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A Global Geomorphologic Map of Saturn's Moon Titan

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Abstract

Titan has an active methane-based hydrologic cycle[1] that has shaped a complex geologic landscape[2], making its surface one of most geologically diverse in the solar system. Despite the different materials, temperatures, and gravity fields between Earth and Titan, many surface features are similar between the two worlds and can be interpreted as products of the same geologic processes[3]. However, Titan's thick and hazy atmosphere has hindered the identification of geologic features at visible wavelengths and the study of surface composition[4]. Here we identify and map the major geologic units on Titan's surface using radar and infrared data from the Cassini orbiter spacecraft. Correlations between datasets enabled us to produce a global map even where data sets were incomplete. The spatial and superposition relations between major geologic units reveals the likely temporal evolution of the landscape and gives insight into the interacting processes driving its evolution. We extract the relative dating of the various geological units by

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Author Contributions:
R.M.C.L. led the work and wrote the paper. M.J.M., A.M.S., T.V. and M.F. carried out the mapping. A. S. carried out the VIMS analysis and advised on the writing of VIMS results. A. L.G. advised on interpretation and wrote part of the radiometry results. A.G.H. and S.P.D.B. provided the projected data for the mapping and advised on interpretation. J.R. and S.D.W. advised on interpretation of radar units. E.P.T. advised on interpretation of ISS data. The Cassini RADAR team acquired and processed the data.

observing their spatial superposition in order to get information on the temporal evolution of the landscape. Dunes and lakes are relatively young, while hummocky/mountainous terrains are the oldest on Titan. Our results also show that Titan's surface is dominated by sedimentary/depositional processes with significant latitudinal variation, with dunes at the equator, plains at mid-latitudes and labyrinth terrains and lakes at the poles.

Titan's surface has been modified by several geologic processes, including impact cratering[5,6], fluvial/aeolian erosion and deposition[7,8,9,10,11], precipitation[12], dissolution[13], tectonism[14] and possibly cryovolcanism[15]. Data returned by the Cassini spacecraft have also revealed Titan to be a world rich in organic materials[9,16], which mantle the surface to a depth of at least several 10's of cm in most places[17]. These materials are eroded, transported, and deposited across the landscape[9,18]. Geological mapping can place Titan's terrain types in stratigraphic order[2,3,19], constraining the relative importance and global distribution of various endogenic and exogenic processes[2].

The dataset best suited for interpreting Titan's surface geology from orbit is Synthetic Aperture Radar (SAR), as Titan's hazy atmosphere limits the signal-to-noise (SNR) of visible and near-infrared observations but is transparent to the radar's operating wavelength of 2.17 cm (K_u Band). We defined six major geologic units based primarily on backscatter and overall morphology on SAR images, as done for prior mapping [2,3], as: plains, dunes, hummocky terrains, lakes, labyrinth terrains, and craters (Fig. 1). Mapping the distribution of these units enables us to discern their latitudinal distribution, superposition relations, composition, and areal coverage, and the implications for Titan's geologic history. We first mapped the areas covered by SAR (~46% of Titan's surface at <1 km resolution), then used correlations between SAR and other data sets, namely low-resolution, high altitude SAR (HiSAR), radiometry, the Imaging Science Subsystem (ISS), and the Visible and Infrared Mapping Spectrometer (VIMS), to extend the mapping to regions not covered by SAR (see Methods) to produce a global 1:20,000,000 scale map of the major geologic units (Fig 2). Correlations between these datasets enabled us to map the global geology even where data sets were incomplete and to place geomorphologic units in relative stratigraphic and areal context to provide a sequence of events for the surface evolution of Titan.

The majority of Titan's surface is comprised of Plains, which make up 61% of the SAR-imaged areas and 65% of the global area. Several types of plains were mapped at a regional scale (see Methods), the most extensive are the undifferentiated plains, which appear near-uniform and radar-dark in SAR images, lacking major topographic relief[11]. The lack of fluvial features in this terrain unit at Cassini SAR scale suggests that it is either porous, is not able to support large, integrated channels, or has buried and reworked older, extinct channel networks[10]. Plains dominate Titan's mid-latitudes and show high emissivity to radar, consistent with organic materials[17]. Previous work[11] argued that undifferentiated plains are depositional and/or sedimentary in nature, perhaps with aeolian deposition being the major process contributing to their formation. However, latitudinal variations exist: Analyses of VIMS data show that plains closer to the equator, and therefore closest to the largest dune fields, have spectral similarities to dune materials[4,11], suggesting some contamination by dune material likely transported into the plains by wind. The high latitude

VIMS spectra are consistent with an unknown material that is also observed in the labyrinth unit[4].

