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Alluvial and fluvial fans on Saturn's moon Titan reveal processes, materials and regional geology

JANI RADEBAUGH[1]*, DARIO VENTRA[2], RALPH D. LORENZ[3], TOM FARR[4], RANDY KIRK[5], ALEX HAYES[6], MICHAEL J. MALASKA[4], SAM BIRCH[6], ZAC YUNG-CHUN LIU[7], JONATHAN LUNINE[6], JASON BARNES[8], ALICE LE GALL[9], ROSALY LOPES[4], ELLEN STOFAN[10], STEVE WALL[4] & PHILIPPE PAILLOU[11]

[1]*Brigham Young University, S-389 ESC, Provo, UT 84601, USA*

[2]*Utrecht University, Utrecht, The Netherlands*

[3]*Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA*

[4]*NASA Jet Propulsion Laboratory, Pasadena, CA 91109, USA*

[5]*US Geological Survey, Astrogeology Division, Flagstaff AZ 86001, USA*

[6]*Department of Astronomy, Cornell University, Ithaca, NY 14853, USA*

[7]*School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA*

[8]*Department of Physics, University of Idaho, Moscow, ID 83844, USA*

[9]*LATMOS Observatoire de Versailles Saint-Quentin-en-Yvelines (OVSQ), Paris, France*

[10]*Proxemy Research, Greenbelt, MD 20770, USA*

[11]*Observatoire Aquitain des Sciences de l'Univers, Universite de Bordeaux, Floirac, France*

**Correspondence: janirad@byu.edu*

Abstract: Fans, landforms that record the storage and transport of sediment from uplands to depositional basins, are found on Saturn's moon Titan, a body of significantly different process rates and material compositions from Earth. Images obtained by the Cassini spacecraft's synthetic aperture radar reveal morphologies, roughness, textural patterns and other properties consistent with fan analogues on Earth also viewed by synthetic aperture radar. The observed fan characteristics on Titan reveal some regions of high relative relief and others with gentle slopes over hundreds of kilometres, exposing topographic variations and influences on fan formation. There is evidence for a range of particle sizes across proximal to distal fan regions, from *c.* 2 cm or more to fine-grained, which can provide details on sedimentary processes. Some features are best described as alluvial fans, which implies their proximity to high-relief source areas, while others are more likely to be fluvial fans, drawing from larger catchment areas and frequently characterized by more prolonged runoff events. The presence of fans corroborates the vast liquid storage capacity of the atmosphere and the resultant episodic behaviour. Fans join the growing list of landforms on Titan derived from atmospheric and fluvial processes similar to those on Earth, strengthening comparisons between these two planetary bodies.

Fans are important depositional landforms associated with surface flow. They emerge from channels, usually from upland or highland terrains, and broaden across a decreasing slope. They are found on the surfaces of planetary bodies at the transition between uplands and adjacent depositional basins of lower internal relief. They represent areas of temporary to long-term storage of sediment in transfer from upland sources to depositional basins and they record how these materials are moved. Saturn's moon Titan, ten times as far from the Sun as the Earth and slightly larger than the planet Mercury, has a variety of landscapes similar to those seen on Earth (Elachi *et al.* 2005; Lorenz *et al.* 2006; Stofan *et al.* 2007; Lunine *et al.* 2008), including features that we interpret as fans.

Despite the similarities in landform morphologies, Titan has materials that are vastly different from those on Earth. In place of water as the working fluid of its hydrological cycle, Titan has methane; in place of silicates as the working geological material, Titan has water ice and organic

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compounds derived from the atmospheric processing of methane (Soderblom *et al.* 2007). The decreased energy available for geological processes because of the larger distance from the Sun, the much smaller value of gravity (one-seventh of that on Earth) and the much denser atmosphere (four times as dense, with a similar pressure to that on Earth) contribute to different process rates from those on Earth. However, when all the variables are taken into account, the mobility of sediments as a function of flow is predicted to be rather similar (Ori *et al.* 1998; Collins 2005; Burr *et al.* 2006; Perron *et al.* 2006). By applying the principles of terrestrial sedimentology to Titan, we can use the presence, morphologies and sedimentary characters of fans to reveal aspects of landscape processes and history. This work aims to provide preliminary examples of how studying alluvial and fluvial fans on Titan's surface can help to unravel the geomorphological processes, landscape history, bedrock topography and the compositions, sizes and origin of mobile debris, its modes of transport and the regional climate. The presently available information – derived almost entirely from the Cassini Saturn orbiter and the Huygens Titan probe it delivered to Titan's surface in 2005 – offers the first opportunities for a geomorphological and sedimentological analysis of fans on the satellite's surface.

Context

Although it was recognized (e.g. Lorenz & Mitton 2008) after the Voyager spacecraft flyby in 1980 that Titan's surface conditions might allow liquid methane, the existence of an active hydrological[1] cycle remained speculative for two decades. Ground-based telescopic observations in the late 1990s and early 2000s detected transient cloud features suggestive of active convection, but it did not directly follow that there would be associated precipitation, nor that it would modify the surface. If precipitation did reach the surface, it was further speculated that a global ethane ocean may cover Titan's surface (Lunine *et al.* 1983). The earliest Cassini observations from July to December 2004 (which included some fans) revealed no global ocean, but were indicative of the traces of recent or active hydrological processes; these traces were still being interpreted when the Huygens probe parachuted to Titan's surface in January 2005. The images from the probe during its descent, and after impact with the ground (an event the probe was not guaranteed to survive, but in fact did), left no doubt that Titan is a hydrologically active world (Fig. 1a). The descent images showed clear, well-developed fluvial networks draining from highlands to lowlands (Fig. 1c) and the surface images (Fig. 1a), located on the global view in Figure 1b, showed a flat plain littered with rounded cobbles up to 15 cm in size (Tomasko *et al.* 2005; Perron *et al.* 2006).

It is interesting to speculate on the probability that if a geomorphologist were to parachute down onto a random spot on the Earth's surface, would they see an alluvial deposit like this? And if such an alluvial surface were all they knew about the Earth, what would they conclude about the planet as a whole? This would certainly depend on which climatic belt the geologist landed in, as there are glaciated, bedrock and sand dune landscapes where not much alluvial (i.e. by runoff) activity could be discerned. Such regions cover perhaps 15% of the Earth's land surface area. On the other hand, in most tropical, temperate, semi-arid and arid landscapes, most morphology is related to fluvial runoff or has been modified by this process at various scales. Therefore an extraterrestrial geomorphologist has a fair likelihood of landing in a location that would help them determine that Earth has an active hydrological cycle and strong atmosphere–surface interactions. This proved true for Titan and the first, essentially randomly landed spacecraft. However, it has not proved true for other bodies on which spacecraft have landed, such as Venus, the Moon and a few asteroids, and it required specific targeting to land on obviously fluvial landscapes on Mars (Williams *et al.* 2013). In terms of the abundance of fluvial landscapes, Earth and Titan are more similar to each other than other bodies in the solar system (Lunine *et al.* 2008; Lorenz *et al.* 2008*a*).

Titan as a fluvially active world

Titan, being located near Saturn in the solar system, acquired substantial amounts of water during its formation: Titan's overall density of 1880 kg m^{-3} suggests the body is about half rock and half water/ice (e.g. Tobie *et al.* 2005). The lithosphere is therefore likely to be predominantly water ice, which at 94 K has mechanical properties similar to soft rocks on Earth (e.g. Litwin *et al.* 2012). Beneath the lithosphere, at *c.* 50 km depth, is a liquid water ocean that operates in a similar manner to the Earth's

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[1] Although various proposals of 'methanological' and similar contrived terms have been made, we advocate the use of 'hydrological' for Titan; by analogy with the use of 'magnetohydrodynamics' and similar terms in astrophysics, we argue that liquid water is not a prerequisite for the use of a 'hydro-' term that describes broad phenomenology.

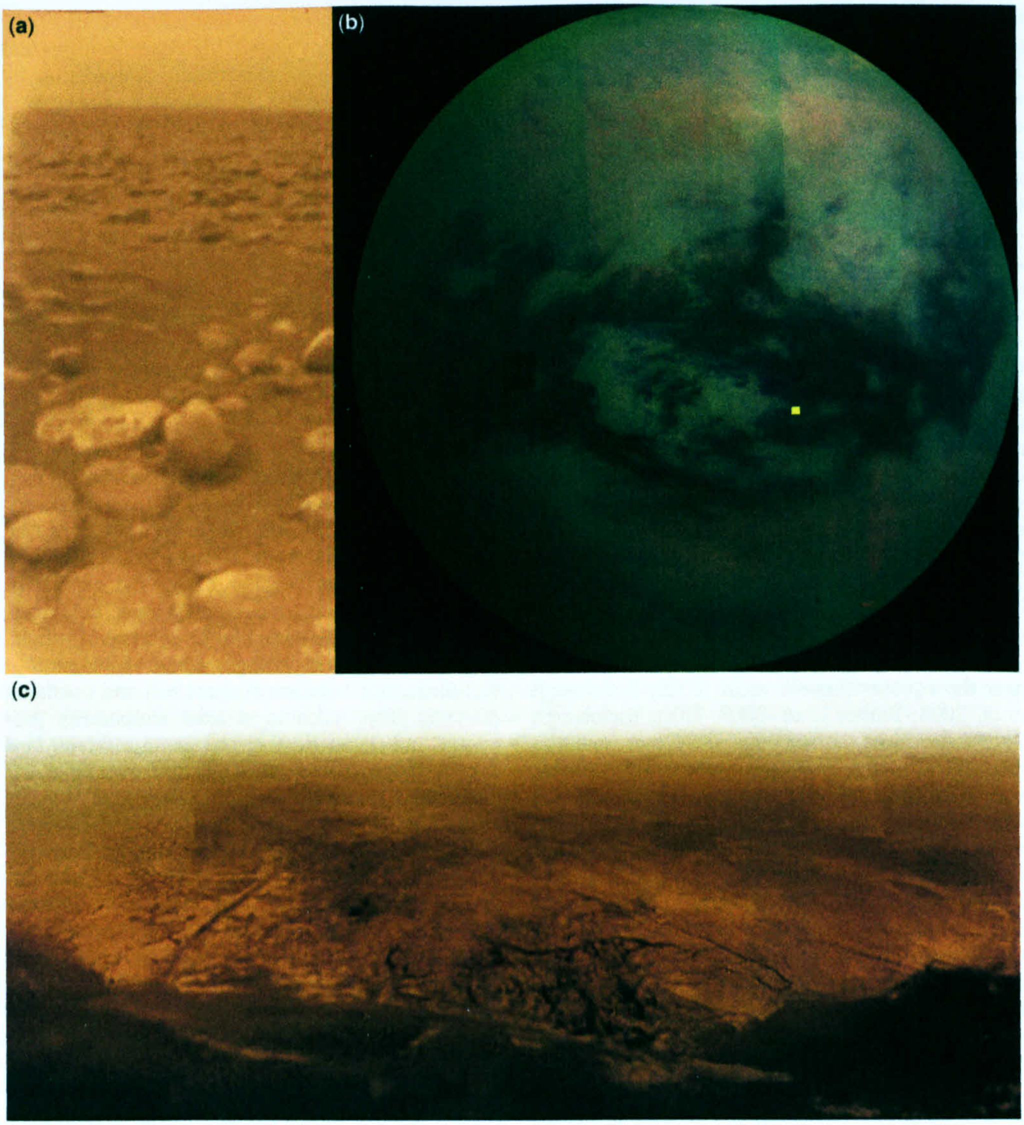

Fig. 1. (**a**) View of the surface of Titan from the Cassini Huygens probe. Rounded cobbles composed of water ice or organic materials can be seen across the surface, interspersed with finer grained materials. Rounding probably occurred in river beds, as on Earth, although the liquid is composed of low molecular weight hydrocarbon fluids at Titan's surface temperature of 94 K. The larger, foreground cobbles are *c*. 15 cm in size. (**b**) Global image of Titan obtained by the Visual and Infrared Mapping Spectrometer taken at wavelength regions that can view the surface through the thick atmosphere. Dark regions are mainly aeolian dune sand seas, bright regions are dominated by bedrock and sedimentary deposits. The colours result from the surface compositions, which are mainly organic materials and water ice. The small yellow square indicates the landing site of the Huygens probe. (**c**) View of the surface of Titan from the Huygens probe during descent, revealing a heavily fluvially dissected terrain. Images courtesy of the Cassini Huygens mission: (a) ESA/NASA and the University of Arizona, obtained 14 January 2005 and (b) image obtained 13 December 2011; (c) images courtesy of ESA/NASA/ Jet Propulsion Laboratory/ University of Arizona; processing and mosaic by Rena Pascal.

asthenosphere, allowing some mobility of the solid surface (e.g. Lorenz *et al.* 2008*b*; Iess *et al.* 2012). There has therefore been tectonism and the resulting production of topographically elevated landforms. Hundreds of mountains are found across the body, mostly as isolated blocks, but some organized into undulating chains a few hundred kilometres long (Radebaugh *et al.* 2007; Liu 2014). Other mountains are associated with impact craters, although there are only a few hundred potential and less than a dozen confirmed features (Neish & Lorenz 2012). All the topography appears to have undergone substantial erosion and there are also well-developed fluvial channels across the body (Fig. 1c; Lorenz *et al.* 2008*a*; Langhans *et al.* 2012; Burr *et al.* 2013*a*). The arrangement of many of these channels suggests tectonic control (e.g. Burr *et al.* 2009; Cartwright *et al.* 2011; Burr *et al.* 2013*b*).

