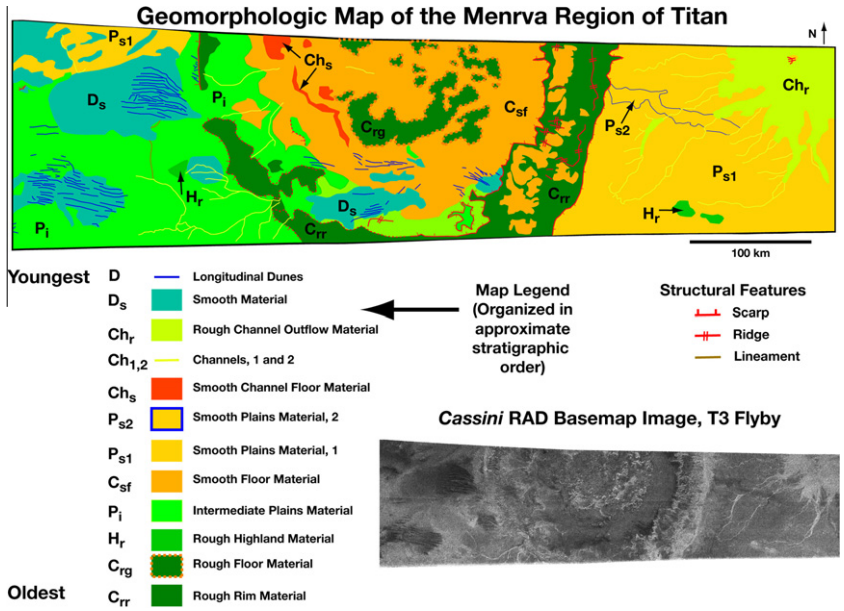

Fig. 1b. Geologic map of the Menrva region of Titan. Ten map units have been defined and characterized from the image, along with dunes and channels, and structural features such as scarps, ridges, and lineaments. Map legend listed in approximate stratigraphic order. See Table 1 for description and interpretation of map units. See Fig. 3 for sequence of map units. These figures are presented as "proof-of-concept" that detailed planetary mapping can be applied to the *Cassini* RADAR data.

and interpretation of these map units (DOMU). We summarize key points below.

Plains units cover the largest percentage of our map area, and include an Intermediate plains material (P_i) and two types of Smooth plains material (P_{s1}, P_{s2}). The stratigraphically lower, older Intermediate plains unit by definition has a radar brightness intermediate between brighter and darker units, and is cut by scarps, ridges, lineaments, channels, and superposed by dunes and radar-dark materials, but embays Rough rim material and Rough highland material. Smooth plains material is a non-uniform radar dark unit that embays apparent topographic highs, and is crosscut by younger dunes and channels. An apparently younger Smooth Plains unit, P_{s2}, overlies the older P_{s1} and is crosscut by younger channels.

Rough highland material (H_r) consists of a relatively radar bright unit that occurs in small, irregular patches embayed by darker units, in which the patches appear to be local topographic highs. We interpret this unit as hills of titanian crustal material poking up through the surrounding plains units. Alternatively, this unit could represent remnants of the Menrva impact ejecta blanket that have not been eroded by other processes.

Units associated with crater materials include the stratigraphically lowest (oldest) unit, Rough rim material (C_{rr}), and Rough floor material (C_{rg}) and Smooth floor material (C_{sf}). Rough rim material consists of a radar bright unit with a speckled surface, in the form of a partial ring bounded by scarps from radar dark surroundings, and with a surface disrupted by patches of dark material and bright ridges. We interpret this unit as the rim of Menrva, composed of heavily degraded, coarse-grained fragmental rock and/or icy material. This interpretation is consistent with the work of Soderblom et al. (2010), who came to an identical conclusion in their interpretation of RADAR observations of the Selk crater rim. The Rough floor material consists of a radar bright unit that occurs in small patches of irregular hills, that is located in the center of a large circular structure that is surrounded and embayed by radar-dark material. We interpret this unit as a possible central peak ring of Menrva, or other exposed crustal material. In contrast, Smooth floor material is a nearly-uniform radar dark unit that embays the Rough floor material, forming an annulus or moat in center of the circular feature (with patches also in other units). The west side of the moat is less uniform than the right side, and is disrupted by channels and other features, and is superposed by younger channels and dunes. This material is interpreted as the floor of the Menrva structure, composed of fine-grained fragmental material.