Dunes (comprising both dunes and interdunes) dominate the equatorial regions (±30 degrees latitude) and make up the second most extensive unit on Titan by areal coverage, 19% of the SAR-imaged area and 17% of the global area. Dunes appear as long, narrow, SAR-dark features, indicating dune materials are smooth and/or absorbing at 2.17 cm. Previous measurements show that dunes are mostly 1-2 km wide, spaced by 1-4 km and can be hundreds of kilometers long[9]. Limited measurements of heights suggest that they are 80-130 m tall[20]. The general transport of sand (W to E) has been inferred from the way dunes interact with topographic obstacles, such as hummocky and mountainous terrains[18, 21]. Their large-scale morphology and sizes are similar to linear sand dunes on Earth[21]. Dunes show high emissivity to radar, consistent with organic materials.[17]

The hummocky unit consists of mountain chains and isolated terrains that are topographically higher than the surrounding areas[18]. This unit covers 15% of the SAR-imaged surface and 14% of the global area. Hummocky terrains appear bright in SAR images because of the roughness and fractured nature of the materials[17], as well as the terrain topography with respect to the SAR look direction and incidence angle (typically tens of degrees). They are characterized by high scattering and low emissivity in radiometry mode[17], indicating water ice materials that increase the likelihood of volume scattering. The largest areal exposure of the hummocky unit is in the equatorial region known as Xanadu[22,23]. Elsewhere, hummocky materials are exposed as locally isolated peaks or ranges (generally under 30 km^2). Mountains are mostly exposed as gently undulating regions from mid to high latitudes, generally aligned E-W, and may have formed by contractional tectonism[14] early in Titan's history. They are a few to tens of kilometers in length and up to a couple of kilometers high above the reference geoid. Analyses of VIMS data for the hummocky unit indicate a relatively high water-ice component[22]. Derived surface albedos of some small exposures of hummocky terrains (not within Xanadu) suggest the hummocky unit is relatively dark, containing a spectrally dark constituent[19] in addition to water ice in the mixture; other VIMS results[22] suggest differences between Xanadu and other hummocky terrains. These results are consistent with the hummocky unit representing exposed remnants of Titan's icy shell[2], in parts covered in a sedimentary veil of organics originating in Titan's atmosphere.

The lakes unit comprises lakes and seas, which can either be dry or liquid-filled. Titan's polar regions contain over 650 lakes[19], either dry or filled with liquid hydrocarbons. The majority of filled lakes and seas (maria) are located in the north polar region, mostly (~80%) in the Kraken, Ligeia, and Punga Maria. These larger northern maria have varied shorelines indicated flooding and draining of pre-existing topography, while the majority of the smaller lakes form steep-sided depressions with no true terrestrial analog[26]. In the south, Ontario Lacus appears as a residual lake inset in a larger paleobasin. The morphologies of both dry and filled lakes and seas on Titan may provide a record of past and current climatic conditions and surface evolution processes[27, 28]. The lake unit makes up only 2.2% of the SAR-imaged areas and 1.5% of Titan's total surface area.

The labyrinth unit consists of terrains with medium SAR backscatter and the appearance of being highly incised and dissected plateaus. These terrains cover 2.1% of the SAR-imaged area and 1.5% of the global area, and primarily located at high latitudes. Topographic data indicate that this unit is locally elevated. VIMS data of the top surface are consistent with a material compatible with OH bearing constituent (this spectral response has been ascribed to water ice[4]). Fluvial valley networks, rectangular to dendritic, inside the labyrinth units suggest some amount of structural and topographic control. Radiometry data show that, like dune materials, this unit has high emissivity consistent with materials that are organic in composition and thus have a low bulk dielectric constant. Labyrinths have morphologies similar to karstic terrain and may have formed through a combination of dissolution, possibly karstic[9], coupled with mechanical erosion, or other processes or phase changes that could allow the formation of closed valleys (at least at the SAR resolution) and transport of materials to the surrounding plains.

Craters occupy only 0.7% of Titan's SAR-imaged area and 0.4% of the global area. Only 23 craters > 20 km in diameter were identified with a high degree of certainty (plus ~10 others as probable) from all data sets, plus a few smaller crater candidates[24]. This suggests that Titan has a crater retention age of several hundred million years[5]. The distribution of craters also shows some latitudinal variation, consistent with the oldest exposed surfaces being located near the equator and the youngest surfaces located near the poles[24], where there is an almost complete absence of craters. Most craters show evidence of erosion by aeolian and fluvial/pluvial processes. The absence of craters in the polar regions could be due to infilling of the polar basins by sediments[19], increased erosion by fluvial processes[24] and/or impacts into former marine environments[25]. The microwave emissivity of the less degraded crater rims and ejecta is among the lowest on Titan[17], consistent with icy materials excavated by the impact. The inferred composition from radar and VIMS data is crustal water ice or a mixture of crustal water ice and organic materials[6].

