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Review Article

Dunes on Saturn's moon Titan as revealed by the Cassini Mission

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ABSTRACT

Dunes on Titan, a dominant landform comprising at least 15% of the surface, represent the end product of many physical processes acting in alien conditions. Winds in a nitrogen-rich atmosphere with Earth-like pressure transport sand that is likely to have been derived from complex organics produced in the atmosphere. These sands then accumulate into large, planet-encircling sand seas concentrated near the equator. Dunes on Titan are predominantly linear and similar in size and form to the large linear dunes of the Namib, Arabian and Saharan sand seas. They likely formed from wide bimodal winds and appear to undergo average sand transport to the east. Their singular form across the satellite indicates Titan's dunes may be highly mature, and may reside in a condition of stability that permitted their growth and evolution over long time scales. The dunes are among the youngest surface features, as even river channels do not cut through them. However, reorganization time scales of large linear dunes on Titan are likely tens of thousands of years. Thus, Titan's dune forms may be long-lived and yet be actively undergoing sand transport. This work is a summary of research on dunes on Titan after the *Cassini* Prime and Equinox Missions (2004–2010) and now during the Solstice Mission (to end in 2017). It discusses results of *Cassini* data analysis and modeling of conditions on Titan and it draws comparisons with observations and models of linear dune formation and evolution on Earth.

Contents

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1. Introduction

One of the primary goals of the *Cassini* spacecraft, launched for the Saturn system in 1997, was to survey the landscape of Saturn's largest satellite, Titan. With an atmosphere of N_2 made optically opaque by hydrocarbon hazes, little of the surface had ever been seen. Upon arrival of *Cassini* to Saturn and Titan in 2004, one of the least-predicted (Lorenz et al., 1995) surface features was seen in great abundance across Titan: sand dunes (Elachi et al., 2006; Lorenz et al., 2006; Barnes et al., 2008; Radebaugh et al., 2008). Dunes herald a mature environment, in which one or more processes have acted on the surface long enough to produceextensive and morphologically consistent landforms. Dunes indicate sand has been generated on Titan in great volumes, transported to a location, and blown by wind into persistent patterns. By other measures, Titan's surface is mature. There are networks of river channels carved into bedrock of water ice and/or organic sedimentary layers by methane, which has been evaporated from polar lakes and seas, collected into clouds and rained onto the surface (Collins, 2005; Stofan et al., 2007; Lorenz et al., 2008a). Mountains are found in isolated blocks, eroded plateaus and belts, and they appear to have undergone extensive erosion (Radebaugh et al., 2007; Moore and Pappalardo, 2011). There are few impact craters for a planetary surface and they are often covered by organic deposits or highly degraded (Lorenz et al., 2007; Wood et al., 2010a; Neish and Lorenz, 2012; Moore and Pappalardo, 2011). It appears an atmosphere with 1.5 bar surface pressure and density 4× that of Earth and an active methane hydrologic system have shaped the surface of Titan into one possessing mature and Earth-like geomorphic landforms (Lunine et al., 2008; Lopes et al., 2010).

Dunes on Titan are dominant features, covering an estimated 16% or 15 million km^2 (Rodriguez et al., in revision), narrowed from 12–20% or 10–17 million km^2 in earlier studies (Lorenz et al., 2008b; Radebaugh et al., 2010a; Le Gall et al., 2011). By comparison, dunes cover up to 4% of Earth's surface, or up to 30% of the area classified as arid (Lancaster, 1995; Bourke et al., 2010), 0.06% of the surface of Mars (though dust and sand streaks can be found ubiquitously there) (Fenton and Hayward, 2010), and 0.004% of the surface of Venus (Bourke et al., 2010). Dunes on Titan are found between 30° N and 30° S latitude and nearly encircle the globe at the equator (Elachi et al., 2006; Radebaugh et al., 2008; Lorenz and Radebaugh, 2009). They are dominantly linear in form and are generally organized into large sand seas, regions of relatively high sand volume (Fig. 1). Over sixteen thousand linear dunes (Lorenz and Radebaugh, 2009) have been observed on Titan by the *Cassini* SAR (Synthetic Aperture RADAR, 2.17 cm, Elachi et al. 2006). Since SAR coverage of dune areas is close to 40% in the middle of the Solstice Mission, there are likely thousands more dunes not yet observed.

Dunes exist in regions dark to *Cassini* ISS, with global but lower-resolution coverage (Imaging Science Subsystems, 938 nm, just to the infrared of optical; Porco et al., 2005), and have been observed to be spectrally distinct from surrounding terrains in lower-resolution images with global coverage from *Cassini* VIMS (Visual and Infrared Mapping Spectrometer, in the near-infrared; Soderblom etal., 2007; Barnes et al., 2008; Rodriguez et al., in revision). Some select, high-resolution VIMS images also reveal spectrally distinct dunes and adjacent interdunes (Barnes et al., 2008). Spectral and radiometric observations of dunes reveal they are likely composed of organic particulates derived from atmospheric processing of methane (Soderblom et al., 2007; Barnes et al., 2008; Clark et al.,