The liquid available to erode and transport sediments at these cold temperatures is methane, which evaporates off the surface to form clouds, rain, rivers, lakes and seas in a currently active hydrological cycle (Griffith *et al.* 2005; Stofan *et al.* 2007). Methane evaporation and delivery to the upper atmosphere leads to its break-up by solar ultraviolet radiation and subsequent recombination into long-chain organic molecules (Soderblom *et al.* 2007). These settle to the surface in pervasive deposits, perhaps as sedimentary layers that then undergo erosion and transportation – for example, to create vast, high-volume dune fields of organic particles near the equator (Lorenz *et al.* 2006; Radebaugh *et al.* 2008; Barnes *et al.* 2008, 2015; Radebaugh 2013). In fact, surface materials that undergo mechanical erosion by fluvial action to form cobbles and sands have spectral signatures consistent not with water ice, but rather with a suite of organic materials with a variety of compositions (Barnes *et al.* 2007; Soderblom *et al.* 2007). Organic materials can have a range of densities, hardness, cohesiveness and erodibility and may also be subject to chemical or dissolution erosion through interaction with methane fluids (Lorenz & Lunine 1996; Malaska & Hodyss 2014). Studies of geomorphology are therefore critical to revealing material properties in the absence of other data. Evidence explored herein reveals that materials in certain regions on Titan's surface undergo primarily mechanical erosion through surface runoff and downslope transportation.

Alluvial and fluvial fans

Fans are sometimes categorized as alluvial or fluvial based on morphological differences that can also reveal sedimentological and genetic differences (e.g. Blair & McPherson 1994; Moscariello 2005). The presence of alluvial v. fluvial fans can reveal information about the local climate, catchment basin hydrology, relief maturity and other characteristics. Alluvial fans are downwards sloping, cone-shaped, depositional landforms that begin at the distal end of upland drainages along mountain fronts, where flows become unconfined (Bull 1972). On Earth, they are typical of high-relief settings and are the result of mostly episodic aggradation by sediment gravity flows, often during catastrophic hydrological events, and of fluid flows (Blair & McPherson 1994; Moscariello 2005). Alluvial fans are generally steeply sloping and poorly efficient and they build up or aggrade over short distances because they are fed by smaller catchments that are poorly integrated, collecting mainly local runoff and shedding it rapidly downstream. Stream hydrographs for alluvial fans are sharply peaked and reveal no protracted discharge. Sediment gravity flows from alluvial fans expand out of the catchment and the system grows more vertically than radially, leading to a morphology that is thick, steeply sloped and short in radius.

By contrast, terrestrial fluvial fans attain much larger radii than alluvial fans and invariably prograde over much lower slopes. This is because they receive input from a wider collection area and they have surface hydrology and catchment attributes that feed true river systems, characterized by protracted (perennial or ephemeral) runoff and a clear geomorphological and sedimentological distinction between channel belt and overbank domains. This leads to at least temporarily protracted and channelized discharge, thus fluvial fans are able to transfer sediment and fluid over large distances with relatively high efficiency (e.g. Moscariello 2005; Hartley *et al.* 2010).

If process and material variations on Titan are analogous to those on terrestrial alluvial and fluvial fans, then such regional conditions and morphogenetic patterns equivalent to those on Earth may be revealed. The presence of alluvial fans on Titan should indicate the presence of steep, abrupt breaks in topography and a lack of long-distance hydrological integration, as well as the transition between high-relief landscapes and adjacent lowlands/basins. The presence of large fluvial fans should indicate longer ranging fluvial system integration over gentler slopes and at least temporarily sustained runoff from larger drainages. They should also show clear fining-downslope trends and a more organized surface morphology, with differently textured areas denoting juxtaposed morpho-sedimentary domains, such as active and abandoned channel belts, floodplains, terraces and other mature floodplain morphologies.

Fans in synthetic aperture radar imagery

Death Valley, in the western USA (Fig. 2), is an active transtensional basin with exceptional relief in a desert setting and, consequently, a variety of fans are present across the valley. These are visible

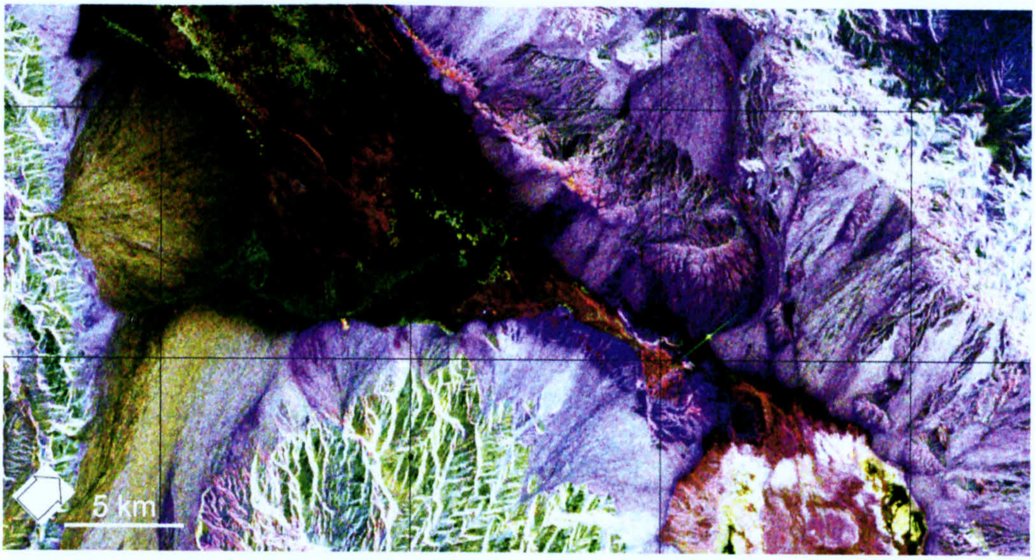

Fig. 2. Dozens of fans are visible in this Shuttle Imaging RADAR (SIR-C) composite image of northern Death Valley. The colours refer to the signal wavelength (L-band 24 cm; C-band 6 cm) and polarization, or orientation of the electric field (HH, horizontal emission and horizontal detection; HV, horizontal emission and vertical detection): RGB = LHH, LHV, CHV (24, 24, 6 cm). The large fans to the west are yellow, indicating a strong signal return in the red and green channels. This is a result of large cobbles and blocks near 24 cm in size. Blue fans in the east and south have many particles close to 6 cm in size, interspersed with fines, which are smooth to the synthetic aperture radar signal and appear dark. The valley floor is dark because of smooth sediments (the Mesquite dune field is the dark deposit in the centre) and evaporites, green from scattering and polarization changes by vegetation and red from scattering by subsurface, longer wavelength features such as layering. SIR-C image courtesy of NASA/Jet Propulsion Laboratory.

in synthetic aperture radar (SAR) imagery, an active remote sensing technique that illuminates a scene with precisely shaped radio waveforms and uses echo delay and Doppler shift information to map the echo energy to different parts of the scene. SAR images can reveal characteristics such as surface roughness, grain size, subsurface layering and composition (Schaber *et al.* 1976; Farr & Chadwick 1996). When the instrument sends out signals at specific wavelengths, particles of wavelength size in the surface and near-subsurface scatter the signal, which is then received back at the instrument. SAR images obtained at different wavelengths and different polarizations (orientations of the electric field) can be combined to create a false colour image that provides information about materials through their reflectivity or absorptivity at the different wavelengths and orientations. In three-band (24 cm horizontal, 24 cm vertical and 6 cm vertical) false colour SAR images obtained by Shuttle Imaging RADAR (SIR-C), fans in Death Valley can be seen emanating from single river channels, such as the large, classic, debris flow fan visible on the western side of Figure 2. The upper and middle parts of the fan scatter and return longer wavelength energy, shown in this SAR image mosaic as yellow (reflecting 24 cm wavelengths), due to the presence of cobbles and blocks close to 24 cm in size. Fine-grained materials distal and lower on the fan are smooth to all the SAR signals, precluding any return to the instrument, and thus appear dark in the SAR image mosaic (Schaber *et al.* 1976).

The uniformly bright, crenulated forms surrounding the basin are highly reflective mountain peaks, with the large facets of boulders and ridges reflecting radar energy back to the instrument. Fans here are part of a broad system of sediment transport from high chains of mountain peaks down broadly sloping flanks, termed bajadas in desert environments of the USA, into the adjacent basin. The fans in bajada systems overlap and interfinger and are typically short; they therefore have high slopes, energies and rates of sediment transport. These materials appear bright blue in Figure 2, which indicates there are cobbles on the fan surface close to 6 cm in size, being shed off tall mountains in the east and south, from small and rugged drainage basins. Mountains in the east form a NW–SE-trending lineament related to recent tectonism, highlighted by fan apex positions and materials. Sediments in the basin floor are dark to SAR because of fine-grained basin-filling materials that are smooth compared to microwave wavelengths. Bright and yellow materials in the playa to the south are rough evaporite deposits or water-lain fans. All of the fans are a result of differing slopes, materials, drainage basin areas and source regions (Moscariello 2005).

In Figure 3, also from northern Death Valley, a higher resolution SAR image obtained by aircraft (AirSAR) reveals more detail on a smaller fan surface. Rugged mountain terrains in the east appear extremely bright to SAR because mountain blocks directly facing the RADAR instrument are illuminated by the SAR signal. Channels wind through these rugged terrains and then give way to broad, sloping bajadas. Multiple overlapping fans, probably a result of different episodes of flow, are visible, as well as the regional, north–south-trending fault system and playa deposition on the west. Fan materials brightest to SAR are generally dispersed across the fan, although they can be seen closest to channel termini and at the base of mountains. These are probably regions where flows have the highest energy and can transport materials close to one of the SAR wavelength bands of 6 cm. Lower down the fan, the abundance of SAR-dark materials increases, indicating the presence of finer grained materials more easily transported over larger distances or the product of reworking and winnowing of coarser deposits over the more proximal fan domains (e.g. Blair & McPherson 1994; De Haas

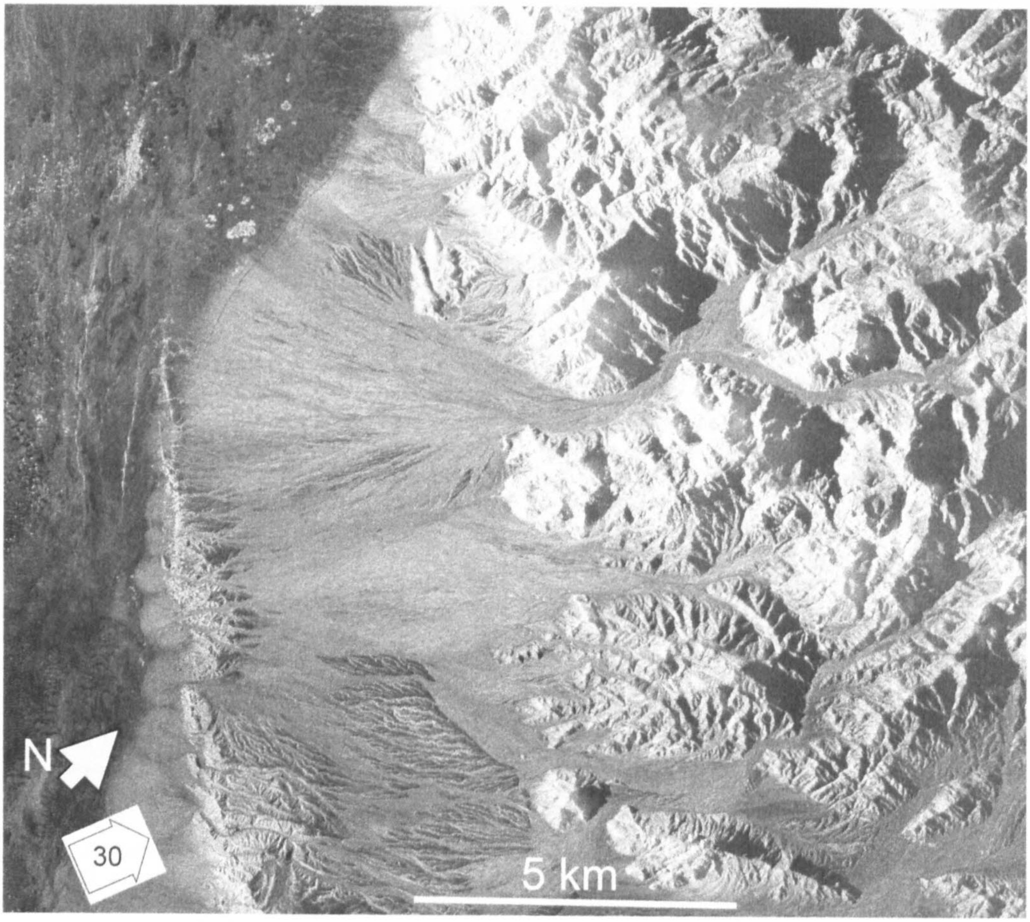

Fig. 3. Details of an alluvial fan and adjacent playa in northern Death Valley can be seen in this AirSAR image, which is a greyscale, three-band image mosaic containing images at 60, 24 and 6 cm. The brightest portions of the image are the rugged mountain peaks that have faces pointing towards the radar that reflect the synthetic aperture radar signal. The medium brightness fan surfaces result from an abundance of particles close to 6 cm in size. The dark portions of the fan and playa surfaces result from the presence of fine-grained materials. The white arrow indicates the look direction of the RADAR and the number in the arrow refers to the incidence angle (with respect to vertical). AirSAR image courtesy of NASA/Jet Propulsion Laboratory.