The scarcity of craters on Titan limit the viability of crater counting statistics for distinguishing ages of different terrains. However, contacts between units and superposition relations can be used to get information on their relative age. Contacts mapped from the complete SAR dataset confirm early suggestions[2] that the oldest units on Titan are the hummocky terrains (including mountains). The plains are younger than both the hummocky and labyrinth units. Dunes and lakes (including seas) are the youngest units on Titan[2, 3, 21]. Because there is no contact between lakes and dunes, it is not possible to distinguish the relative ages of these units and, given active seasonal weather patterns including rainfall[12] and wind[29], it is likely that both are still forming and changing on Titan. Craters are an intermediate unit in relative age, some are seen in hummocky terrain, particularly in the Xanadu area, and several are infilled by dune and plains materials.

The resulting global-scale geologic map shows significant latitudinal dependence of the major units. Equatorial regions are dominated by vast dune fields and the mid-latitudes are dominated by plains, while the lakes and labyrinth units are found primarily in the polar regions. This is possibly related to more humid conditions in the polar regions. Superimposed on top of the global latitudinal unit distribution is a dichotomy in liquid inventories between north and south. The vast majority of filled lakes is currently situated in the northern hemisphere, while the south is nearly dry, possibly the result of global climate cycles[19, 27]. The hummocky unit, interpreted as exposed crustal materials, is seen at all latitudes, but primarily in the equatorial Xanadu region, for reasons yet unknown[23].

In terms of composition, the emissivity data are consistent with organic materials forming the plains, dunes, lakes, and labyrinth units, while the emissivity of the crater and hummocky units indicates a higher abundance of water-ice materials[17, 30]. This suggestion that the latter terrains expose icy crustal material is consistent with previous work that predicted and later showed[16] that organic materials produced by high-altitude photochemistry of methane and nitrogen in Titan's atmosphere form a surficial unit that covers much of Titan's surface. Relative ages and distribution of the major units imply that Titan's old, icy crust (hummocky materials) has been covered by sedimentary materials like the dunes and plains, particularly at lower latitudes, with the exception of Xanadu. In the polar regions, where cumulative rainfall outpaces infiltration/evaporation of liquids, lakes are abundant. Labyrinth terrains, which are older than plains and mostly located at higher latitudes, may have begun as uplifted or otherwise elevated terrains, predominantly of organic deposits, that later became heavily incised and dissolved by rainfall, like karstic formations on Earth.

Titan is covered by organic sediments that are reworked, to varying degrees, by aeolian, pluvial, and fluvial processes. Though rainfall occurs at all latitudes, Titan's equatorial climate is arid over long enough timescales that aeolian deposition and dune formation dominate. Toward the poles, relative humidity increases, and liquid hydrocarbon lakes and seas dominate the polar landscape. Between these two extremes is a vast area of mid-latitude, featureless, organic plains. The clear distinction between these units and where they are found on Titan indicates this is a body with a variety of processes acting on the surface controlled by climatic, seasonal and elevational conditions.

Methods

Titan's hazy atmosphere scatters light at visual to near-infrared wavelengths, limiting the detailed visual and infrared spectroscopy data that can constrain surface composition. Longer-wavelength microwave radiation, however, penetrates the atmosphere and interacts with the surface with no significant atmospheric interference. We primarily used data from the Cassini RADAR in its Synthetic Aperture Radar (SAR) mode to map Titan's geology, following methodology outlined in previous work[2, 3, 30, 31]. SAR data respond to near-surface roughness at the wavelength scale (2.17 cm), to surface slopes at the pixel scale, and to near-surface dielectric properties of the materials. SAR can penetrate many wavelengths into some materials as well[17]. Global maps by ISS[32,33] (at 0.938 µm) and VIMS[34,35,36] (1-5µm) are helpful in unit characterization and global distribution; they provide a complementary dataset, sensitive to the top surface coating on the order of tens of microns, while microwave emissivity penetrates tens of centimeters into the surface[17]. Furthermore, analysis and interpretation of VIMS data provide information on the spectral nature and chemical composition of the surface[4]. Terrain units have therefore been characterized in terms of radar backscatter, morphology, contact relations, internal texture, topographic relationships, and observed characteristics (ISS, VIMS, and radiometry), following the method outlined in previous work[3].