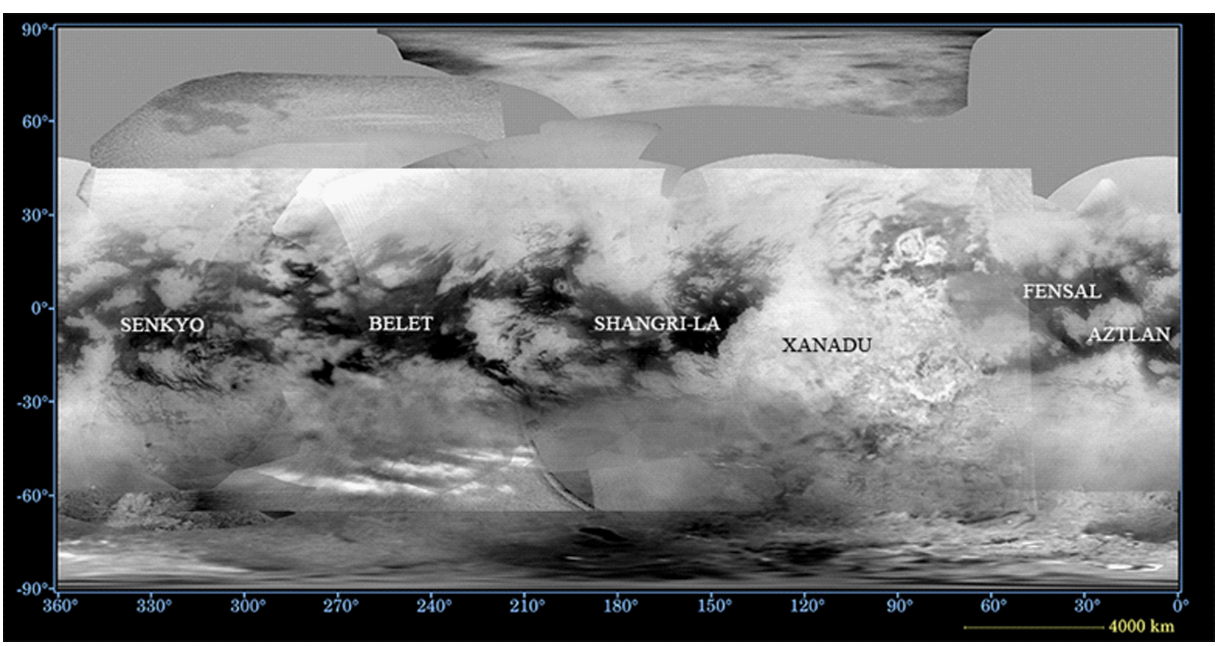

Fig. 1. Global map of sand sea distributions on Titan. Areas dark to visible-to-near-IR instruments near the equator generally correlate with dune regions. Each labeled region was originally named for being a region of anomalous albedo, and since then, Belet, Shangri-La, and Fensal/Aztlan have also become names for sand seas. The basemap is from ISS (visible-to-near-IR camera) images; mosaic assembled Feb. 2009 with an update from January 2013. Updated from NASA image PIA11149.

2010; Le Gall et al., 2011), eventually deposited on the surface and eroded by methane rainfall into sand-sized particles ideal for saltation in Titan's winds. As *Cassini* continues its journey around Saturn and satellites in the Solstice Mission, this paper discusses the current understanding of dunes on Titan. It reviews their morphologies, distribution, composition, and relationship to the atmosphere and climate as compared with similar dunes on Earth.

2. Dune morphology

Dunes on Titan generally appear as SAR-dark lines against muted or bright substrate (Fig. 2a) because dune sands are absorbing to the SAR signal (Elachi et al., 2006; Lorenz et al., 2006), similar to X-band (3 cm) SAR images of terrestrial dunes (Fig. 2b). However, as with terrestrial SAR dune observations, Titan's dunes can appear SAR-bright when they are illuminated appropriately to reflect the SAR signal. This can only occur when the dunes are parallel to the *Cassini* track and when the slope of the dunes is within several degrees of perpendicular to the direction of incidence. SAR image resolutions are 350 m near the center of the image swaths obtained during *Cassini* flybys and at least 1 km near the swath edges or in HiSAR (high-altitude SAR) images (West et al., 2009). Even at poor SAR resolutions, dunes are visibly distinct from surrounding materials, but small flanking dunes or small barchans may not be visible (see Section 3).

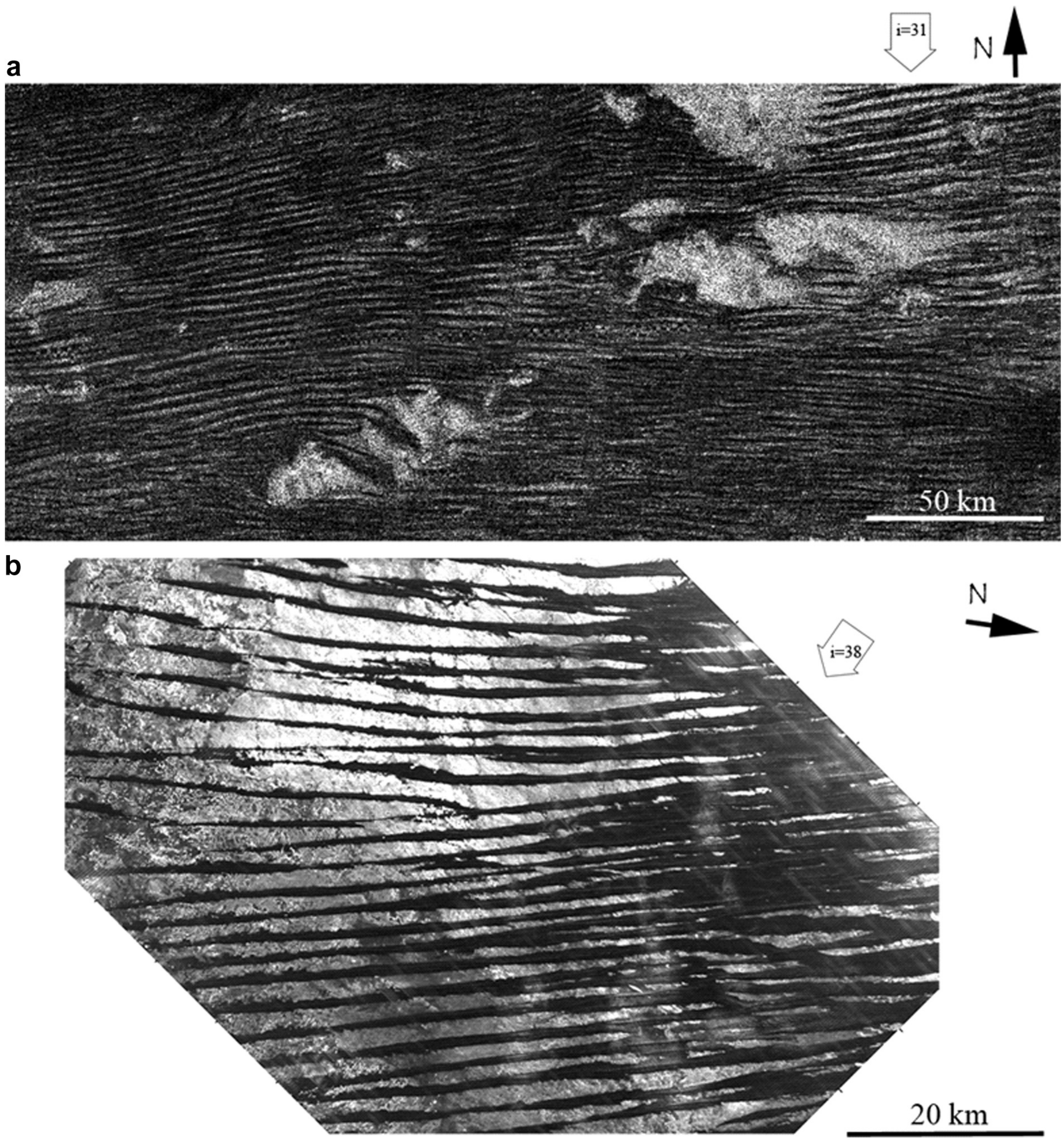

Fig. 2. (a) Dunes on Titan as seen by the *Cassini* SAR. Dunes are smooth and absorbing to SAR and thus appear as SAR-dark lines against a radar-bright, and therefore rough and/or fractured, substrate. The wavelength of the *Cassini* SAR is 2.17 cm, with resolution of 350 m. Open arrows demonstrate direction of SAR illumination and incidence angle. From the Belet Sand Sea, from the T61 swath on the equatorial leading hemisphere, at 11° S, 255° W, Aug 2009. (b) Dunes in the Eastern Sahara desert as seen by X-band (3 cm) SAR, 1994. Dunes are smooth and absorbing, and appear as SAR-dark lines. Some glints from the radar-facing slopes can be seen. Track and incidence angle shown in open arrow. Image located at 25° 18′ N, 26° 32′ E, from the Shuttle Imaging Radar mission, SIR-C/X-SAR, courtesy of Tom Farr and NASA/JPL.