Units associated with channels include both Smooth channel floor material (Ch_s) and Rough channel outflow material (Ch_r), and at least two populations of channels (Ch_1, Ch_2). The Smooth channel floor material has a single occurrence in the form of a sinuous trough with nearby dark patches that may have been previously connected, now filled with a radar dark unit. We interpret this unit as the floor of a fluvial channel filled with a radar-dark,

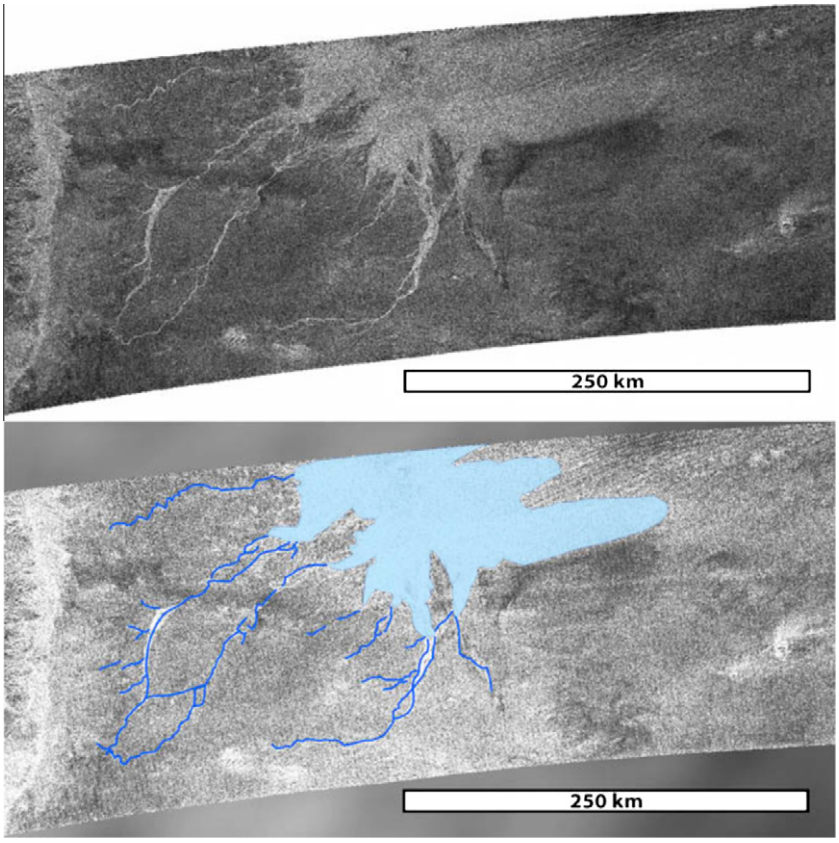

Fig. 2. (Top) *Cassini* RADAR image from the T3 flyby, showing part of the terrain east of the Menrva feature. (Bottom) Geologic mapping showing channels (dark blue lines) and the channel outflow region (light blue) of Elivagar Flumina, from Lopes et al. (2010). A comparison of the mapping at left with that in Fig. 1 are very similar, suggesting that a variety of process-related features, including dunes and channels, channel outflows, impact deposits, and structural features such as scarps, ridges, and lineaments, can be mapped confidently. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

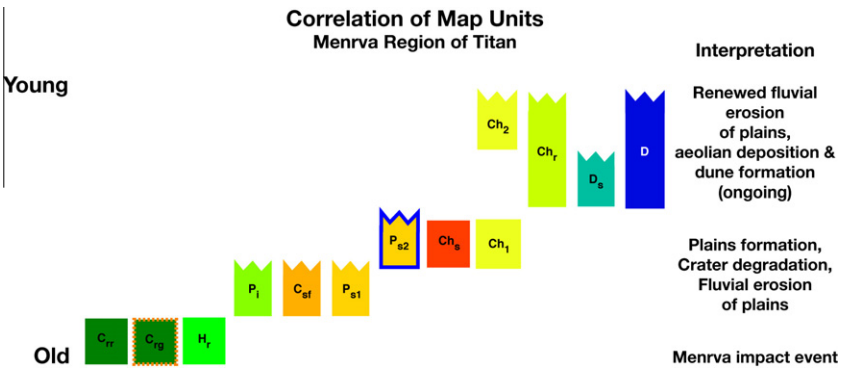

Fig. 3. Sequence of map units (COMU) for the geologic map of the Menrva region of Titan (Fig. 1). Both distinct events and ongoing activity can be recognized from this mapping effort.