The Cassini RADAR[37] operated in four modes – SAR, altimetry, scatterometry, and radiometry. The SAR mode was mostly used at spacecraft altitudes under ~5,000 km, imaging Titan's surface at incidence angles from 15-35°. The data yielded images with spatial resolutions from ~350 m to ~1.5 km, sufficient to identify major terrains for geologic maps[30]. During each Titan encounter with SAR imaging, a swath 120–450 km in width and 1,000–5,000 km in length was created from 5 antenna beams, with coverage largely determined by spacecraft range and orbital geometry. SAR data (in nominal mode) cover ~46% of Titan's surface at <1 km resolution, while higher altitude SAR (HiSAR) data cover an additional 24% at < 5 km resolution. The SAR dataset was used as a basemap for our geomorphological mapping. We used SAR data to define the boundaries of the terrain contacts and the main units, but data from other radar modes and other instruments were important as supplemental datasets, particularly in areas where SAR was not available. Topographic data were obtained from the SAR swaths by SARTopo[38] and in some other locations by using the RADAR in altimetry mode. The RADAR radiometry mode provided a global map of microwave emissivity[17]. With the use of specific tools, the analysis and interpretation of VIMS data can provide useful information on the spectral nature and chemical composition of the surface[4]. The terrain units were therefore characterized in terms of SAR backscatter, morphology, contact relations, internal texture, topographic relationship, and observed characteristics in ISS, VIMS, and radiometry, following the method previously outlined[3].

Global coverage of the surface was acquired by ISS, VIMS, and RADAR radiometry, with variable spatial resolution. The characteristics of each unit in the different datasets provide other information and can be used to infer the main type of unit in areas not imaged by SAR. Therefore, areas not covered by SAR were mapped at the 1:20,000,000 scale using data from these additional datasets. This scale is appropriate for defining the 6 major units we present in this paper, although coarser than the 1:800,000 scale maps done for individual regions such as that of the Afekan crater[3]. The main difference between the 1:800,000 scale and the 1:20,000,000 scale maps is that the sub-units in the finer scale map do not appear in the 1:20,000,000 map (Fig. 3). We therefore removed areas too small to be observed at the 1:20,000,000 scale (approximately areas <30 km^2 in spatial extent). For example, the crater sub-units in the 1:800,000 regional maps (crater rim, crater ejecta, central peak, crater fill 1 and 2) were simply mapped as the crater unit in the 1:20,000,000 global map. Likewise, areas showing linear dunes and dark areas interpreted as featureless sand sheets were mapped as the dune unit; filled and empty lakes and seas were mapped as the lake unit; hummocky, mountains, and degraded mountain sub-units were mapped as hummocky; and plains sub-units (undifferentiated, streak-like, variable featured, dark irregular, scalloped, and bright gradational) were mapped as plains. Detailed discussions of these different terrains are given in a previous work[3].

The mapping was done using ArcGIS™(ESRI) software. Starting with the SAR imaged areas, we identified contacts between regions based on radar backscatter and gross geomorphology[2,3]. These were then used to build polygons with attribute tables describing the units. The units used the geometry of the contacts, sharpness of contact, internal texture, channel density and sinuosity, degree of dissection, preferred orientation of diagnostic features or contacts, and overall morphology. Data from the other radar modes and instruments were used to further characterize each unit[3]. Crosscutting and superposition relations were used to determine relative stratigraphy, and the available topographic data were used to confirm the stratigraphic sequence among the terrain units. The plains units are extensive and appear continuous in many areas. More importantly, the plains unit shows a direct contact with all other terrain units mapped. Therefore, the Plains unit was used to determine embayment and superposition relations with other units, from which relative ages could be inferred, with the caveat that exposures of the Plains units may not have been formed at the same time in the same location[3]. All units were in contact with the Plains, however, some units were not in contact with one another, so a stratigraphic sequence could not be determined for them. For example, direct contacts were not observed between hummocky and labyrinth units, but both were observed to have been superposed by Plains (and therefore older).

We used correlations obtained from the SAR mapping with the other datasets to extend the mapping to the areas not imaged by SAR. For these areas, we used the global datasets from ISS, VIMS, radiometry and, where available, HiSAR and topographic information from altimetry and SARTopo. For example, undifferentiated plains appear bland and dark in SAR and HiSAR but bright in ISS and have high emissivity in radiometry[11]. Correlations across several data sets have been discussed in detail in several published papers[3,4,11]. An example of mapping is shown in Fig. 3. Because the non-SAR areas were mapped at a much lower resolution than the SAR-area, they are already at a scale appropriate to be included in the 1:20,000,000 global map. Below we describe the sub-units within each of our major units.