Dunes appear as some of the darkest materials to ISS (at 938 nm) and have a low albedo and red slope as seen by VIMS, thus comprising the VIMS dark brown spectral unit (Soderblom et al., 2007; Barnes et al., 2007a; Barnes et al., 2008; Rodriguez et al., in revision). They were also observed to be dark by Hubble telescopic observations(Smith et al., 1996) and Voyager reprocessed images (Richardson et al., 2004). The dunes are predominantly linear in form, being parallel over great distances with lengths much greater than widths. Linear dunes on Earth have widths 0.2–2 km, spacings 0.2–3 km and lengths over tens of kilometers (Lancaster, 1995). They comprise an estimated 50% of all dunes on Earth and fill much of the vast Saharan, Namibian, Australian, and Arabian deserts (Lancaster, 1982). Linear dunes often reside in sand seas, large collections of sand from local and regional sand transport systems (Wilson, 1971; Fryberger and Ahlbrandt, 1979). Similarly, linear dunes occupy large regions on Titan,considered to be sand seas (Lorenz et al., 2006; Radebaugh et al., 2008; Le Gall et al., 2011).

In the middle of Titan's sand-rich regions, dunes are narrow, closely spaced, long and straight. Near the edges of Titan's dune fields, dunes have greater widths and they are short and sinuous (Fig. 3). Increased dune sinuosity near dune field edges has also been noted in the Australian Simpson desert, where it is thought to result from a difference in sediment availability (Fitzsimmons 2007). It is expected that there would be less sand at the edges of dune fields, generally at high latitudes on Titan. The dune forms appear to reflect this change in sand availability.

Dunes on Titan interact with topographic obstacles, termed inselbergs, contained within sand seas. Dune forms reflect the disrupted winds around these obstacles and appear to divert around inselbergs or become halted on the margin that is upwind of the predominant wind direction. This is typical for similar dunes on Earth, and can be seen in morphologies in the Namib Sand Sea and other locations (Fig. 2; Lancaster, 1995; Radebaugh et al., 2010a). Dune long axes range from straight and parallel to slightly undulatory, perhaps reflecting varying amounts of sand, wind conditions, intervening inselbergs and substrate conditions (Radebaugh et al., 2008).

While most (>90%) of the dunes visible to *Cassini* SAR are considered linear in form, there are some other dune morphologies near the resolution limit that reveal a changing wind regime (Ewing et al., 2013). Features such as discontinuous crestlines, elongate horns, star dunes and overall degradation and patchiness can be

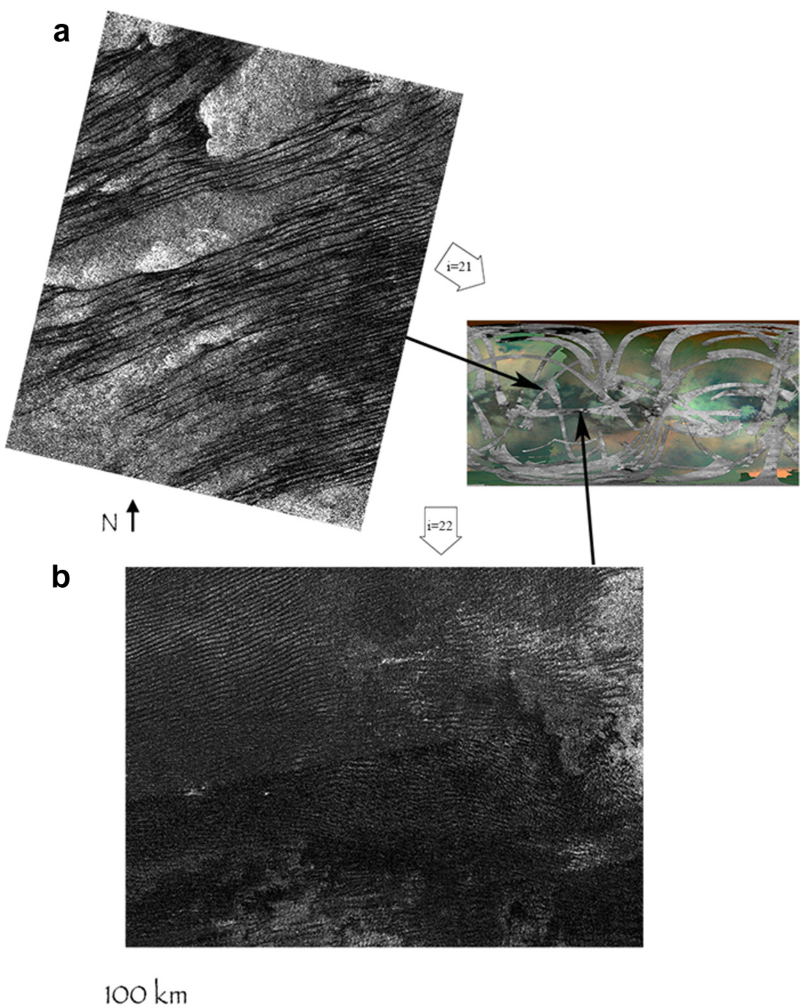

Fig. 3. (a) Dunes found at high latitudes on Titan, where dunes are sparsely distributed and there is clear contrast between dark dunes and bright interdunes. From the Belet Sand Sea, the T21 swath, 12/06, 11° N 278° W. (b) Dunes found in the middle of a sand sea, where interdunes are dark and sandy interdunes and dunes are closely spaced. Mosaic of dunes in the Belet Sand Sea, from the T8 and T61 swaths, 10/05 and 8/09, 7° S 240° W. Locations of the images are indicated on the inset global map of Titan, which contains b/w SAR swaths on top of a VIMS basemap. Open arrows demonstrate direction of SAR illumination and incidence angle.

seen in regular SAR images and more clearly when those images have been noise-reduced (Ewing et al., 2013). Some regions in the sand seas show evidence of superposition of one set of linear dunes atop another set, leading to a diffraction-type pattern in the dunes (Radebaugh et al., 2008). These features all reveal changing wind conditions, at least locally (Radebaugh et al., 2008; Ewing et al., 2013).