et al. 2014). Detailed morphological and quantitative surface studies by RADAR remote sensing in Death Valley and other locations have enabled the determination of material properties, landscape slopes and catchment areas; they have also allowed for the analysis of changes over time resulting from erosion and climate change and have allowed surface units to be distinguished (Schaber *et al.* 1976; Daily *et al.* 1978; Farr & Chadwick 1996). These studies enable us to make similar distinctions in fan-bearing regions on Titan.

Fans on Titan from Cassini SAR imagery

Alluvial and fluvial fans of various sizes and morphologies are observed in locations across Titan, as imaged by the Cassini spacecraft (Lorenz *et al.* 2008*a*; Burr *et al.* 2013*a*). The instrument technique with the best resolution (350 m) to view these features is the Cassini RADAR operating in SAR mode at a wavelength of 2.17 cm (Elachi *et al.* 2005). This resolution is challenging for the identification of surface features. Figure 4 is a greyscale version of Figure 2 down-sampled to Cassini SAR resolution; note that the large fan on the west is visible, as are the broad bajadas, but the identification of small, individual fans is difficult (Fig. 4).

Fans on Titan are generally found at the termini of fluvial channels that are SAR-bright, which suggests they may contain cobbles close to the SAR wavelength in size (Le Gall *et al.* 2010). Channel brightness also indicates they are not, at least currently, liquid-filled, as they would appear dark from the loss of signal through reflection from the smooth liquid surface and/or changes in the dielectric contrast at liquid–solid boundaries. In addition, there are no filled lakes at the channel termini, as might be expected if the channels were filled, so we retain the assumption that the SAR-bright fluvial valleys are dry.

Generally empty channels with cobbles are also found in alluvial systems on Earth formed in or at the margins of continental basins where runoff is ephemeral, water tables mostly low and surface hydrology active only during significant precipitation events. Several channels interpreted to be filled with liquid can be seen near the north and south polar regions of Titan, where they terminate in lakes and seas (Stofan *et al.* 2007; Wall *et al.* 2010). Some of these fluvial systems terminate in deltas or fans (Burr *et al.* 2013*a*). The largest fans seen so far on Titan are Leilah Fluctus, Elivagar Flumina and the Mezzoramia fans, described in detail in the following sections, and with the locations on Titan shown in Figure 5. There are also a number of smaller fans visible at the termini of smaller river channels and perhaps along the bajadas of mountain slopes; these are also described.

Leilah Fluctus

A region in Titan's temperate northern hemisphere and in the leading position as the satellite orbits

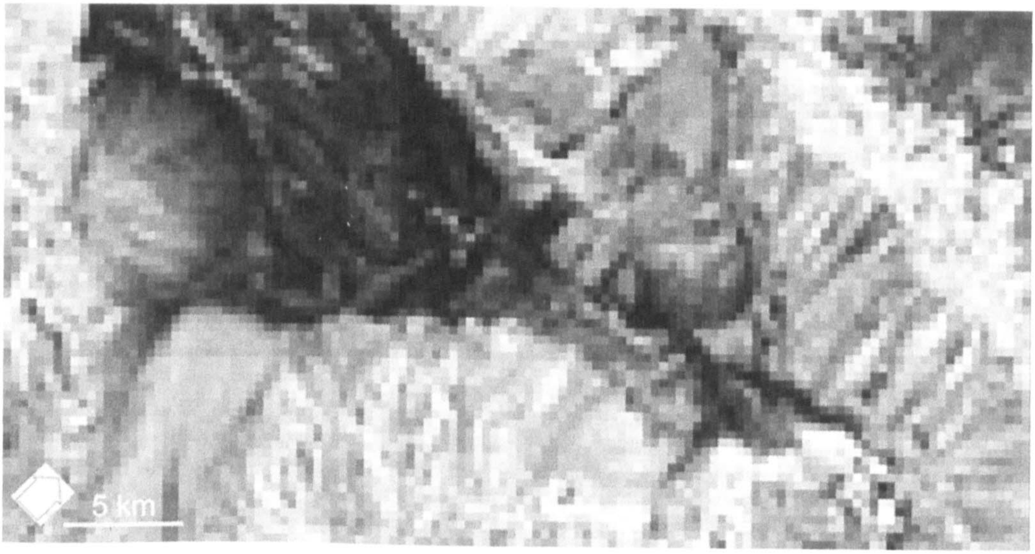

Fig. 4. Greyscale version of the Shuttle Imaging RADAR image of Death Valley fans from Figure 2 degraded to Cassini synthetic aperture radar resolution (350 m) for Titan. The larger fans are still visible, particularly the fan to the west, but individual fans and channels are difficult to discern at this resolution.

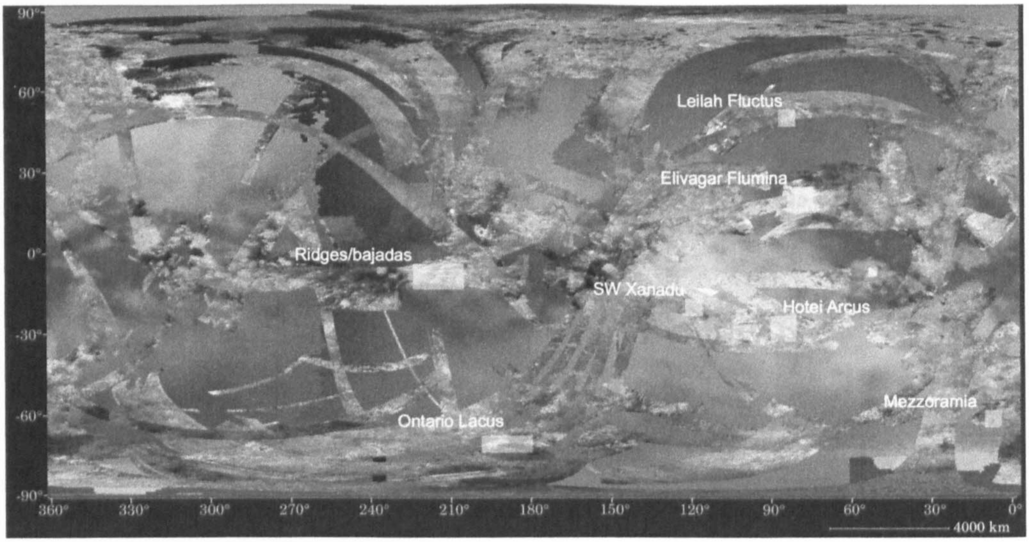

Fig. 5. Locations of all fan features on Titan discussed in the text. Base map is from Cassini synthetic aperture radar, Visual and Infrared Mapping Spectrometer and Imaging Science Subsystem (ISS) images. Synthetic aperture radar swaths are long, thin images obtained throughout the closest approach during the Cassini flybys. Note the fan features are fairly evenly distributed latitudinally.

Saturn (keeping the same face to Saturn, as does the Moon to Earth), was the first location imaged by Cassini SAR (Elachi *et al.* 2005). A portion of the region is characterized by a landscape of overlapping, lobate, flow-like features with rounded and fingered margins, variably bright to Cassini SAR (Fig. 6, west side). The flows could be cryovolcanic in origin (Lopes *et al.* 2007) or they could result from mass wasting and surface flow, perhaps triggered by methane rainfall (Moore & Pappalardo 2011).

Interspersed within the lobate flows are narrow, bright channels (Fig. 6) that appear to originate in the highlands. These channels terminate in broad fan systems that are bright to SAR. There are two major and several minor overlapping fans in Leilah Fluctus (Fig. 6), showing a classically distributive, fan-shaped morphology. They are generally SAR-bright, indicating an abundance of cobbles close to 2.17 cm in size, although the brightness varies across the fans, indicating a broad granulometric range at the surface.

A digital elevation model (DEM) (Fig. 7a), made from two images of the same region taken from different angles during different flybys, overlain on a higher resolution SAR image, has a resolution of *c.* 100 m, with green at the highest and purple at the lowest elevations. Channels wind through mountainous highlands, which are elevated in the DEM, and then terminate in fan-shaped features to the east (Lorenz *et al.* 2008*a*). The slope profile from the DEM (Fig. 7b) reveals a gentle overall slope from west to east, with some steep excursions from this gentle profile that may be a result of the profile jumping out of the fan system, of variations in the topography in the fans, or of the overall low resolution of the DEM. The slope of the short, bright portion of the southern fan from the profile is 0.6°. Paganelli *et al.* (2005) interpreted these features as fluvial flows. The fact that the fans are distal to channels coming from elevated topography is strongly suggestive of subaerial alluvial processes for the origin of these fan-like landforms.

The SAR-brightest materials in Leilah Fluctus occur close to the channel termini, forming fans *c.* 30 × 15 km in size (Fig. 8). SAR-bright materials also extend downslope of these SAR-bright, proximal fans (marked 'a' and 'b' in Fig. 8). The proximal zones and brightest materials may be where the most vigorous flow occurs, where relatively coarse gravel (cobble grade) is transported, and where finer materials, such as sand or atmospheric organic debris, have not been deposited on the cobbles. They may also mark the most recently active fan regions, as these appear to overlap other, probably older portions of the fans. Materials of varying SAR brightness extend from the apex of the fans to over 100 km distance. Some portions of the distal fan are fairly SAR-dark (Fig. 8), probably from the presence of fine-grained sands, smooth to the SAR signal, that were carried greater distances by increasingly depleted flows.