Plains:

Plains were classified into several sub-units[3], but undifferentiated plains[11] are by far the most extensive on Titan. They are low-backscatter regions that appear largely uniform in SAR data, having only a few (<5% by surficial area) observable features at the mapping scale of 1:800,000. Topographically, there is some variation in relief across the undifferentiated plains; however, they are lower in local elevation than the hummocky unit. These terrains appear bright in ISS data. The same is true for VIMS data for the undifferentiated plains located in the high latitudes. Significantly smaller patches of other types of plains have been identified in our 1:800,000 regional mapping, generally at mid to high latitudes. They are divided into bright lineated plains, bright streak-like plains, variable-featured plains, dark irregular plains, and scalloped plains[3]. Both types of bright plains are interpreted as aeolian-dominated landscapes consisting of high-backscatter materials. Variable-featured plains are interpreted to result from erosion of hummocky terrains, possibly involving fluvial erosion and deposition. Dark irregular plains are topographically lower than surrounding terrains, interpreted as areas dampened by liquid hydrocarbons, or lowland muds (within the top 10’s of centimeters of the surface). Scalloped plains are interpreted as eroded hummocky terrains with a cover of organic materials not thick enough to mask their nature. Scalloped plains may be transitional between hummocky terrains and undifferentiated plains. All the plains are mapped as a single unit in the 1:20,000,000 global map.

Dunes:

These areas were mapped at the regional 1:800,000 scale as three sub-units: linear dunes, reticulated dunes, and featureless dune sands[3]. The linear dunes sub-unit shows characteristic dune lineations in the SAR image across most of the areal extent of the terrain unit, while the featureless sand sheets contain only a few extended broad lanes that can be discerned in select areas. Both types of terrains are interpreted as deposits composed of sand-sized grains[9] that form linear dunes that are located generally at lower latitudes. Reticulated dunes are small patches of linear dunes showing a pattern perpendicular to the orientation of linear dunes nearby. These areas are interpreted as regions where the wind field is varying, and the deposition occurs in a more complex pattern than those that generate linear dunes. Dunes appear dark in both ISS and SAR, have high emissivity in microwave radiometry measurements consistent with organic materials, and correspond to the VIMS "dark brown unit" in 3-band VIMS global maps[39, 40]. Radiative transfer analysis of VIMS data from various dune fields showed (generally including both dune and interdune features where resolution limit prevents VIMS from distinguishing between the two) that the dunes are spectrally flat and very dark in the VIMS range[4]. In the 1:20,000,000 map, all the dune sub-units were mapped as dune unit.

Hummocky:

This unit consists of four sub-units previously described[3] as hummocky, mountains, degraded hummocky, and cross-cut hummocky. All are areas of high SAR backscatter and show locally positive topographic expression. The main difference between mountains and hummocky sub-units is that the mountains appear elongated in shape and show RADAR uprange-downrange bright-dark pairing, while the hummocky unit shows uniform to grainy internal textures. Degraded hummocky are small (<5 km across) and generally found in plains. Cross-cut hummocky terrains are larger (>100 km in diameter) and cut by linear features, possibly graben. All sub-units of hummocky terrains appear bright in ISS images. The microwave radiometric response for all these sub-units indicates that they are composed of fractured water ice or mixtures of fractured water ice and organic materials[17], and these areas are interpreted as exposures of ancient crust or bedrock, consistent with the interpretation of the hummocky/mountainous unit previously proposed[2].

Lakes:

We mapped both filled and empty lakes following criteria discussed in previous work[19]. Filled lakes are generally radar dark, although their darkness varies as a function of their fill state. Due to the transparency of liquid methane to Cassini's RADAR[44], all the filled liquid bodies mapped by SAR are at least a few meters deep. The filled lakes and seas are also clearly seen in ISS and VIMS images, allowing for an accurate assessment of lake/sea surface areas in areas not imaged by SAR. Empty lakes appear similar in planform to the filled lakes, as they form closed topographic lows[19, 45]. Their perimeters form steep sided walls, with a distinct curvature that indicates expansion by uniform scarp retreat[26]. They have a variety of radar appearances, however, with some appearing radar-bright relative to their surroundings, while others show a similar return to their surroundings. In all cases, empty lakes are morphologically distinct features that are recognizable at a 1:800,000 scale. At both poles, lakes (either empty or filled) always appear in clusters, while the seas occupy topographic lows. The total number of filled/empty lakes is similar at both poles[19], however, 97% of Titan's liquids (by area) reside in the north polar region, with only 9 filled lakes observed in the south.

Labyrinth:

All the labyrinth terrains are mapped as one unit in both the regional and global maps, although variations exist in terms of widths of valleys and intervening ridge spacing. This unit appears to be highly dissected, with a clear uprange-downrange bright-dark pairing[3] in SAR images, representing plateaus with valleys containing fill material that appears dark in SAR. The labyrinth unit shows overall medium radar backscatter and exposures are generally >5000 km^2 in extent. Topographic data show that labyrinths are locally elevated. Valley and ridge widths are variable, in areas where the valleys are wide (>2 km) and the exposures of elevated terrain are narrow (<2 km), the area appearance is of a series of remnant ridges. In contrast, where the valleys are narrow (< 2 km) and the intervening elevated terrains are wide (> 2 km), the area can appear as highly dissected plateaus. ISS and VIMS data shows the labyrinth unit to be slightly darker in the near-infrared than the surrounding plains[3, 41]. The labyrinth unit is interpreted as dissected plateaus and remnant ridges of organic materials that then transport plains materials into the valleys and downstream basins[3]. Undifferentiated plains are often found in the valleys as fill and at the distal edges of the valleys, suggesting that the labyrinth terrains may be plateaus composed of undifferentiated plains materials.