3. Dune morphometry and pattern analyses

Detailed analyses of dune parameters such as length, height, width and spacing reveal correlations and provide comparisons between linear dunes in the solar system. In addition, studies of dune parameters, or pattern analyses, reveal the history of surface conditions and dune-forming processes over time. This kind of mor-

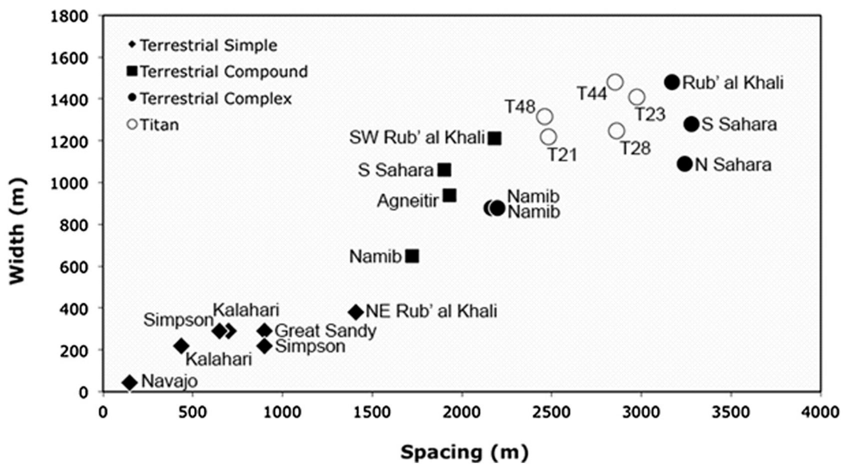

Fig. 4. Scatter diagram showing the correlation between mean dune crest spacing and mean dune width in relation to dune form for various linear dunes around the world and for each measured swath on Titan (terrestrial data from Breed and Grow, 1979 and Lancaster, 1995). Note that most of Titan's dunes plot in the upper right, among the largest terrestrial linear dunes. Averages for each Titan swath are from several hundred data points. From Savage et al., in revision.

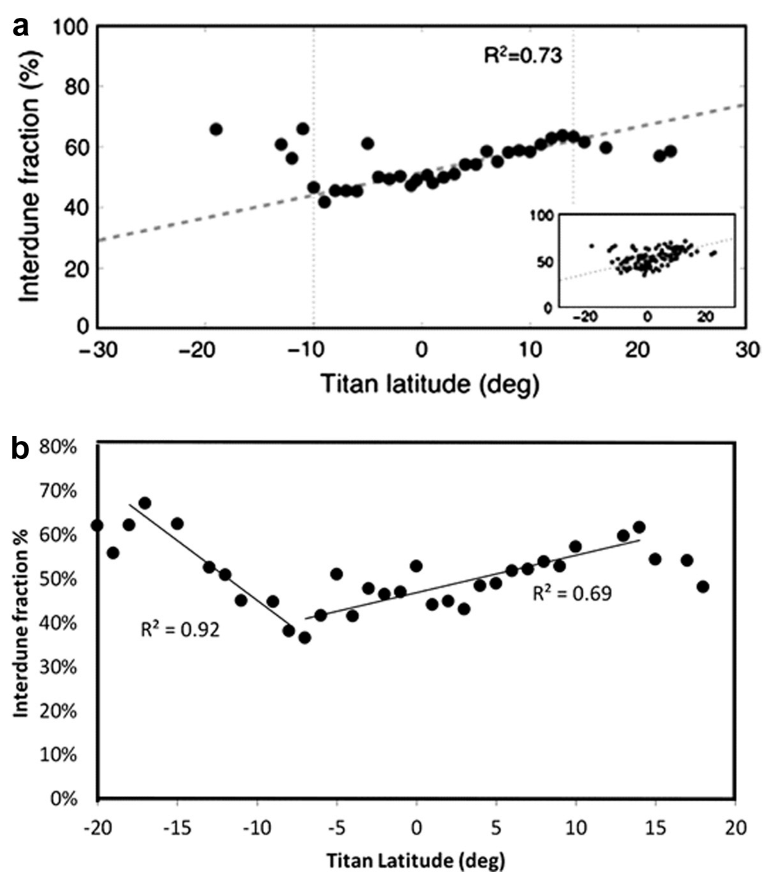

Fig. 5. (a) Average interdune fraction (interdune width/dune with) per degree latitude for five study areas on Titan (T21, T23, T28, T44, T48) all at a variety of locations across the globe. Inset shows averages for each swath. Interdune fraction increases toward the north up to 14° N latitude, likely because of increasing exposure of interdune substrate. From Le Gall et al. (2011). (b) A similar plot for a single Titan study area, T25 (equatorial leading hemisphere), which contains more data at southern latitudes than previously studied swaths, also reveals an increasing interdune fraction south of 7° S latitude. From Mills et al. (2013).

photometric and morphologic pattern analysis has been used in dune studies on Earth (e.g. Lancaster, 1989; Ewing et al., 2006), was recently applied to Mars (Ewing et al., 2010), and is currently being applied to Titan (Savage, 2011; Savage et al., in revision).

Approximately 7000 dune width and 7000 interdune width measurements in five representative regions across Titan yielded dune widths ranging from 0.4 km to 3.6 km with a mean of 1.3 km and effective dune crest-to-crest spacings ranging from 1.4 km to 5.3 km with a mean of 2.6 km (Savage, 2011; Savage et al., in revision). Crest-to-crest spacings were obtained by averaging the mean dune width plus interdune width per degree of latitude, since it is difficult to discern actual dune crests (Fig. 1). These sizes and spacings are similar in value and relative relationship to the largest terrestrial linear dune sizes and spacings, suggesting these features are comparable, and revealing commonalities in the essential dune-forming processes (Fig. 4; Lancaster, 1995; Savage et al., in revision). Dune width, and in particular the interdune fraction (interdune width to dune width), decreases toward higher northern latitudes (Fig. 5a; Le Gall et al., 2011), which may be partly due to the fact that sand appears to become more sparse toward higher latitudes. A new study of the T25 swath in the Fensal/Aztlan sand sea reveals this trend is also seen in the southern hemisphere; interdune fraction increases south of 7° S latitude (Fig. 5b; Mills et al. 2013). Dune terrains on Titan have a low SAR backscatter and have a high emissivity and brightness temperature in the microwave, indicating the materials are efficient at absorbing and emitting radiation (Le Gall et al., 2011). Consistent with measurements of dune widths and spacings described above, dune terrains are less emissive and brighter toward higher latitudes, in particular toward the north, which indicates more substrate is exposed (Fig. 6; Le Gall et al., 2011).

Lengths of 3294 dunes measured in the Belet Sand Sea, at Titan's equatorial trailing hemisphere, where Y junctions or points at which azimuth changed substantially were considered dune terminations, are on average 38 km (Radebaugh et al., 2008). Similar lengths were recorded for thousands of dunes measured in the Fensal Sand Sea, at Titan's equatorial, Saturn-facing hemisphere. Some dunes in the Belet Sand Sea, however, can be traced across Y-junctions and azimuth changes for hundreds of kilometers.