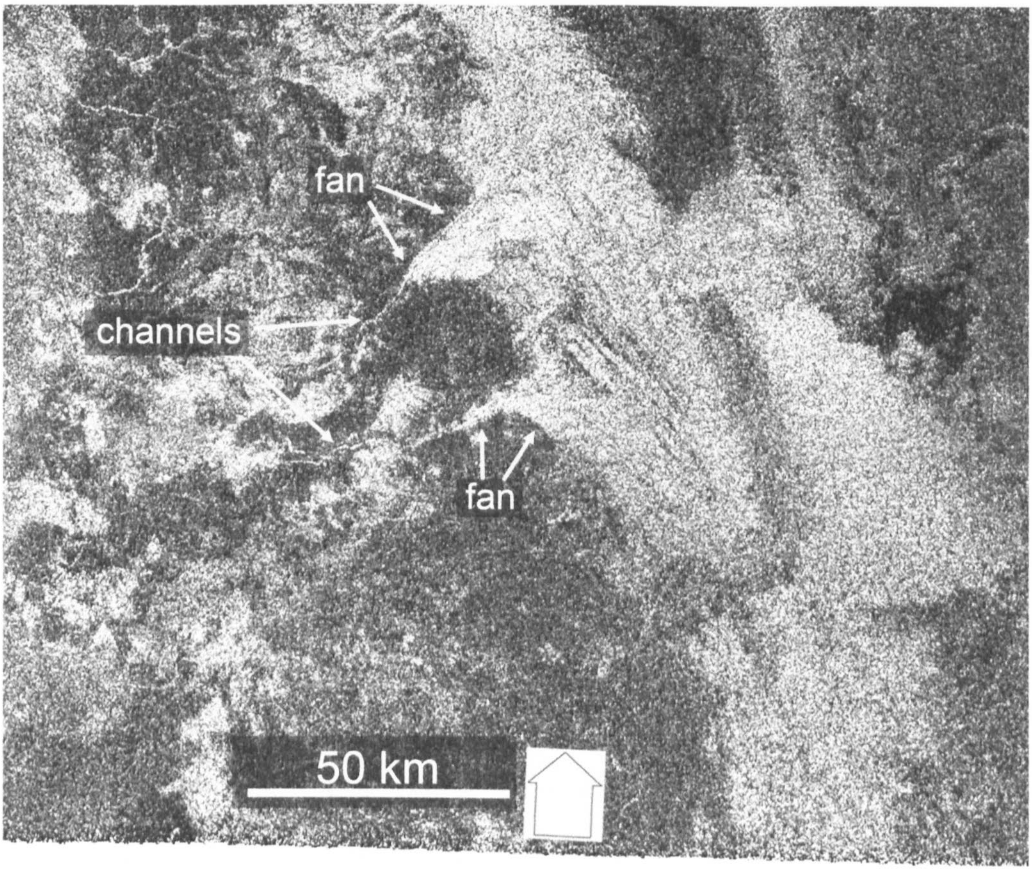

Fig. 6. The Leilah Fluctus fans seen by Cassini synthetic aperture radar (SAR) in the first SAR image of Titan's surface. The fans are SAR-bright, indicating an abundance of cobbles close to the Cassini SAR wavelength of 2.17 cm. Variabilities in brightness across the fans reveal differences in sizes and probably zones of more or less recent activity. Rivers feeding the fans are thin and SAR-bright and wind through a variegated, SAR-bright and SAR-dark terrain to the west. Large, white arrow indicates the look direction of the SAR. Features located at 51° N 80° W; SAR image 350 m resolution obtained in the Cassini Ta flyby, 26 October 2004.

At the bottom of the proximal fans is a set of bright/dark lineaments (Fig. 8, marked 'd'), similar in size and spacing to linear dunes found in abundance near the equatorial region of Titan (Lorenz *et al.* 2006). They appear to be slightly elevated in the DEM and the fans terminate against or divert around them ('d' and 'c' in Fig. 8). These may be remnant dunes, active during a previous climatic phase, perhaps now immobile (Radebaugh *et al.* 2011), or they could be active dunes composed of SAR-brighter materials. It is also possible that if the dunes were more recently active, then they are overriding the fans. However, the fan morphologies are more complete and continuous than the possible solidified dune morphologies, which supports the fans being more recently active.

The elevation profile from the DEM (Fig. 7b) confirms that there is a general downslope trend from the uplands in the west down through the fans to the SE. All these observations indicate that the area west of the fans forms an elevated plateau and has significant topography that feeds drainages ending in broad fans as they enter lowlands to the east.

Elivagar Flumina

In the northern tropics of Titan, also in the leading position as the satellite orbits Saturn, is the largest identified impact crater on Titan, Menrva, imaged in Cassini's second SAR-imaging flyby of Titan (Lunine *et al.* 2008). At 450 km in diameter, it is heavily eroded, with walls breached by channels

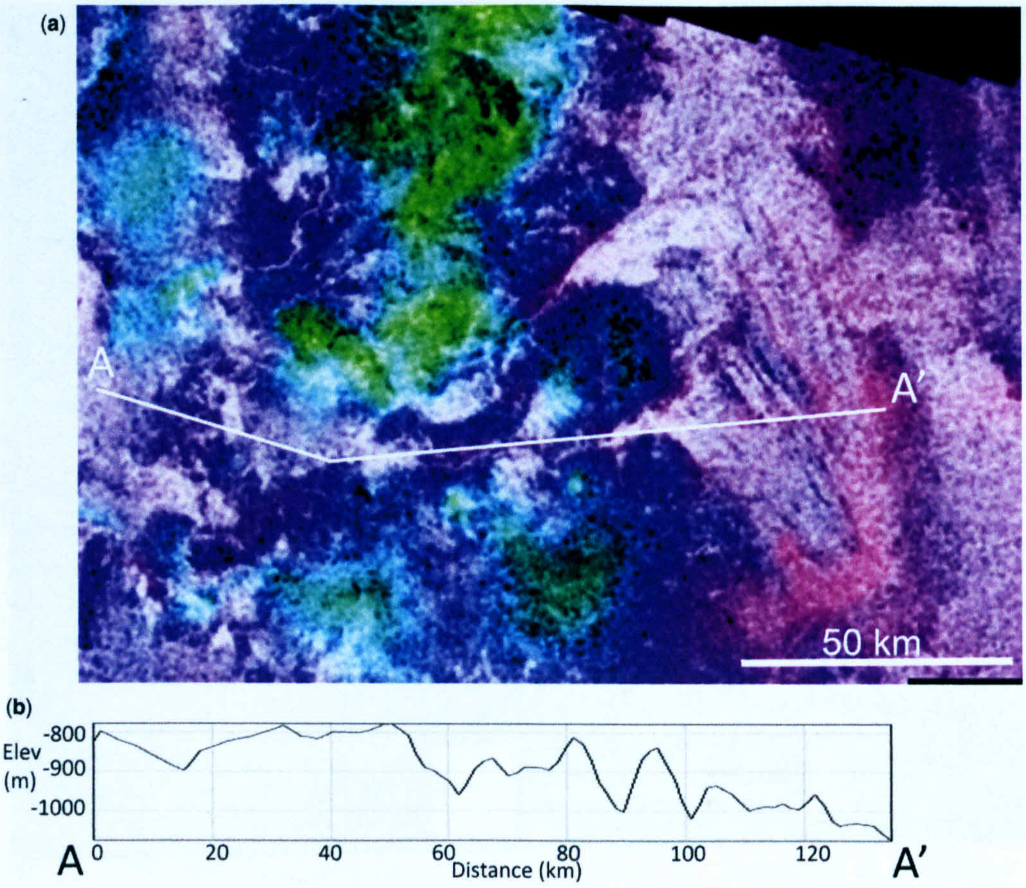

Fig. 7. (**a**) A digital elevation model overlain on the synthetic aperture radar (SAR) image of the Leilah Fluctus region created from overlapping Cassini SAR images obtained at different times. Green is at the highest and purple at the lowest elevations. The highest regions are found NW of the fan system; channels wind around the highlands and terminate in the fans to the east. (**b**) Elevation profile from the highlands across the fan system. The intrinsic vertical resolution of the digital terrain model is *c.* 100 m, so the apparent oscillations in the profile may be 'noise'. The overall slope across the short, southern fan is *c.* 0.6°. North is up; features located at 51° N 80° W; SAR image 350 m resolution; obtained in the Cassini Ta flyby, 26 October 2004 and the T23 flyby, 13 January 2007.

(Fig. 9a; Lorenz *et al.* 2007; Lunine *et al.* 2008; Wood *et al.* 2010; Williams *et al.* 2011). The crater is associated with a regional upland that feeds a giant, integrated channel system immediately to the east (Fig. 9a). It is also possible that the cratering event led to an underground structure that channels groundwater and forces flow to the east. Elivagar Flumina, named for 12 poisonous ice-cold rivers in Norse mythology, has close to that many tributary channels coalescing across a broad fan system (Fig. 9a).

On the western end of the system, at the headwaters, the channels are narrow and SAR-bright, suggesting they are dry, confined and perhaps incised into the terrain, and hosted flows large enough to transport *c.* 2 cm cobbles. Towards the east, surface patterns suggest that the channels become unconfined and anastomosing and the flows spread out onto an overlapping fan system. Each fan is about 40 km long and they vary significantly in width, particularly because in many cases the fans overlap. Some minor variation in brightness across the fans is indicative of a range of particle sizes. The general morphology of Elivagar Flumina has been compared to gravel bed, braided, ephemeral river systems that tend to terminate in fluvial distributary systems (Lorenz *et al.* 2008*a*; Burr *et al.* 2013*a*). Given the strong connection of the fans to a well-established fluvial system and the length and elongate morphology of the tributaries and fans, these

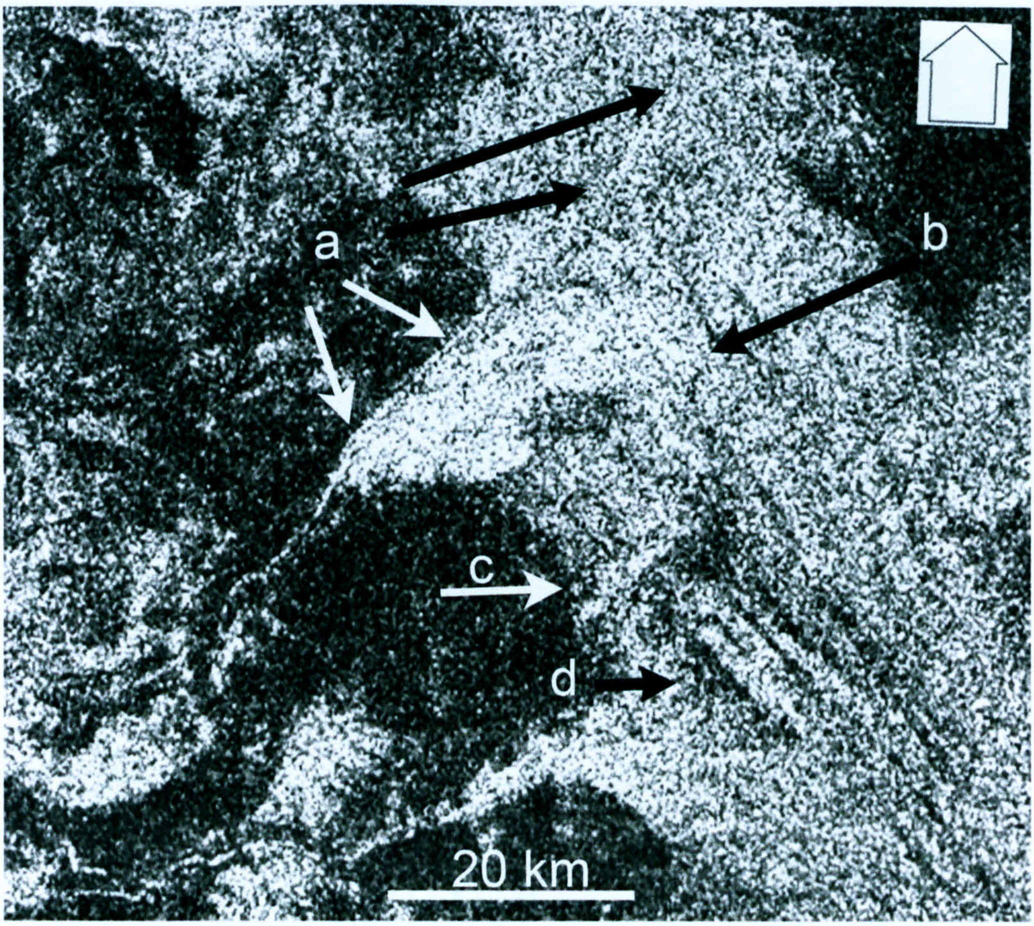

Fig. 8. Close-up Cassini synthetic aperture radar (SAR) image of the Leilah Fluctus fan system. Materials are brightest to SAR near the apex of the fans and in bright channels that wind downslope on the north of the northern fan (arrows at 'a'). Very bright materials can be seen all the way to 'b'. Linear features that run NW–SE could be relict dunes causing fan materials to stop ('d') or divert ('c'). White arrow indicates the look direction of the radar. Image scale is from 0 to 6 dB. SAR image located at 51° N 80° W; SAR image 350 m resolution; obtained in the Cassini Ta flyby, 26 October 2004.

may best be termed fluvial fans, which are depositional landforms of larger scale and more complex morphology than alluvial fans (e.g. Nichols & Hirst 1998; Smith 2000; Moscariello 2005).

A method to derive elevation from overlapping SAR sub-swaths in a single SAR image mosaic, termed SARTopo (Stiles *et al.* 2009), was applied here and reveals a gentle regional gradient from the Menrva impact crater in the west to the termini of the Elivagar Flumina fans in the east (Fig. 10a). The topographic profile from the SARTopo data (Fig. 10b) shows this gentle regional gradient. The slope across only the fans is 0.1°, lower than that for Leilah Fluctus (Fig. 7). Note that the intrinsic vertical resolution of the SARTopo technique is *c.* 100 m with a horizontal sampling of *c.* 10 km (Stiles *et al.* 2009) and thus the bumps on the profile may not be real.