Crater:

The overall morphologic expression of a Titan crater is a partial or complete circle of high SAR-backscatter materials. Craters can be easily identified if they are larger than several tens of kilometers in diameter. Impact craters and ejecta can often be identified in VIMS and ISS images[6]. The challenge of identifying partial circular features as craters was previously described[5, 42]. We cross-checked our crater identifications with previous mapping[5,42] and found agreement in all but a few cases where identification was subjective, generally because of rim erosion and no discernible ejecta. Craters may be surrounded by an extended region of crater ejecta, plains or other near-IR-bright units, these terrains often extend in the inferred downwind direction (eastward)[3]. In a few craters, a central peak is observed at the center (or inferred center) of the circular rim. The margins of the crater rim may have become dissected by fluvial erosion or mass wasting processes[6, 43]. Ejecta may be covered over by plains materials, which are also seen inside several of the craters, interpreted as wind-blown deposits[11].

Data Availability Statement:

The Cassini data used in this paper are available from NASA's Planetary Data System (PDS). Data on map units are available from the corresponding author upon reasonable request.

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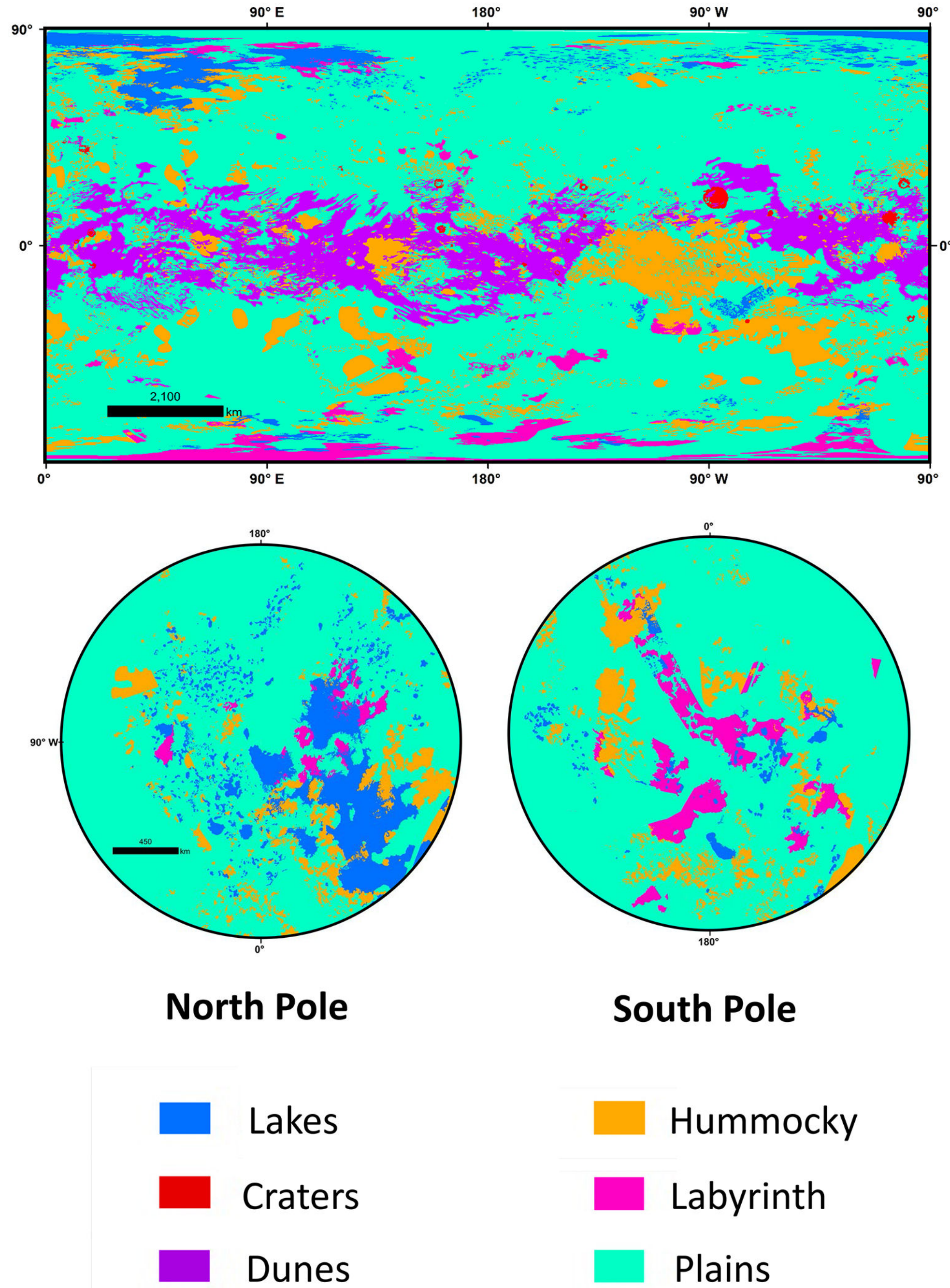