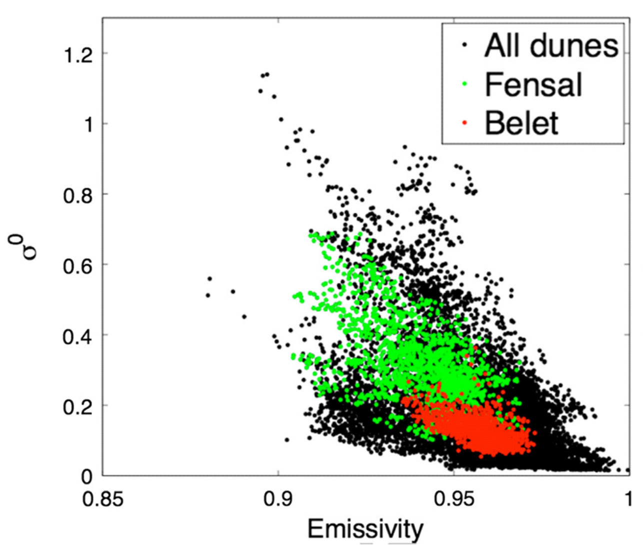

Fig. 6. Dunes on Titan have generally low backscatter, or sigma^0 (materials absorb rather than reflect the signal; vertical axis), and high emissivity (materials emit the absorbed radiation; horizontal axis). Where dune regions are especially sandy, such as in the Belet Sand Sea, these trends are amplified, while in dune regions with exposed bedrock interdunes, such as Fensal, backscatter increases and emissivity decreases. From Le Gall et al. accepted.

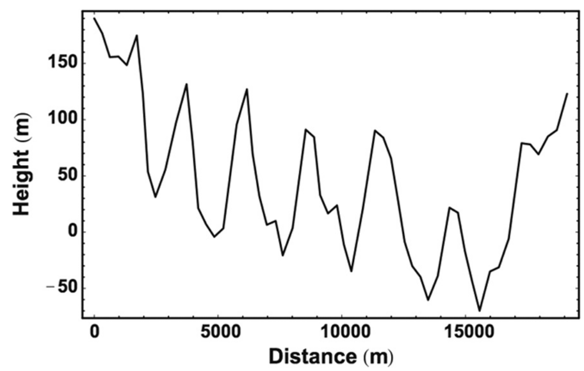

Fig. 7. Cross sectional profile of dunes on Titan based on a radarclinometry, or shape-from-shading, study (Neish et al., 2010). This requires the dune face to be perpendicular to the SAR, which happens in only a few locations. Average dune height is 114 m, SD 24 m. Region under study is the eastern Belet Sand Sea, ~240° W, 7° S. From Neish et al. (2010).

Heights have been obtained for dunes in a few select locations using radarclinometry, or shape-from-shading techniques based on the expected SAR signal return. Data for heights are sparse on Titan because they rely upon the dune face being nearly perpendicular to the SAR signal. Heights calculated for dunes in the middle of the Belet Sand Sea are 100–150 m (Lorenz et al., 2006), and are similar to dune heights in the sand-rich regions of the Namib and northeastern Saharan Great Sand Sea (Lancaster, 1995). Photoclinometric analyses of dunes in high-resolution VIMS images resulted in heights of 30–70 m for dunes in a northern dune field (Barnes et al., 2008). A radarclinometry study of dunes in the Eastern Belet Sand Sea by Neish et al. (2010), calibrated by radarclinometry studies of dunes in the Namib Sand Sea, yielded heights of 80–130 m, with errors of ~40 m (Fig. 7). These results are also consistent with *Cassini* altimetry waveform simulations (Callahan et al., 2006). Slopes were found to be 6–10° (Lorenz et al., 2006) and 4–6° (Neish et al., 2010). Such low values exist because dune heights were measured from their base to their summit, and thus incorporate the gently sloping plinth.

The relationship between dune height and spacing has been related to the conditions within a dune field, those of either growth and accumulation or transportation and extension (Lancaster,1989). Dunes on the northern margin of the Belet Sand Sea have a height/spacing relationship characteristic of transportation and extension (data from Barnes et al., 2008; study by Neish et al., 2010), according to the relationship $D_h = cD_s^n$, where $n = 0.23$ for the northern Belet region and $n > 1$ indicates accumulation (Neish et al., 2010). The same relationship for dunes in the middle of the Belet Sand Sea yields values of $n = 0.76–0.96$, indicating they are on the threshold between transportation and accumulation (Neish et al., 2010).

4. Dune distribution and description of Titan's sand seas

Titan's dunes are found dominantly near the equator, between 30° N and 30° S latitudes. There are dozens of isolated dune fields across Titan, but the majority of dunes are located within large, integrated sand seas at equatorial regions. *Cassini* SAR imagery to date covers ~40% of Titan's surface, up to 50% if HiSAR images are also considered (obtained at a greater distance, so much lower resolution; Rodriguez et al., in revision). Boundaries of dune regions on Titan were delineated in SAR images by Le Gall et al. (2011), and using the percent of SAR coverage at equatorial regions compared to the percent dune areas found in SAR images, they extrapolated to estimate the total dune coverage on Titan to be 11–13 million km^2, or ~13% of Titan's surface (Le Gall et al., 2011). Studies of dune regions using VIMS images utilize the correlation between dunes and the dark brown spectral unit, given that VIMS images are global in coverage but at lower resolution. Le Corre et al. (2008) and Stephan et al. (2009) found total dune coverage of 18% of Titan's surface, and a more recent survey by Rodriguez et al., (in revision) found total dune coverage from VIMS of 16%, or 13.6 million km^2, comparable to 1.5 times the surface area of the Sahara desert. A similar study is underway relating the global, low-resolution ISS images with dune areas as seen at higher resolution by SAR by Arnold et al. (2013); Fig. 8. Edges of dune fields are clearly seen in SAR, and these correlate with a certain ISS brightness, which is consistent locally but changes across regions, depending on illumination angle, surface albedo and other factors. Maps of dune field boundaries in a correlated SAR/ISS study were first created for the Fensal/Aztlan sand sea (Fig. 8; Arnold et al., 2013), which was found to be 2.3 million km^2, and will eventually become a global map to be used for comparison with that of Rodriguez et al. (in revision) and Le Gall et al. (2011).

Maps of dune surface areas are also used to determine total sediment volumes in Titan's sand seas. Lorenz et al. (2008b) estimated sediment volumes of $2–8 \times 10^5$ km^3, Le Corre et al. (2008) and Stephan et al.(2009) found 3×10^5 km^3, Le Gall et al. (2011) found $0.5–5 \times 10^5$ km^3, Arnold et al. (2013) estimated volumes of $1.5–3 \times 10^5$ km^3 and Rodriguez et al. (in revision) found $\sim 3 \times 10^5$ km^3 of sediments, or ~340,000 GT, in comparison with ~4000–30,000 GT of hydrocarbons in the polar lakes and seas.