The general morphology of the Elivagar Flumina system reveals regional controls. In the western uplands, the landscape is relatively elevated and the channels are highly confined. At the bajada, materials spread out into distinct fans across a slope decreasing in gradient, based on the geomorphological trends, to the east. This heralds the transition between two principal landscape zones, where conditions for sediment transport change abruptly (Harvey 2010). At the base of the fans and bajada, in the lowlands, SAR-bright materials continue to the east, although these become mixed

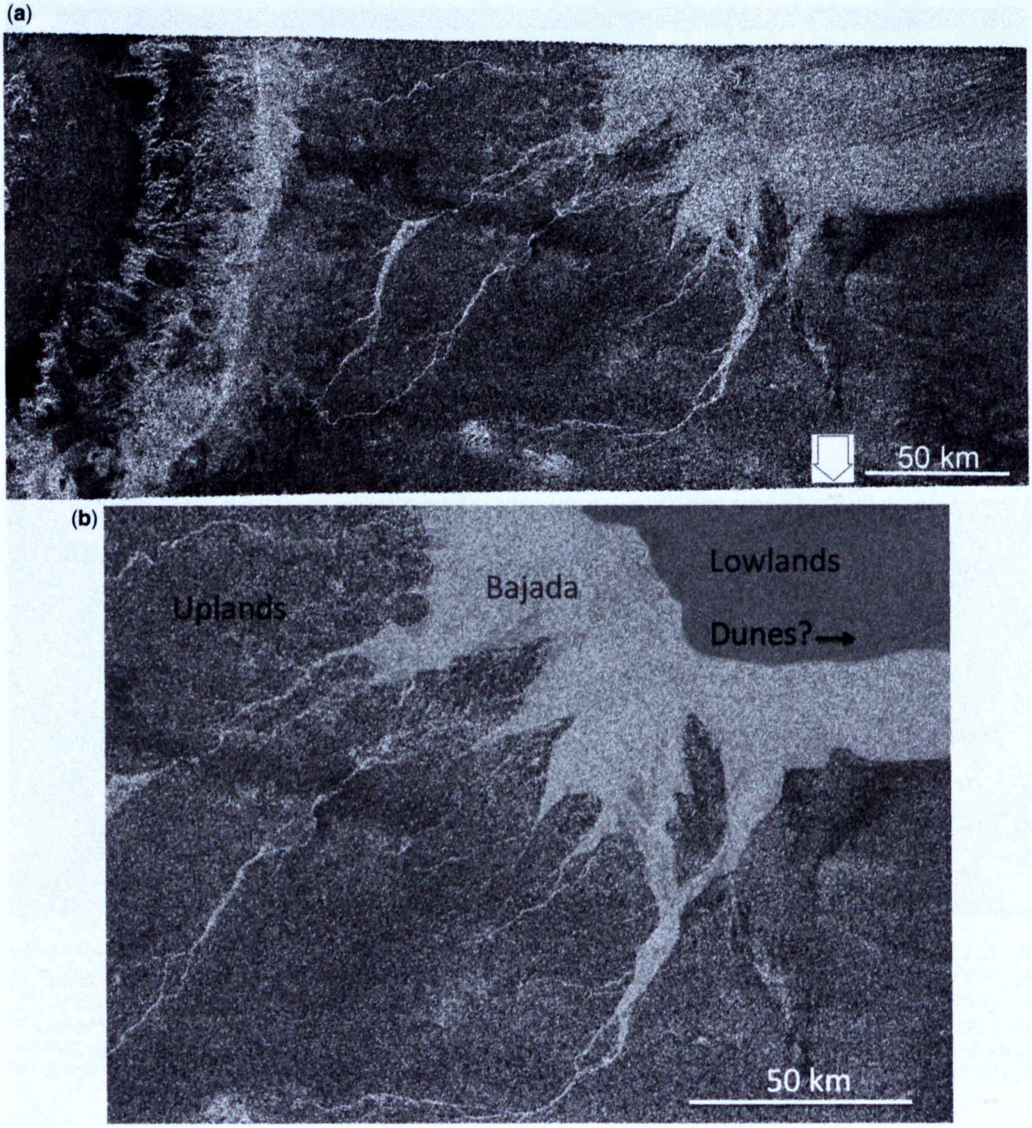

Fig. 9. (**a**) The Elivagar Flumina river and fluvial fan system seen by Cassini synthetic aperture radar (SAR). Bright channels originate at the margins of the 450 km diameter Menrva impact crater, the rim of which is visible, heavily eroded, on the west of the image. The channels extend over 200 km to the east, where they terminate in a set of overlapping fans. As with Leilah Fluctus, the fans terminate near dune-like features. (**b**) Regional geomorphological sketch map of the Elivagar Flumina system. Channels are incised into the terrain in the west, termed 'uplands'. A broad, overlapping fan system exists in the 'bajada'. All materials are in the process of being transported to the 'lowlands'. North is up; white arrow indicates the SAR look direction. Features located at 21° N 87° W; SAR image 350 m resolution, obtained in the Cassini T3 flyby, 15 February 2005.

with SAR-dark materials. As with Leilah Fluctus, these materials include bright/dark lineaments that may be dunes or relict aeolian dunes (Lopes *et al.* 2010; Williams *et al.* 2011). This is typical of fan systems that transition to depositional basins, where there is interdigitation with sabkha and mudflats, and where fine-grained materials transported there can be organized into aeolian dunes. The wide distribution of mostly featureless SAR-bright materials across the lowlands may be evidence of sheet flooding over an unconfined floodplain.

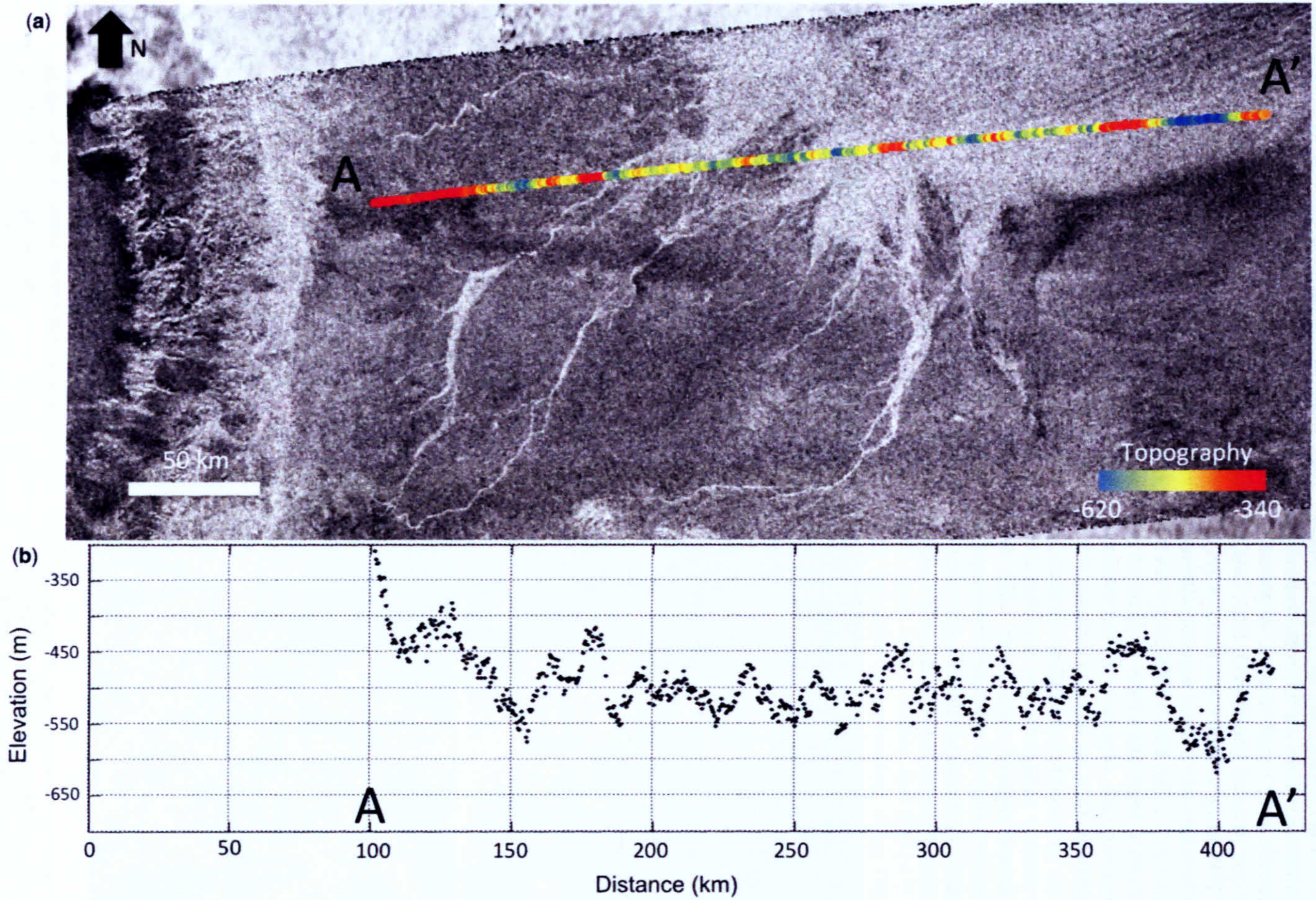

Fig. 10. (**a**) The Elivagar Flumina system seen by Cassini synthetic aperture radar with a SARTopo topographic trace overlain. Low elevations are in blues and high elevations in reds. (**b**) Topographic profile from SARTopo data correlated with the image. Note high elevations, close to the Menrva impact crater rim, decreasing across the fan to low elevations in the west. The slope across only the fans is 0.1°. Image located at 21° N 87° W.

Cassini Visual and Infrared Mapping Spectrometer (VIMS) data, which consist of images taken at wavelengths in the near-infrared of surfaces illuminated by sunlight through the thick, hazy atmosphere, provide constraints on the compositions of surface materials over broad regions, at generally low resolutions (tens of kilometres). SAR images on top of VIMS images of Elivagar Flumina reveal differences between this system and the surrounding terrains (Fig. 11a, b). This VIMS image reveals that the materials beginning at the location of the fans and trending east, especially in the locale of the basin east of the fans, are made of different materials from the surroundings, or that this region has been active recently enough that the erosional activity and transport happens on a faster scale than the uniform deposition of atmospheric photoproducts. In addition, the compositional signal seen by VIMS is coloured a deep blue based on the spectral signature, which is consistent with the presence of water ice or with a mixture of water ice and organic compounds. This indicates that the crustal bedrock from which Elivagar derived its cobbles for transport has similar spectral characteristics to that of water ice (Barnes *et al.* 2007). Although the crust of Titan is thought to be dominantly water ice, there is a large proportion of the surface that has similar spectral characteristics to organic compounds, visible in this image as light green (Fig. 11b). This is to be expected considering the vast amounts of atmospheric organic condensates that have been deposited over time across the surface, followed perhaps by the formation of hardened organic layers. These layers are then subject to erosion by methane rainfall. In regions that appear to be most active in terms of erosion and thus clastic sediment supply, such as steep mountain peaks and fluvial systems, the composition has similar

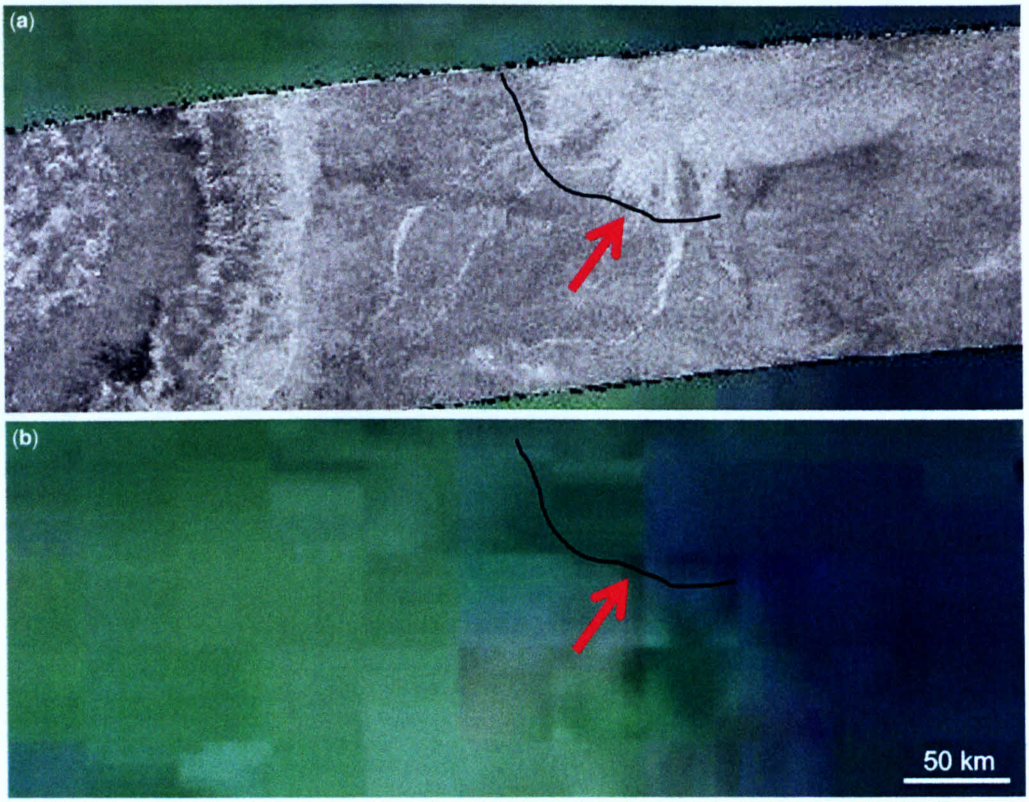

Fig. 11. Cassini (**a**) synthetic aperture radar and (**b**) Visual and Infrared Mapping Spectrometer (VIMS) images of Elivagar Flumina. VIMS data reveal that the materials beginning at the fan system and moving towards the east are different from the surrounding terrain and are dark blue (compared with the dark green surrounding materials), or relatively darker at 2.0 μm, consistent with an enhancement in materials with a spectral response similar to water ice. Red arrows show the same location on the surface; a black line traces the rough division between the uplands and fan materials, visible in the VIMS image as light green v. dark blue. The spectral colour scheme is red = 5.0 μm, green = 2.0 μm and blue = 1.28 μm (Barnes *et al.* 2007).

spectral characteristics to those of water ice based on VIMS data (Barnes *et al.* 2007; Soderblom *et al.* 2007). This interpretation is consistent with observations of the Elivagar Flumina system.