Figure 1:

SAR images showing examples of the main classes of geomorphologic units on Titan. Scale bars are 50 km, with global area percentages covered by each major unit provided below.

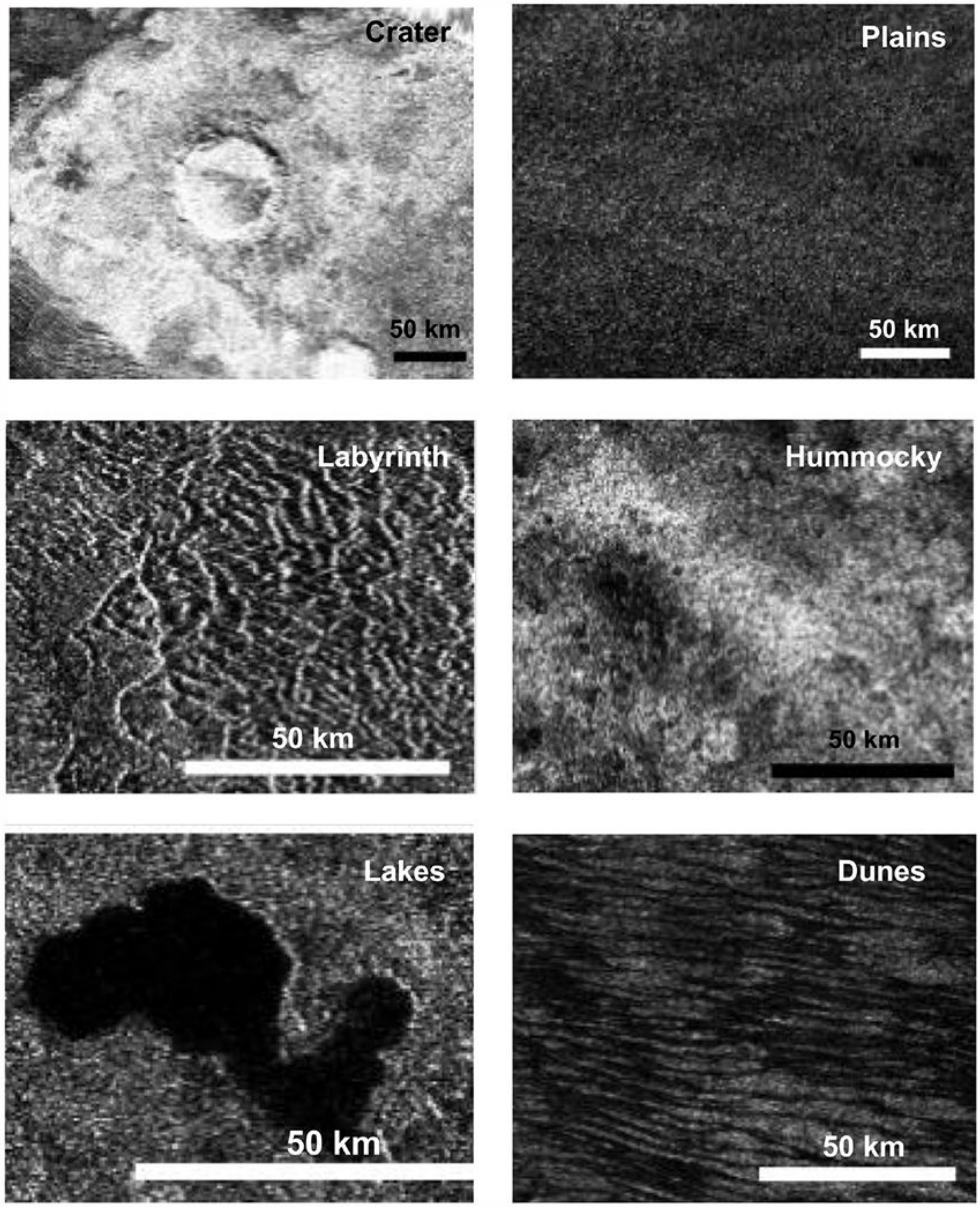

Figure 2:

Global map of Titan's major geomorphologic units. The map projections are Mercator (top) and Polar Stereographic (bottom, for >55° N and S).