A collection of named sand seas rings the equator of Titan (Fig. 1). They are fairly regularly spaced and are separated from each other by bedrock,as discerned by the SAR-bright, ISS-bright, and VIMS-blue (characteristic of water ice) characters of bedrock materials. Some sand-free landscapes are not very large, however; and often one sand sea grades into another through smaller dune fields or areas of sediment throughput. Dune areas on Titan are found at generally moderate elevations as revealed by previous studies (Le Gall et al., 2012) and a new global topography map (Lorenz et al., 2013) (Fig. 9). They are not found at the lowest elevations, which is where lakes and seas are located, nor are they at the highest elevations, which is where mountains and land masses are found (though Xanadu, the largest landmass, is relatively low). Thus, their locations must be a function not only of topography, but of winds and sediment availability. A description of each sand sea is below.

4.1. Belet Sand Sea

The Belet Sand Sea, located between 220° and 300° W longitude and 20° S and 20° N latitude, is the largest sand sea on Titan, spanning over 2500 km of longitude and 1000 km of latitude (Fig. 10). Four *Cassini* high-resolution SAR passes cross this region, T8, T21, T49, T61, T91 and T92. Dunes in the central portion of Belet are closely spaced, narrow, long, and straight. The region is especially sand-rich, and even interdunes are covered in sand (Fig. 10), as indicated by the generally uniform *Cassini* SAR and ISS darkness and VIMS spectraacross the dunes (Le Gall et al., 2011). Isolated topographic obstacles, or inselbergs, jut up above the substrate and act as local disrupters of wind and sand transport that can divert dune forms around the obstacles (Lorenz et al., 2006; Radebaugh et al., 2008). The inselbergs are bed-

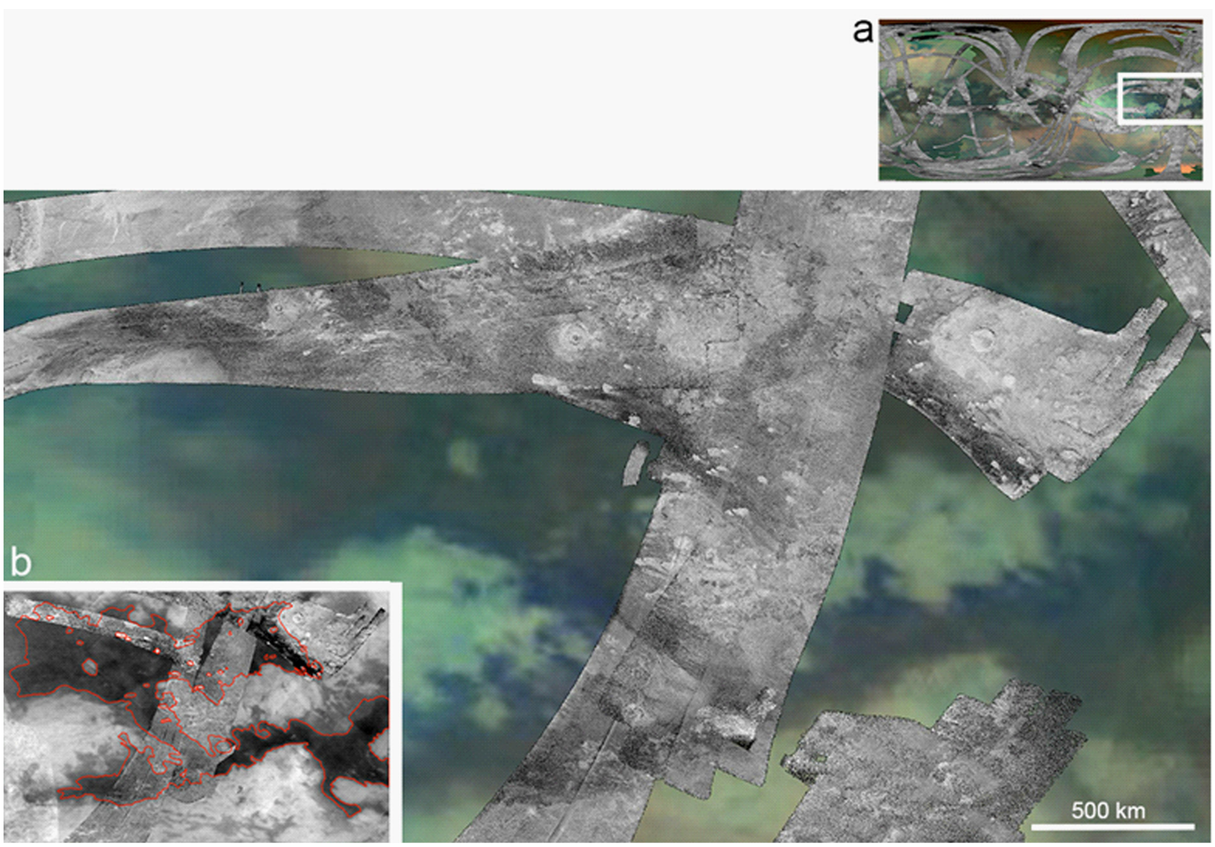

Fig. 8. *Cassini* SAR images (large, b/w swaths) overlain on a basemap of *Cassini* VIMS of the Fensal/Aztlan Sand Sea, at Titan's equatorial leading hemisphere. Inset a. shows the location of the image on a global basemap of SAR images over VIMS. Inset b. shows the same location, but with *Cassini* SAR over an ISS basemap, and contains an outline of the sand sea as determined from SAR and ISS image correlation (Arnold et al., 2013). Dunes are among the darkest (lowest albedo) features seen in the near-infrared by VIMS and ISS, and make up the dark brown spectral unit of VIMS (see Section 5). Individual dunes can be discerned in the SAR images, as well as SAR-bright outcrops, including impact crater rims and ejecta (top left, center and right). Image approximately 3800 km across, centered at 50° W longitude, just above the equator.