Mezzoramia (T7) fan

The third region imaged by Cassini SAR is in the southern mid-latitudes and also contains a large fan system (Elachi *et al.* 2005; Lorenz *et al.* 2008*a*; Lunine *et al.* 2008). This system begins in southern low latitudes in a canyon or hoodoo-like highland region, characterized by highly dissected terrains (Fig. 12a). This transitions to a uniformly SAR-grey region with incised channels that emanate from the dissected regions (Fig. 12b), similar to the channels in the uplands of the Elivagar Flumina system. South of this channelized terrain is a dramatic morphological transition to a broad distributary network, *c.* 200 km long and *c.* 150 km wide (Fig. 12c). It is moderately SAR-bright, indicating the transport of pebbles near *c.* 2 cm in size, and has channels that are SAR-dark, indicating the presence of finer grained materials. This distributary system empties into a region that is SAR-dark, perhaps a basin filled with fine-grained materials or with shallow or near-surface liquids (Fig. 12d). With a smooth surface such as that of a calm liquid, the SAR signal is reflected away from the instrument, leading to effectively no return of signal, which was seen at the northern lakes and seas and southern Ontario Lacus (Stofan *et al.* 2007; Hayes *et al.* 2013).

SARTopo topography (coloured line on the SAR swath, Fig. 12) reveals a fairly dramatic gradient from the northern dissected terrains, down through the fan to the dark basin, with an overall elevation difference of 1400 m, compared with 300 m at Elivagar Flumina over nearly the same distance (Fig. 10b). The average slope along just the fan is 0.3°, intermediate between the slopes measured for Leilah Fluctus (Fig. 7b) and Elivagar Flumina (Fig. 10b). A slight elevation increase at the edge of the dark basin correlates with lobate features that may be slightly elevated evaporite or karst-related landforms (Mitchell *et al.* 2014), lobate cryovolcanic features (Lopes *et al.* 2007) or landslide deposits (Moore & Pappalardo 2011).

The distributary system has mild braiding and intersecting of long, straight channels, revealing a smooth basement and gentle slope, also described in Burr *et al.* (2013*a*). SAR-dark, straight channels demonstrate an uninterrupted path downslope and are probably filled with fine sands. A similar morphology can be seen at the same scale in the massive Qarn Alam fan in Oman, which transitions from a large, resistant ophiolite complex to the Rub al Khali desert floor (Fig. 13a). Long, straight channels with varying brightness seen in a visible spectrum image of Oman slice through the fan system, revealing the efficiency of the fan in transporting materials of all sizes. Similar morphologies, of large channels perhaps traversing the angular boundaries of elevated landforms, and of straight, distributary systems moving downslope, can be seen in the fan region of Mezzoramia (Fig. 13b). These similar morphologies may partially be a result of the similar overall slopes of the Qarn Alam (0.2°) and Mezzoramia (0.3°) fans or their placement on a broad, unconfined slope.

Small fans into basins

The three major fan systems described in the preceding sections are large by any standard and were clearly visible at Cassini SAR image resolutions. Notably, these were observed in the first three SAR image passes and similarly large systems have not been observed since. Other regions on Titan, however, contain smaller fan systems, although the limited image resolution precludes the identification of all their features. Most visible fans are at the ends of river systems that originate in mountainous regions and then debouche into apparent basins or morphological slope breaks. Several large river systems drain the southern Xanadu mountainous terrains and terminate in small fans (Fig. 14). These systems contain the brightest surface materials visible to SAR, an apparent result of a combination of the ideal size of the rounded particles (*c.* 2 cm) and a radar-transparent composition allowing efficient retro-reflection of the radar energy (Le Gall *et al.* 2010), much in the way that 'cats-eyes' in road markings reflect light. Cold water ice and organic compounds are suitably radar-transparent materials. The fact that such bright channels are >100 km long has some important implications with respect to alluvial processes. Specifically, it shows that clasts can be rapidly rounded because there are SAR-bright materials near the source regions, but they do not quickly become comminuted because there are so many large particles at great distances from their source. In other words, the material may be relatively resistant to fracture and indeed may have a somewhat plastic rheology – the particles become rounded more easily than they break. The channels appear to terminate into a SAR-dark lowland, not dark enough to indicate deep liquids, although there could be shallow or near-surface liquids. The small fans decrease in SAR brightness away from the channel termini, thus possibly fining downstream, percolating into porous material or evaporating (Fig. 14).

Other channels emptying into apparent basins end in fans. Hotei Regio, which is located at the SE margin of Xanadu and contains tangled flows

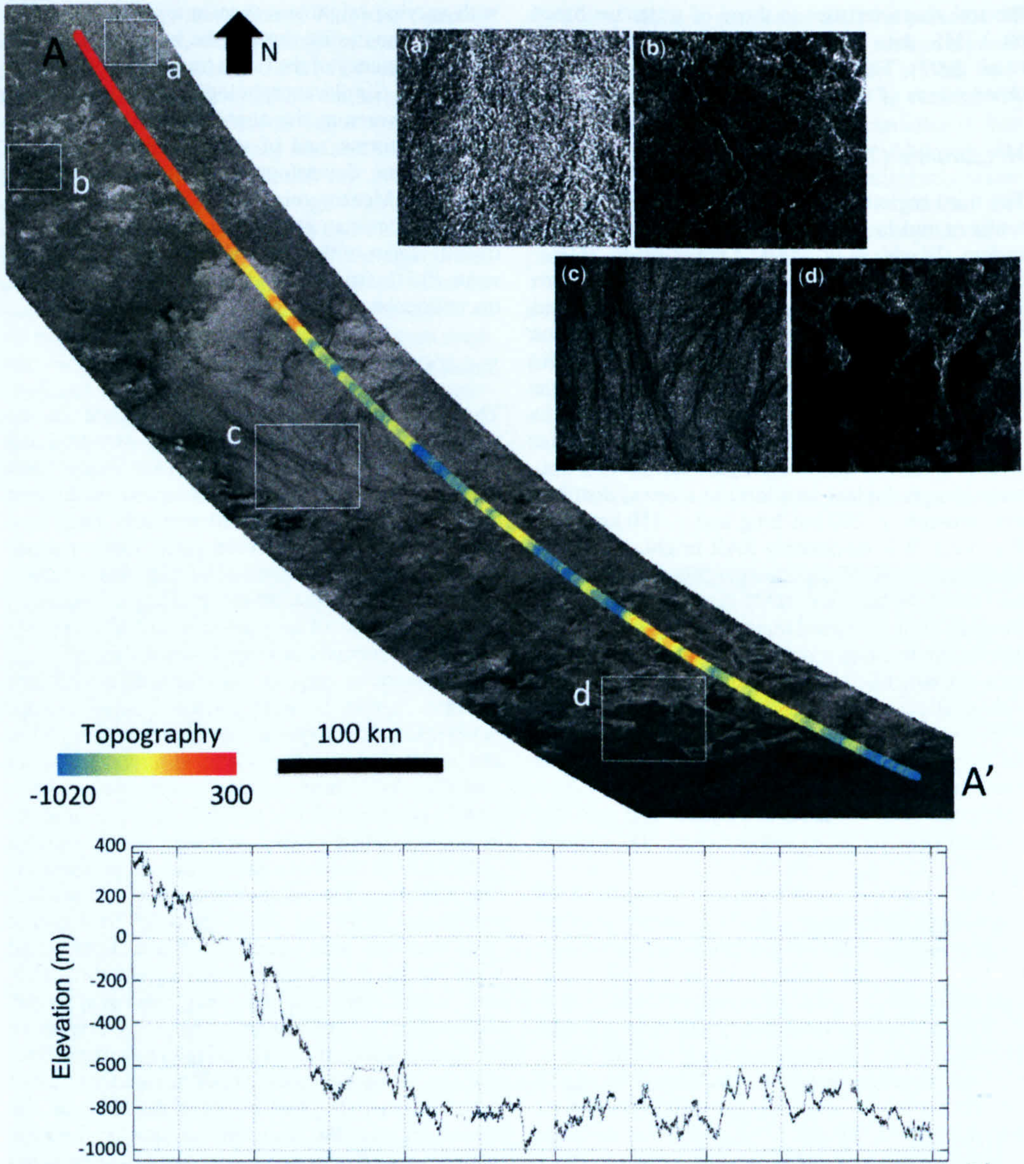

Fig. 12. The Mezzoramia (T7) fan system seen in regional context (long, curved image swath) by Cassini synthetic aperture radar (SAR). In the north (**a**) is heavily dissected terrain, with steep, closely spaced canyons and hoodoos. This transitions to (**b**), where a few channels emerge from the dissected terrain and become heavily incised into an otherwise smooth landscape. These few, incised channels emerge to a broad, distributary fan system (**c**) of high variability in SAR brightness. South of the fluvial system is a region of lobate morphologies (**d**), elevated as seen by SARTopo. These sit on the margin of a shoreline-like feature. The image swath has SARTopo elevation data overlain (coloured strip). The corresponding profile reveals a distinct decrease in elevation from the dissected terrains, down the fan, to the shoreline. The average slope along just the fan is 0.3°. A slight elevation increase near the shoreline may be from deposits of tufa, volcanic or landslide origin. Image located at 60° S 5° W; SAR image 350 m resolution, obtained in the Cassini T7 flyby, 7 September 2005.