fine-grained material. In contrast, the Rough channel outflow material consists of irregularly-shaped, radar bright surface units that are fed by sinuous to sub-linear filaments. This material has distinctive contacts with and is superposed on the surrounding Smooth plains material. We interpret this unit as relative topographic lows that contain relatively coarse-grained fragmental material that was transported by fluvial channels (the sinuous to sub-linear filaments). We recognize two groups of channels, which have the appearance of irregular, radar bright, sinuous to sub-linear filaments that crosscut all other units except the dunes, and are composed of relatively coarse-grained fragmental material.

We characterize dunes as very dark, linear to sub-linear filaments, usually occurring in groups that are parallel to sub-parallel with a generally east–west orientation. These features are superposed on all other units and embay inferred topographic highs. The appearance and descriptions of these features are consistent with their previous interpretation as longitudinal dunes (e.g., Lorenz et al., 2006), composed of fine-grained fragmental material, presumably sands, deposited by aeolian processes. Dunes occasionally overlie or are close to smooth material (D_s). These are smooth or absorbing to radar, consistent with being fine-grained aeolian deposits. These are not obviously organized into dunes at

Table 1
Description of map units (DOMU) from the geologic map of the Menrva region. Use of terms "rough" and "smooth" are relative to the wavelength of the *Cassini* SAR (~2.17 cm).

Symbol	Unit	Description	Interpretation
C_{rr}	Rough rim material	Radar bright unit with speckled surface, located in a partial ring and bounded by scarps from radar dark surroundings. Surface disrupted by patches of dark material and bright ridges	The rim of impact crater Menrva, composed of coarse-grained fragmental rock and/or icy material, heavily degraded
H_r	Rough highland material	Radar bright unit that occurs in small, irregular patches embayed by darker surroundings, appear to be local topographic highs	Local hills of titanian crustal material, possibly remnants of Menrva impact ejecta
P_i	Intermediate plains material	Unit that is intermediate between radar bright and radar-dark materials, with a surface cut by scarps, ridges, lineaments and superposed by channels, dunes, and radar-dark materials	Relatively old plains, modified by tectonic, fluvial, and aeolian processes
P_{s1}	Smooth plains material, 1	Non-uniform radar dark unit that embays apparent topographic highs, and is crosscut by younger channels and dunes	Relatively young plains, consisting of fine-grained fragmental material
P_{s2}	Smooth plains material, 2	Non-uniform radar dark unit that is superposed on P_{s1}, and is crosscut by younger channels	Relatively young plains, likely consisting of finer-grained fragmental material relative to P_{s1}
C_{rg}	Rough floor material	Radar bright unit that occurs in small patches of irregular hills, in the center of large circular structure, surrounded and embayed by radar-dark material	The remnants of a central peak ring of crater Menrva, composed of coarse-grained fragmental rock and/or icy material
C_{sf}	Smooth floor material	Nearly-uniform radar dark unit that embays bright, topographic highs, forms an annulus in center of circular feature (patches also in highlands). West side is less uniform and disrupted by channels and other features. Unit is superposed by younger channels and dunes	The floor of crater Menrva, composed of relatively fine-grained fragmental material, with a similar appearance in radar data to the Smooth plains material
Ch_s	Smooth channel floor material	Nearly-uniform radar dark unit that fills a sinuous trough and nearby irregular patches that may have been previously connected	The floor of a fluvial channel, filled with fine-grained material
Ch_r	Rough channel outflow material	Irregular radar bright units that are fed by sinuous to sub-linear filaments. These units have a distinctive contact with and are superposed on surrounding Smooth plains material	Relative topographic lows that contain relatively coarse-grained fragmental material that was transported by fluvial channels
D_s	Smooth material	Non-uniform radar dark unit that typically underlies darker, linear filaments. Mantles underlying materials, and embays local highs	Fine-grained fragmental material deposited by aeolian processes (Lorenz et al., 2006) associated with overlying dunes
Ch_1, Ch_2	Channels	Irregular radar bright sinuous to sub-linear filaments that crosscut all other units except dunes	Fluvial channels whose floors mostly contain coarse-grained fragmental material
D	Dunes	Very dark linear to sub-linear filaments, usually occurring in groups that are parallel to sub-parallel. Superposed on all other units and embay topographic highs	Longitudinal dunes (Lorenz et al., 2006), composed of fine-grained fragmental material deposited by aeolian processes

Cassini radar resolutions, and thus could be either sand sheets or dunes smaller than 300 m.