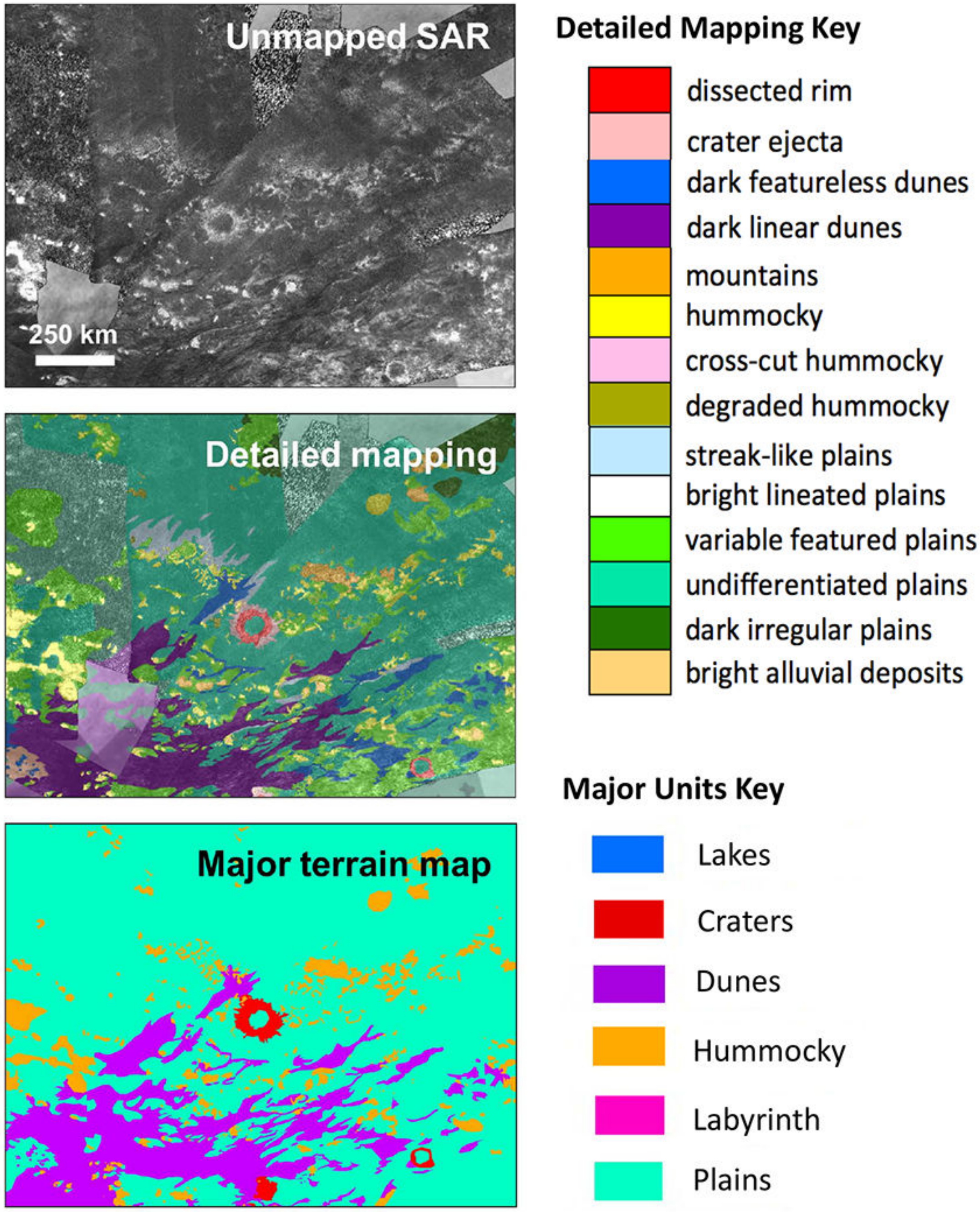

Fig 3:

Example of the mapping method from regional to global. Top left: SAR data over ISS data. Top right: contacts drawn for regional-scale mapping. Bottom left: detailed mapping over SAR (at 1:800,000 scale) and mapping of areas covered by ISS and other data sets but not SAR (pale colors). Bottom right: merging of units for the 1:20,000,000 scale map.

Table 1:

Percentage of the total area on Titan covered by each of the main classes of geomorphologic unit

Plains	65%
Dunes	17%
Hummocky	14%
Lakes	1.5%
Labyrinth	1.5%
Crater	0.4%