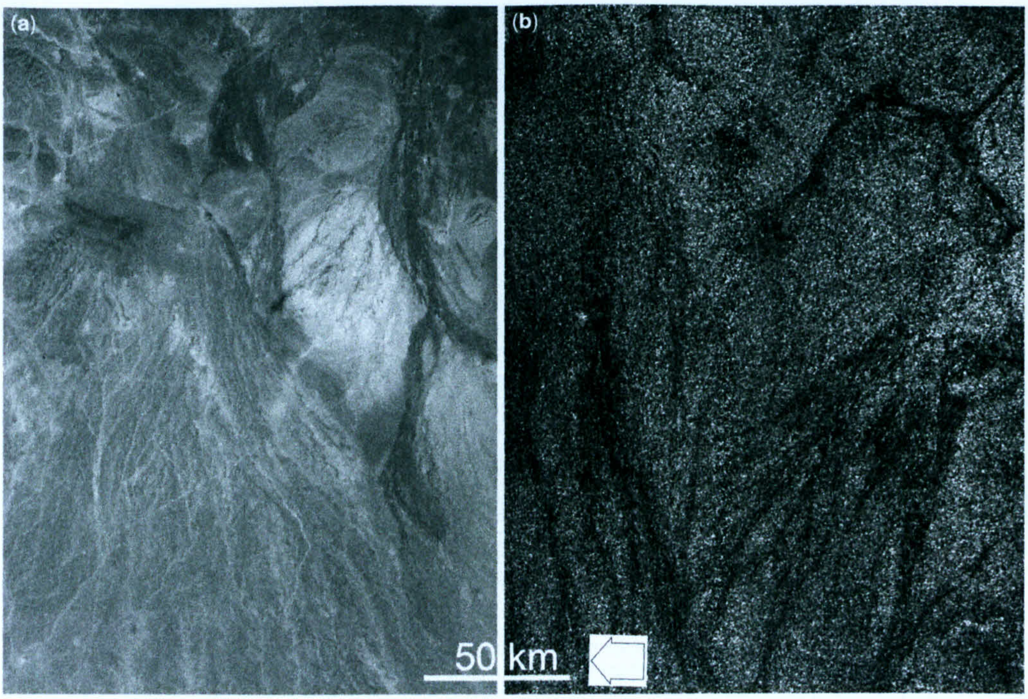

Fig. 13. (**a**) Visible image of the Qarm Alam fan, Oman, at the same scale as a Cassini synthetic aperture radar (SAR) image of the (**b**) Mezzoramia (T7) fan on Titan. Generally long, straight and branching morphologies are seen in both images, as well as alternating light/dark materials, although in the visible image the variations are in albedo and thus composition, while the SAR brightness variations are probably more related to texture. The slopes are similar. Image (**a**) is centred on 21° 50′ N, 57° 20′ E, courtesy of Google Earth; the SAR image (**b**) is located at 60° S 5° W; SAR image 350 m resolution; white arrow indicates direction of radar illumination; obtained in the Cassini T7 flyby, 7 September 2005. Both images are roughly north up.

of unknown origin, was first determined to be a regional low because there are several channels emptying into it from the surrounding mountains (Barnes *et al.* 2006; Soderblom *et al.* 2009). These channels, some with associated fans, can be seen in the T41 and T43 swaths, which cross Xanadu's SE margin. Most of Titan's basins are SAR-dark, probably because they are filled with fine-grained sediments transported by fluvial systems. Some basins may also contain fluids in the near-subsurface, like swamps. However, there are some basins that are SAR-bright. There is a 150 km wide basin in the south polar terrain (Fig. 15) that has SAR-bright channels emptying into it, grading into fans that are of similar SAR brightness to the channels. These fans are small and they grade into materials of moderate SAR brightness in the centre of the basin (Fig. 15). It is unclear what sedimentary processes are linked to these bright basins; they could be filled with *c.* 2 cm bedload material from fluvial transport, they could be made of sediments with a different dielectric constant to the surrounding terrains, or they could be surfaces made rough through the evaporation process (Barnes *et al.* 2015). However they formed, their sedimentology must be different from the SAR-dark, dry basins.

Ontario Lacus, the first lake discovered on Titan and also the largest in the south polar region, is 250 × 70 km in size (Fig. 16). It is bordered on the north by mountain peaks that appear to have been partially submerged. The mountains have an isolated morphology and there are broad, filled drainages and possible old shorelines (Wall *et al.* 2010; Hayes *et al.* 2011), all evidence of changing lake levels over time. To the west there is a large, dark (and therefore probably filled) channel that meanders to the coast of the lake, where it ends in a bright, lobate form interpreted as a deltaic deposit (Wall *et al.* 2010); we label this here as a 'fan delta'. The southern margin is curved and has streaked lineations pointing towards the lake that could be partially submerged fan deposits. On the east is a smooth, arcuate shoreline at the base of mountains (Fig. 16; Wall *et al.* 2010). Upslope of the shoreline are morphologies consistent with broad, coalesced

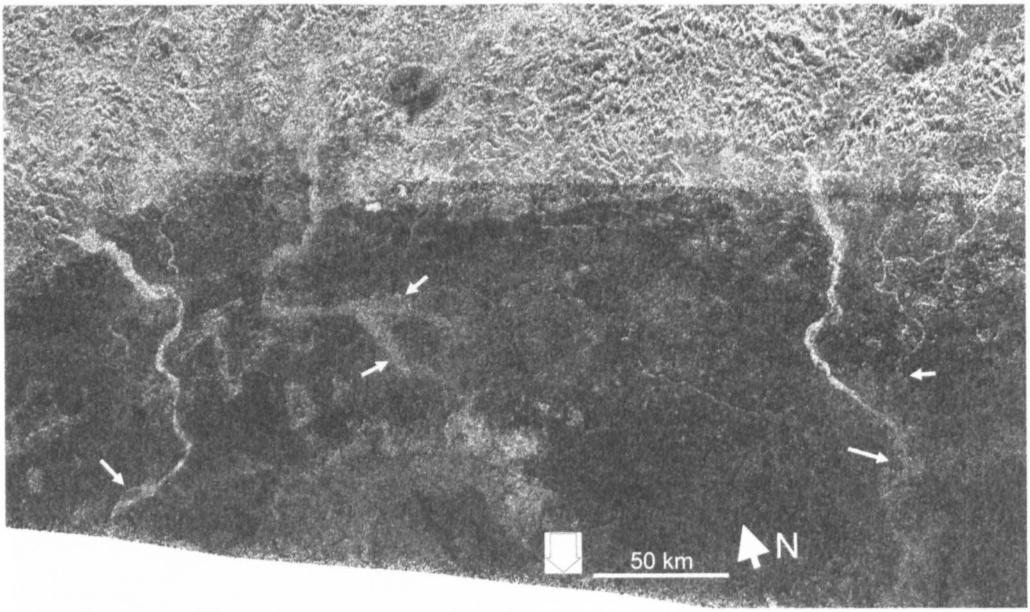

Fig. 14. Mountainous, highly dissected highlands in the Xanadu terrain source wide, extremely synthetic aperture radar (SAR)-bright channels that terminate in fans, indicated by small, white arrows. The SAR-dark character of the channel termini reveals fine-grained materials that have been carried from the highlands to a basin. Channels grade from SAR-bright to moderately bright then grey as particles become increasingly fine. Image located at 60° S 5° W; SAR image 350 m resolution; white arrow indicates direction of radar illumination; obtained in the Cassini T7 flyby, 7 September 2005.

fans prograding into the lake. Alternatively, the morphology could indicate shoreline deposition from a past condition of higher lake stand. The lake may be subject to repeated cycles of desiccation and infill, similar to ephemeral, closed basin lake systems such as Racetrack playa in Death Valley, compared previously with Ontario Lacus (Lorenz *et al.* 2010); the Etosha pan in Namibia has similarly been proposed as an analogue (Cornet *et al.* 2012).

Bajada fans on Titan?

Mountain peaks on Titan are visible as bright/dark pairs of pixels, indicating illumination of one face and shadowing of another by the side-looking RADAR instrument (Radebaugh *et al.* 2007). In addition, most mountains have basal aprons of SAR-bright materials, which appear to be clastic talus blankets shed off by erosion and mass wasting. At the equatorial regions of Titan, the mountains are found in linear chains hundreds of kilometres long, indicating a tectonic origin (Radebaugh *et al.* 2007; Mitri *et al.* 2010; Liu 2014). These are located in Titan's deserts, where many active dune systems reside, and are thus similar in morphology and climatic context to the mountains of the Basin and Range Province and Death Valley in the western USA. By analogy with this region, the SAR-bright blankets could represent broad, bajada-related fans.

To determine the ability of Cassini SAR to reveal smaller fan systems, we compared a high-resolution Shuttle Radar Topography Mission (SRTM-X) band SAR image in southern Death Valley with a version of the same image degraded to 700 m resolution. (Fig. 17a, b). Fans of different brightness, resulting from variations in materials and slopes related to the SAR illumination angle, dominate the image scene at high resolution (Fig. 17a). Although individual fans cannot be resolved in the degraded image (Fig. 17b), the blankets of varying SAR brightness are still recognizable where the presence of a bajada would be expected. We then compared the SAR images from Death Valley with a Cassini SAR image of an equatorial mountain belt (Fig. 17c). There are some similarities in that the long mountain belt is prominent in Figure 17b, c; however, the bajada fans appear different in the two images. The resolution is worse in the degraded SRTM-X image, but the speckle noise is greater in the Cassini SAR image. Therefore the fans and mountain ridges still appear more prominent in the SRTM-X image. The noise in the Cassini SAR images is in part

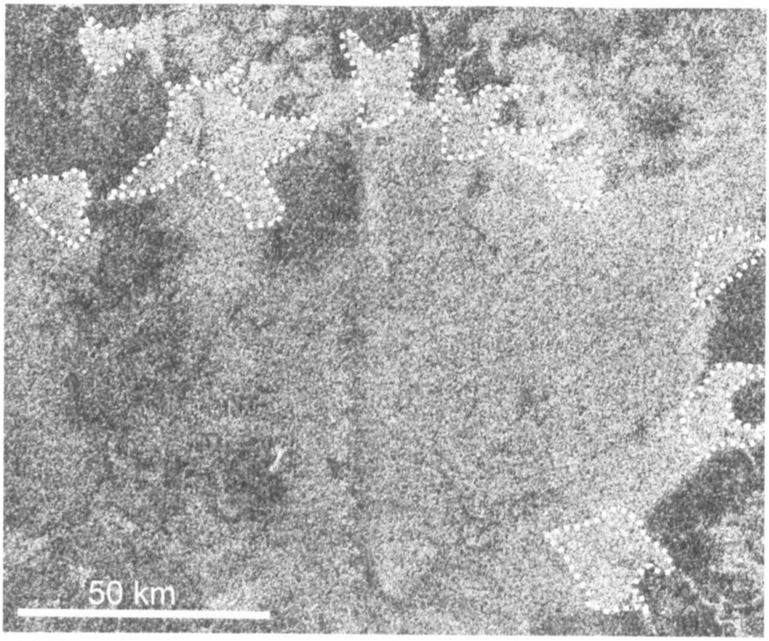

Fig. 15. Channels terminate in fans at the edge of a dry, synthetic aperture radar (SAR)-bright basin near Titan's south pole. Channels are seen ringing the edges of the image as thin, bright lines, all of which are flowing towards the centre of the image. The channels grade into small fans of similar SAR brightness. These give way to a central basin, which extends across the middle of the image and is moderately SAR-bright, although not as bright as the channels or fans. SAR image at 350 m resolution; obtained in the Cassini T39 flyby, 20 December 2007.

because the SAR signal responds differently to Titan materials, scattering more in the subsurface. In addition, relief is generally lower in the Cassini SAR image (Radebaugh *et al.* 2007). However, there is a visible SAR-bright blanket surrounding the Titan mountain peaks, which could possibly be overlapping fans (Birch *et al.* in revision). Consideration of the horizontal scale indicates a higher probability for it to be composed of coalescent to adjacent alluvial fans, rather than commonly less extensive colluvial aprons/debris cones. Future higher resolution studies should be aimed at mapping such landforms to determine the areas and volumes of fan-related deposits on Titan (Birch *et al.* in revision).

Fan parametric comparisons

Studies of the sizes and shapes of landforms, or landscape parametric analyses, are yielding important results for the origin and evolution of planetary surface features (e.g. Perron *et al.* 2009; Ewing *et al.* 2010; Savage *et al.* 2014). We analysed the relationship between fan radius and area to determine what this can reveal about the underlying terrain, regional slopes and volume in a system. We grouped Titan's fans by region – for example, as the entire Leilah and Elivagar systems – and also analysed the separate, contributing fans within these systems. These values are plotted in Figure 18 against measurements for selected fans on Earth and Mars.

To a first order, all measured alluvial and fluvial fans lie on the same curve for fan length v. area, indicating they have the same general morphology, which is that of a basically triangular distributive, fan-shaped system radiating out of an apical region. This observation supports the interpretation that these features are fans formed from the processes of flow and deposition similar to other fan systems on Earth and Mars (Birch *et al.* in revision). This general shape is less consistent with a cryovolcanic (volcanism from melting of water ice bedrock), landslide, slumping, surface ponding or dissolution origin, all of which are other processes known to occur on Titan.