Finally, we have mapped structural features in the Menrva region including scarps, ridges and lineaments. Scarps (dashed where inferred) delineate the contact boundary of the Rough rim material unit with surroundings, marking an interpreted topographic high thought to represent the Menrva crater rim. Only a few small ridges are visible, in the Rough rim and Smooth floor units. Lineaments are linear to sub-linear features that cannot be confidently mapped as another type of material unit or structural feature, a couple of which were identified in the western part of the map region.

The geologic history of this region can be assessed from the sequence of map units (Fig. 3). The oldest event would have been the Menrva impact on the surface, producing a crater with a floor, rim, and ejecta blanket. The original crust may be preserved in the Rough rim material, the Rough floor material, or the Rough highland material, although the latter may be the remains of the impact ejecta blanket. Subsequent geologic activity would include formation of the Intermediate and Smooth plains units, degradation of the crater rim and ejecta blanket, filling of the crater floor, and addition of aeolian materials. There is no evidence for a cryovolcanic or tectonic origin of the plains, whereas the plains units do show evidence for an episode of fluvial erosion via channelization, and aeolian deposition. The youngest, most recent activity in this region includes a second episode of fluvial erosion via channelization, and apparently ongoing formation of longitudinal dunes.

4. Discussion

Our mapping results are consistent with and support the conclusions based on previous studies of the T3 RADAR images. For instance, Lorenz et al. (2008a) and Wood et al. (2010) interpreted Menrva as a multi-ring impact basin, in which the outer ring marks a local topographic high such that the >200 km long channels of Elivagar Flumina trend to the NE away from the basin and away from Xanadu, which Lorenz et al. (2008a) suggest may be indicative of a regional slope. They interpret these radar-bright, curvilinear to sinuous features as shallow channels typical of desert washes that lack topographic expression. In contrast, Lorenz et al. (2008a) noted that the western rim of Menrva is more degraded than the eastern rim (as typical for Titan, although the cause is unknown), and that it is breached in the west by a channel, which has small meanders not present in Elivagar Flumina, perhaps indicative of a different substrate composition, slope, or degree of fracturing. Wood et al. (2010) noted that bright knobby material (our Rough Floor Material) apparently defines a broad, elevated inner ring about 100 km in diameter. They noted the dark floor or moat of Menrva has clumps of dunes in the south, which we were able to map. Topographic information on Menrva was provided by Stiles et al. (2009), which reported that the eastern rim of Menrva rises about 300 m above the nearby plains, the moat is ~500 m below the eastern rim, and the central area is up to 450 m higher than the moat. Wood et al. (2010) suggested that, because the highest point of the central region of Menrva is about the height of the basin rim, and it is higher than the terrain east of the basin, that this could be evidence for deformation of the Menrva basin by viscous relaxation, common on icy satellites. But the general E–W flow of channels on both sides of Menrva suggests it formed on sloping terrain (Wood et al., 2010), and the evidence for viscous relaxation is not conclusive.

What other insights can be obtained about the Menrva region of Titan from this preliminary mapping effort? First, the morphologies