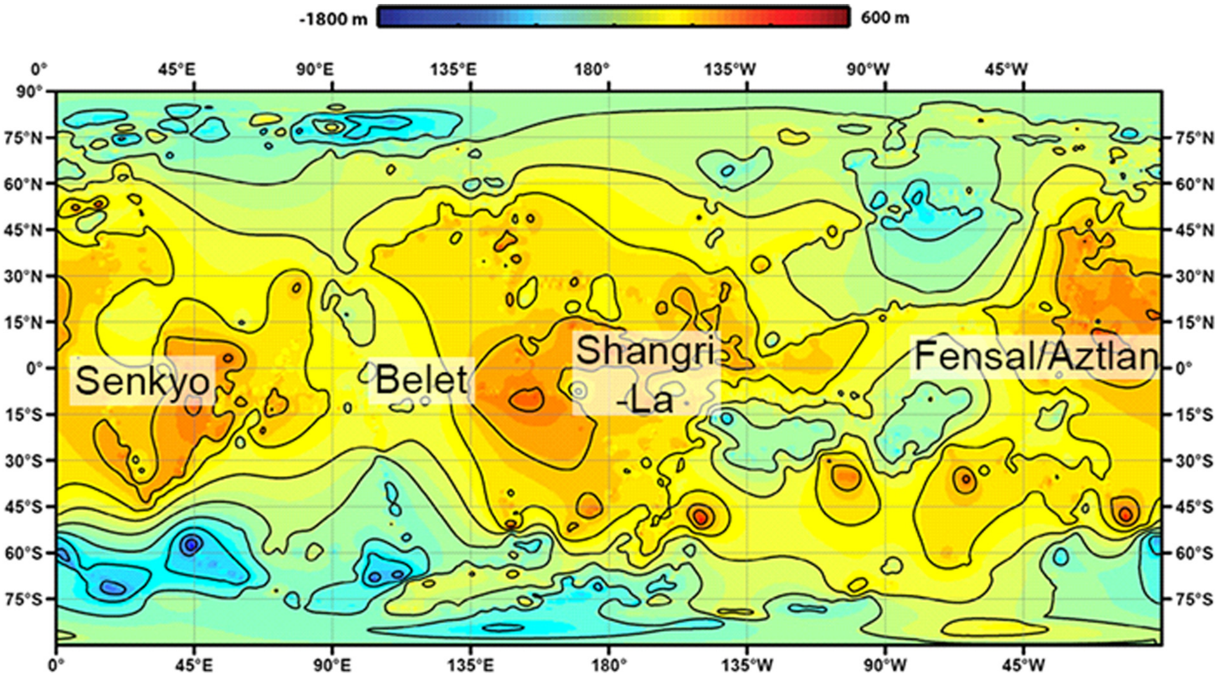

Fig. 9. A global topographic map, generated from *Cassini* SARTopo (topography from overlap of portions of individual SAR images) and altimetry data, reveals dune areas are at neither the lowest nor the highest elevations on Titan. From Lorenz et al. (2013).

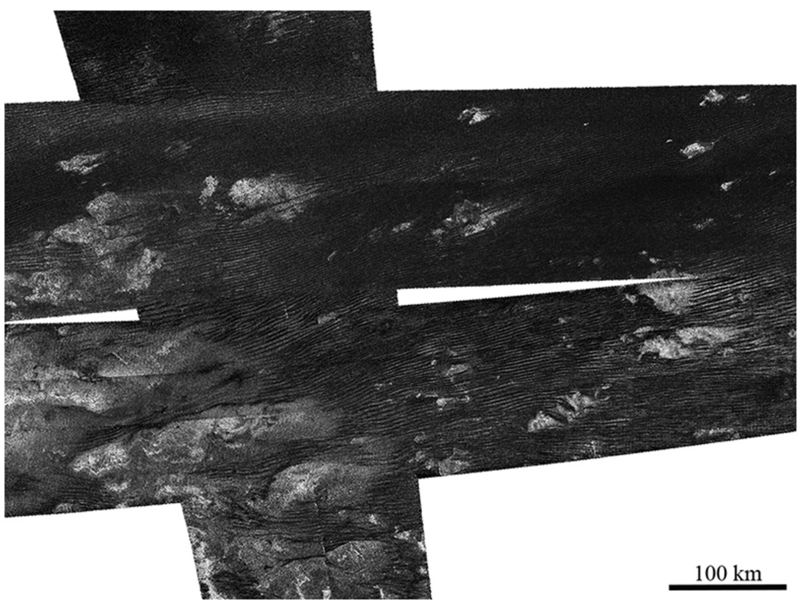

Fig. 10. The western portion of the Belet Sand Sea, on Titan's equatorial trailing hemisphere. Marginal dune forms are shorter, more sinuous, and more widely spaced than those in the sand sea interior (upper right), where even interdunes are SAR-dark and sandy. Dunes interact with inselbergs by diverting around small obstacles (upper, lower right) or stopping upwind of larger obstacles (lower left). Some reflections can be seen off dune faces (upper left center). Mosaic from swaths T8, T61, and T49, from ~20–5° S, 250–270° W.

rock, likely comprised of water ice or organic sedimentary layers, or some combination of these, consistent with their SAR properties and VIMS spectra (Soderblom et al., 2007). Much of the Namib Sand Sea of southwest Africa has an abundance of sand, including sandy interdunes. In the south-central portion of the Namib Sand Sea (~25° 15 S, 15° 20 E), dunes are diverted around obstacles as a result of local disruption of wind. This region in the Namib has therefore been used as an analog to the sand-rich regions of Titan's Belet Sand Sea (Radebaugh et al., 2010a; Neish et al., 2010; Paillou et al., 2013). Dune forms in Belet change from long, straight, narrow, and sand-rich at lower latitudes to shorter and more widely spaced, with SAR-bright, sand-free interdunes, at higher latitudes and at sand sea margins (Fig. 10). There are abundant inselbergs in the Belet Sand Sea with which dunes interact (Figs. 2 and 10). Dune forms diverge around a really small obstacles then resume their pattern on either side of the obstacle, or they stop abruptly on one side of the obstacle, assume to be the time-averaged upwind side (see Section 6), and resume some tens of kilometers downwind (Figs. 2 and 10).

4.2. Fensal Sand Sea

The Fensal Sand Sea is located nearly 180° away from the Belet Sand Sea, between 30° and 90° W longitude and 5° S and 20° N latitude (Fig. 8). It is smaller than the Belet Sand Sea, spanning about 2000 km by 1000 km, and has been covered by the T17, T25, T28, T29 and T77 *Cassini* SAR swaths. Initial estimates of the size of Fensal from a combined study of *Cassini* SAR and ISS images yielded an aerial coverage of the Fensal Sand Sea of 2.3 million km^2, comparable in size to the combined areas of the Libyan and Saharan Sand Seas (Arnold et al., 2013).

The majority of dunes in this sand sea cover a SAR-bright, probably sand-poor substrate that is clearly visible between dunes (Fig. 11). Dunes here are generally shorter, wider and have greater spacing, and they are not as straight as dunes in Belet. Additionally, diffuse scattering is stronger here than in Belet (Le Gall et al., 2012). Le Gall et al. (2011, 2012) concluded these observations reflect a higher ratio of interdunes/dunes in this region (Fig. 6).