Note that fluvial fans on Earth (Earth FF Max and the Qarn Alam fan, Oman; Fig. 18) are much larger than alluvial fans, which is a result of the differences in their collection areas, stream lengths and slopes, as discussed earlier. All fans on Titan fall between the maximum sizes for alluvial and fluvial

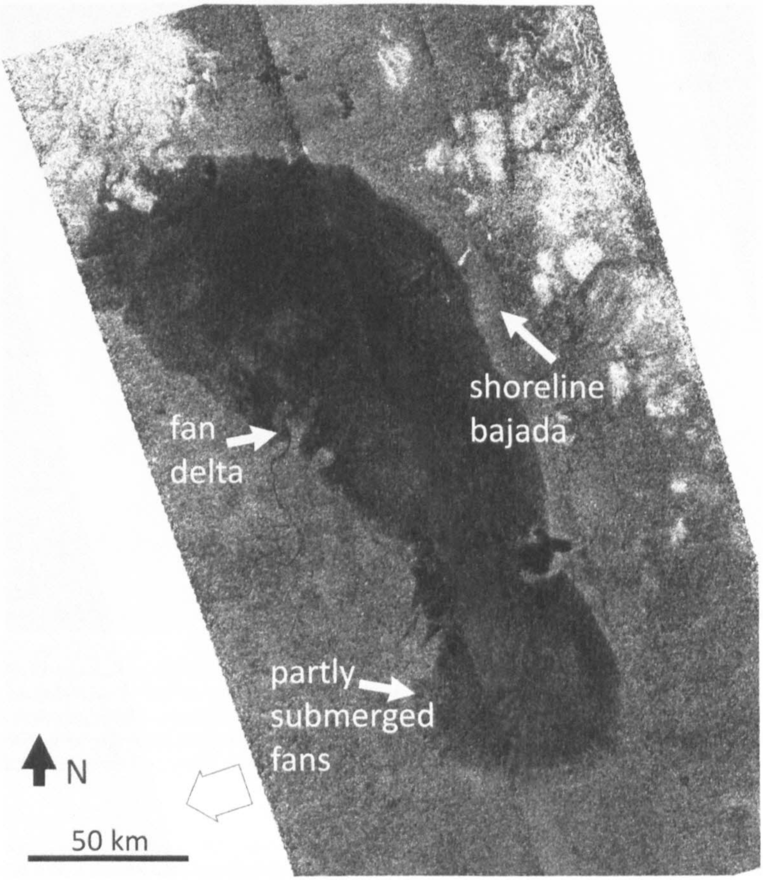

Fig. 16. The Ontario Lacus of Titan from Cassini synthetic aperture radar (SAR) imagery. Possible fans on the margins of the lake prograde out into the lake. Open arrow shows direction of SAR illumination; SAR image 350 m resolution; located at 72° S, 183° W; obtained in the Cassini T65 flyby, 12 January 2010.

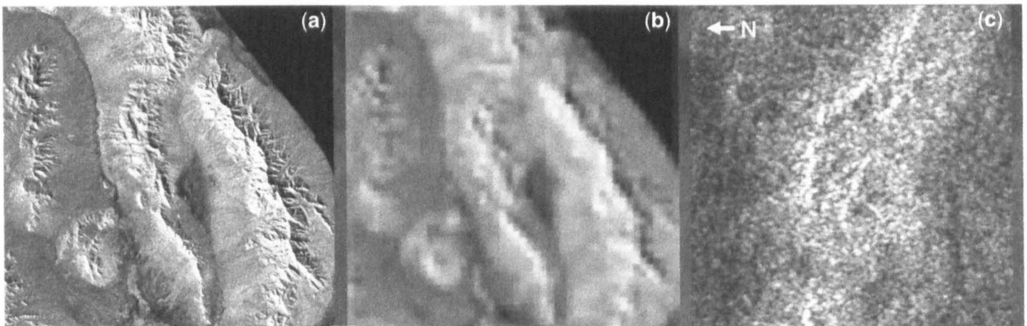

Fig. 17. (**a**) Shuttle Radar Topography Mission (SRTM-X) band (3 cm) image of southern Death Valley. (**b**) The same image degraded to 700 m resolution. (**c**) Cassini synthetic aperture radar (SAR) image of equatorial mountain belt at 350 m resolution, with speckle issues not present in (a) or (b). SRTM-X image (a, b) courtesy of DLR (German Space Agency). Cassini SAR image (c) 350 m resolution; obtained in the Cassini T8 flyby, 28 October 2005.

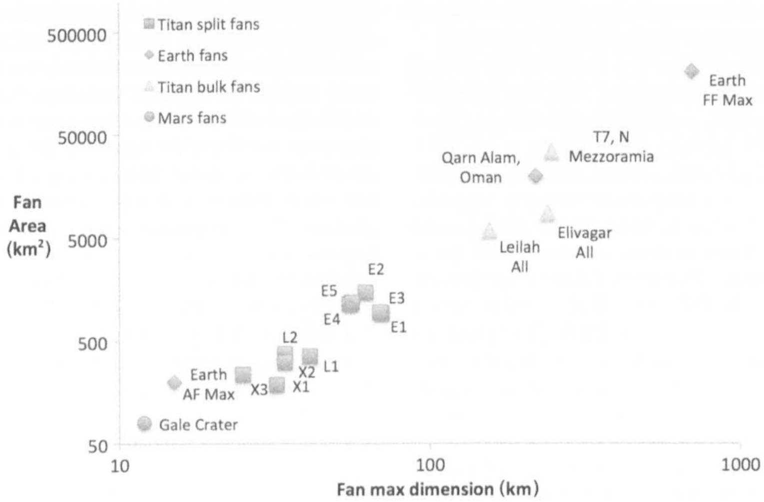

Fig. 18. Fan maximum dimensions with respect to areas for selected fans on Earth (diamonds), Mars (circles) and Titan (squares and triangles). In general, all the features sit on the same curve, indicating they are morphologically similar. The largest alluvial fans (Earth AF Max) and fluvial fans (Earth FF Max) on Earth effectively bracket all the fans on Titan discussed here. L fans are separate Leilah Fluctus fans; E fans are separate Elivagar fans; and X fans are separate Xanadu channel termini fans. The Gale Crater fan is a characteristic small alluvial fan on Mars.

fans on Earth, including individual fans within the larger Leilah Fluctus and Elivagar Flumina fan systems. These individual fans cluster together by region, indicating similarities in slopes, materials, channel energies and other conditions within separate regions. The Mezzoramia fluvial fan is the largest of the three main fans, which may result from overall smaller particles to transport (the SAR brightness is lower, consistent with finer grains) and smooth, gentle slopes. It is not only similar in general morphology, but also in dimensions to the Qarm Alam fan in Oman. Given the similarity in slope of the two systems, 0.2° (Oman) v. 0.3° (Mezzoramia), this may lead to the possibility of predicting slopes for systems of similar dimensions, where slope information is not otherwise available.

Discussion and conclusions

SAR imagery of Titan reveals that the features distributed across Titan are best interpreted as alluvial and fluvial fans. This reveals the action of precipitation-related runoff processes persistent over timescales long enough to produce the large, well-developed fan systems described here. Fans provide important information about the properties and behaviour of surface materials. Radial changes in SAR brightness along alluvial and fluvial fans reveal coarse-grained materials in the proximal portions of these landforms and fine-grained materials in the distal portions. The consistent recognition of such textural trends represents confirming evidence that the identified landforms are depositional in origin, paralleling the typical grain size distribution of analogue alluvial systems on Earth (Bull 1972; Blair & McPherson 1994; De Haas *et al.* 2014).

Although Titan's overall relief is relatively low compared with Earth, regional and local differences exist and are emphasized by landforms, particularly various kind of fans. Fan morphologies can constrain the origin and character of the local topography. For example, the Leilah Fluctus fans are overall shorter and wider than other large fans on Titan (Fig. 18). This is consistent with the results from the DEM that reveal greater slopes down the Leilah Fluctus fans (0.6°), which would lead to more vertical aggradation than in the regions with gentler slopes. In the Elivagar and Mezzoramia regions, slopes are gentler (0.1 and 0.3°) and down-fan deposition appears to dominate. Continued analysis of topographic data across Titan, where available, will allow more characterization of fan morphology and especially estimates of their thickness and volumes (Birch *et al.* in revision). This kind of information may help establish whether alluvial fans on Titan are related to passive dismantling of local topographic highs, or tied to continued clastic shedding from relief sustained by long-term tectonics. The range of sedimentary and other processes modifying Titan's landscape makes it difficult to detect indications of tectonics, which are only revealed in the presence of mountain chains and the control of river networks. Alluvial fans may provide a new window into tectonism on Titan.

The existence of fans is a result of the overall character of Titan's atmosphere: first, that precipitation currently occurs and reaches the surface (Tomasko *et al.* 2005; Griffith 2009; Turtle *et al.* 2011; Barnes *et al.* 2013); and, second, that the precipitation which drives transport is strongly episodic (Lorenz 2000; Lorenz & Sotin 2010). Because the atmosphere of Titan is thick and extended, it can hold large volumes of liquid methane before becoming saturated, a condition that leads to brief, severe and episodic rainfall (Lorenz 2000). Therefore we can correlate the known behaviour of Titan's atmosphere with the resultant fan morphologies to learn more about the requirements for fan formation in general.

Geomorphological and sedimentological studies on Earth have long demonstrated that fan-shaped, distributive alluvial systems of various kinds tend to develop as poorly efficient, transport-limited systems, thus with a marked tendency to aggrade large volumes of sediment in relative proximity to the source area(s) (Bull 1977; Richards *et al.* 1993; Blair & McPherson 1994; Bryant *et al.* 1995; Mohrig *et al.* 2000; Harvey 2010). Mostly, this is related to a long-term excess of sediment supply compared with the potential availability of runoff to redistribute such sediments further towards the basin. In addition to the geomorphological and geological contexts (e.g. an active tectonic relief with immature catchments or highly erodible bedrock shedding large volumes of terrigenous material), climate may be one more variable limiting the transport efficiency of the system. Runoff in arid to semi-arid climates, for example, with sporadic precipitation and ephemeral discharge regimes, is typically unable to sustain sediment transport over long distances from the source areas, except for occasional events of intense, concentrated precipitation (e.g. Beven 2002; Hartley *et al.* 2005; Reid & Frostick 2011). This is one reason why alluvial fans are almost ubiquitously developed in desert environments (although not exclusively typical of such settings, as frequently believed), in the presence of significant topographic relief. On Titan, brief bursts of effective transport (Lorenz 2000) may transfer sediment from the mountains, plateaus and uplands into valleys and basins, where it spreads out into fan deposits.

The typical fan shape of such alluvial systems is probably indicative of autogenic switching of active sectors of transport and deposition through time; the relocation of active fan sectors in these systems is typically due to dominant deposition, which builds up positive topography and forces runoff to find alternative routes through the remaining topographic lows (e.g. Beaty 1963; Denny 1967; Viseras & Fernández 1994; Ventra & Nichols 2014). The observation that the fluvial fans in Leilah Fluctus and Elivagar Flumina are the only such features in their respective regions, and that they appear to exist adjacent to possible relict or active dune fields, seems to confirm that runoff in these systems has never been sustained long enough to characterize the whole region with a dominantly alluvial morphology. This emphasizes the concept that hydrological activity on Titan is probably sporadic, ephemeral and occurs in restricted time windows. The large sizes of the fluvial fans, however, indicate that these are fed by relatively extensive catchments that can collect large volumes of precipitation and distribute it over relatively longer times, indicating a probable range of different hydrological sensitivities and responses over different areas. In addition, the attainment of fully developed fan-shaped patterns for these systems indicates that depositional events have been necessarily repeated over a relatively recent period of time. Otherwise, there would be single, elongate, depositional lobes rather than symmetrical, radiating, fan-shaped features. It is notable that the largest alluvial and fluvial fans discussed here were recognized in the first, second and third Cassini SAR observations of Titan, and that none as large have been seen since in over three dozen more SAR observations. In addition, the large fans are relatively isolated, which correlates well with the idea that Titan's precipitation is brief, severe and strongly episodic (Lorenz 2000).

Titan is to the hydrological cycle what Venus is to the greenhouse effect: a terrestrial process taken to extremes (Lorenz 2012). On Earth, there is enough solar energy to evaporate about 1 m of water per year. The atmosphere can hold only a couple of centimetres of moisture before clouds and rain form, so terrestrial weather is broadly characterized by showers dropping a few centimetres of rain every week or two. On Titan, the feeble sunlight allows only about 1 cm of evaporation per year, insufficient to sustain a particularly dynamic hydrological cycle such as on Earth (Lorenz & Lunine 2005). However, the atmosphere can hold the equivalent of about 10 m of liquid. So Titan's weather should feature torrential downpours, causing flash floods, interspersed by centuries of drought (Lorenz 2000). It was predicted (Lorenz 2000), and shown to be true, that we would observe river channels as a result of active rainfall and erosion, but few of them are full because of the long periods between rainfall events. Indeed, Titan's boom/bust weather cycle is an extreme version of what may become more common on Earth as our climate evolves. As our troposphere expectedly warms, it holds more moisture and both rainstorms and droughts may become more intense. In this respect, alluvial fans may provide a window, throughout the solar system, into the character of precipitation. In addition to its potential for a first-order assessment of Titan's climate, research on the moon's surface, informed by ongoing geomorphological and sedimentological work on the Earth's systems, highlights the importance of interpreting various alluvial landforms and their different genetic implications to pave the way to our advancing knowledge of a planetary surface far from our own.

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EDITED BY

D. VENTRA
Utrecht University, the Netherlands

and

L. E. CLARKE
University of Gloucestershire, UK

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