and types of material units defined and characterized for the Menrva feature are consistent with the interpretations of Wood et al. (2010), who compared the inferred morphology of Menrva with those of degraded impact basins on other planetary bodies. The interpreted impact event that formed the Menrva feature is the oldest event in this region (Fig. 3), with multiple geologic processes having acted to subsequently modify the feature and its surroundings. Second, there is no identifiable impact ejecta blanket surrounding the feature (at least in the east–west direction that is visible in the radar swath, and in contrast to the well-defined ejecta blanket around Selk crater: Soderblom et al., 2010), suggesting that the processes resulting in plains formation are vigorous enough to erase the inferred crater's ejecta blanket, or alter it beyond recognition. Third, the degree of modification to the inferred crater rim and central peak ring are considerable, such that the southwestern segment of the rim has been breached in multiple locations by the fluvial channels of Elivagar Flumina (see also Lorenz et al., 2008a). Disruption of the crater rim by fluvial channels is also inferred at Selk crater (Soderblom et al., 2010). Fourth, there is evidence of multiple episodes of channel formation, erosion and burial by fine-grained, radar-dark materials (Fig. 3), possibly aeolian deposits (see also Lorenz et al., 2006; Wood et al., 2010), in which at least one ancient channel appears to be covered (the sinuous "lineament" west of the crater rim appears to be the remnants of an older channel), and presumed radar-dark aeolian mantles (but not dunes) are cut by later channels. A similar circumstance of an older channel being covered by younger dunes was noted in T17 RADAR and T20 VIMS data (Visual and Infrared Mapping Spectrometer: Brown et al. (2004)) by Barnes et al. (2008). Fifth, the roughness of most of the channel floors indicates that the fluid that cut them had a low enough dynamic viscosity and/or high enough flow rate to entrain coarse-grained particles (relative to the wavelength of the *Cassini* RADAR: 2.17 cm), and deposit them on the channel floors and in local topographic lows (channel outwash plains). In this case, based on the Rayleigh criterion and flyby parameters, the bright-dark transition occurs for particle sizes of ~1–3 mm (i.e., sand-sized particles: L.F. Bleamaster, personal communication, 2010). Larger-sized particles would also appear bright and could be present. Thus, the right margin of unit Ch_r (Fig. 2) looks to be windblown in nature and fades into what look to be longitudinal dunes. This is consistent with a smaller clast size. However, this bright (rough) terrain may still contain clasts significantly larger than the optimum particle size for saltation on Titan (0.18–0.25 mm: Greeley and Iversen, 1985). Sixth, we agree with Lorenz et al. (2008a) that the rough channel outflow landforms of Elivagar Flumina have the morphology of channels formed during episodic, variable flow, typical of generally dry, "flashy" streams such as arroyos found in the deserts of the southwestern US. Thus, this region may not experience frequent rainfall but is instead more like a desert, consistent with the presence of dunes at these latitudes (Lorenz et al., 2007). Seventh, there are local variations in particle supply and in topography around the Menrva feature, and/or also in the regional wind direction or speed, such that the visible dune fields are restricted to specific areas rather than forming the large dune seas seen in other regions, and the dunes themselves are short and widely spaced, leaving underlying substrate visible, typical of dunes formed under low particle supply (Lorenz et al., 2006; Radebaugh et al., 2008; Lorenz and Radebaugh, 2009).

Note that this proof-of-concept map was produced using Adobe™ Illustrator software, and that more detailed and quantitative results (including lengths of linear features and areal extents of map units) can be obtained using ArcGIS™ software on geospatially referenced data. Use of Geographic Information Systems-type software such as ArcGIS™ is now required by NASA for all planetary geologic mappers funded by the Planetary Geology and Geophysics and other programs.

5. Implications

We suggest, based on the modest results obtained here, that it would be useful to apply geologic mapping techniques to a larger subset of the RADAR images, geographically distributed across Titan's surface, to assess better the utility of detailed geologic mapping to identify and determine the relative roles of the impact, volcanic, tectonic, and gradational processes in shaping Titan's surface. We want to stress, however, that there is still considerable uncertainty associated with interpreting the *Cassini* RADAR data (e.g., brightness is controlled not only by surface roughness, but also volume scattering, composition, and topography). These factors are still not well constrained, and we did not include variations due to volume scattering, composition, and topography in our unit definitions. To a first order, we think surface roughness should dominate the observed variability in the RADAR data, but further work is clearly required to investigate these other factors. Additional geologic mapping of Titan using *Cassini* RADAR and ISS (Imaging Science Subsystem: Porco et al. (2004)) image data would further assess their utility as basemaps for a future global geomorphologic map of Titan. A detailed global map of Titan, using a basemap of higher-resolution RADAR strips merged with lower-resolution ISS and VIMS images, will undoubtedly be proposed after the *Cassini* Solstice Mission is complete and the greatest amount of coverage of the surface at highest spatial resolution is obtained. A global map is desirable: (1) to synthesize the state of knowledge prior to future Titan missions; (2) to provide a global correlation of sites of surface changes with other features and hopefully enable a stratigraphic framework to be determined; and (3) to complete the geologic reconnaissance of the available image data. To produce the most useful map, use of other *Cassini* data sets, such as VIMS data should also be assessed. These data could be used to extend and extrapolate the mapping away from the RADAR strips to cover larger parts of Titan's surface. Before this can be done, however, the potential of using these data must first be assessed through mapping of individual, geographically distributed, regional-scale images.

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