Sands in Fensal/Aztlan are sparse on the west, near the sand-free Xanadu terrain. Dunes are more widely spaced and feathery in texture on the eastern margins, then dunes become more closely spaced, with sandy interdunes, toward the east (Fig. 11). Dunes about the raised ejecta blanket of the Ksa impact crater then reassemble downwind. Disruption of the wind by a large obstacle (bottom of Fig. 11) has resulted in crossed or overlapping dune patterns downwind of the obstacle. Regions of low sediment volume are similar to those observed in linear dune fields in the Libyan Sahara, where sand accumulation is diminished due to transportation or sediment bypassing (See Section 6). Collection of sand is limited in favor of transportation to other collection areas, resulting in sand-free regions and wide, sand-free interdunes. Sandy, SAR-dark interdunes are found in some locations within Fensal (e.g., just upwind of Ksa crater in T77) where sand accumulation has occurred, perhaps because of locally dimished winds (Le Gall et al., 2011). Some small patches on the margins of the sand sea or near wide regions of SAR-bright substrate are SAR-dark, yet not organized into large linear dunes. These areas may contain sand sheets but lack dunes or they contain dunes smaller than can be observed at *Cassini* SAR resolution.

4.3. Shangri-La Sand Sea

The Shangri-La Sand Sea grades eastward from Belet and halts abruptly on the western boundary of the cratonic terrain Xanadu, unique in its great size, SAR and near-IR brightness, and ancient geomorphology (Fig. 1; Wood et al. 2010b; Radebaugh et al. 2011a). Shangri-La ranges from 150° to 200° W longitude and 20° S to 20° N latitude and it is similar in size to Fensal/Aztlan, though more latitudinally extensive and compressed in longitude. The region was covered by swaths T13, T41, T43, T48, T55, T56, and T68 (with some overlap), and as such has the greatest coverage of any sand sea by *Cassini* SAR. The central portion of Shangri-La has SAR-dark interdunes and is inferred to be sandy. The dunes are straight and closely spaced, similar to those in the central portion of Belet. Dunes pass by isolated mountains and in some cases cover obstacles, like the 80-km, round feature Guabanito (Radebaugh et al., 2010a), which has the morphology of an eroded impact crater (Wood et al., 2010a). The northern reaches of the sand sea, however, are considerably variable in sand thickness and abundance of dunes.

4.4. Senkyo and other dune areas

The Senkyo region east of Fensal/Aztlan and west of Belet has relatively poor *Cassini* SAR coverage but does have abundant dunes where SAR images can be found, and has materials dark to ISS and dark brown to VIMS, with interspersed bright materials (Fig. 1). Thus, with the exception of Xanadu, which is free of sand or dunes, sand seas nearly completely encircle Titan's equator. It is possible to consider that these dune regions are one, vast, integrated system of sand circling the equator. Sand seas cover close to 40% of the equatorial region of Titan (Lorenz et al., 2008b; Le Gall et al., 2011; Rodriguez et al., in revision).

A number of isolated dune systems can be found at higher latitudes than the sand seas. Dunes in these regions are short, often sinuous, and are widely spaced over bright substrate. They do not extend poleward of 30°. They appear to result from gradual thinning of sand away from the main collection areas of the equatorial sand seas, or are isolated, low-volume systems (Radebaugh et al., 2008).

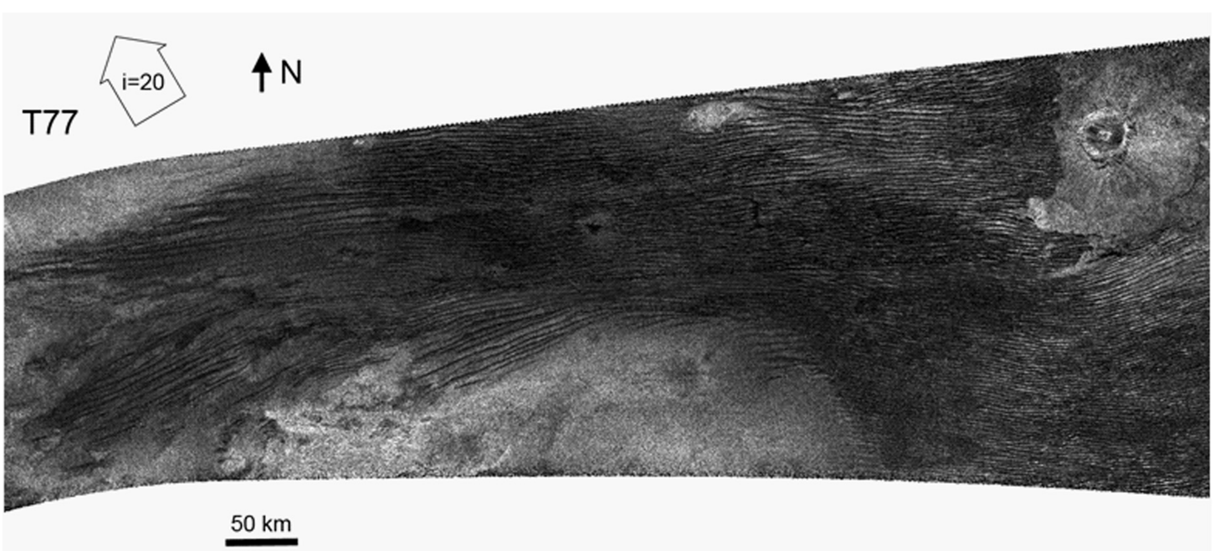

Fig. 11. Dunes in the northern Fensal Sand Sea, just east of Xanadu. On the western side of the image, sands are just beginning to collect into dunes, east of a large, sand-free area. Dunes become more closely spaced and interdunes more sandy toward the east, until sands accumulate upwind of the ejecta blanket of the elevated impact crater Ksa. Disruption of winds by the obstacle at bottom center is evident in overlapping dune patterns east of this obstacle. From T77, obtained 6/20/11, centered on 12° N, 75° W.

Dune-like ridges that are muted to SAR but appear to exhibit reflections resulting from being elevated are found in close to ten locations near 50° to 60° latitude. One explanation for these features is that they are formerly active dunes now solidified by organic deposition or fluid encroachment and cementation (Radebaugh et al., 2011b). That dunes may have been active this far away from the equator, and no longer are, is a possible indication of climate change on Titan (Section 7).

5. Dune composition and sand sources

Given that there are dunes present on Titan, and that their morphologies are so similar to those of linear dunes on Earth, it is assumed these dunes are formed by saltation of sand-sized particles. Morphologies are not consistent with these features being erosional, rather than depositional forms, such as yardangs, which are carved out of fine, cohesive sediments, though some isolated examples of yardangs may exist at high latitudes on Titan (Radebaugh et al., 2011b). One model calls on cohesive particles attaching to one another downwind to form linear dunes, as has been seen in the Qaidam Basin desert in China (Rubin and Hesp, 2009), though such dunes are not areally extensive on Earth because sticky particles (clays) are not as abundant as non-sticky sands. Particles on Titan of the compositions expected have a range of possible cohesions (Lorenz, accepted). If particles on Titan are inherently sticky, perhaps the dunes could form by this manner, yet their morphology is identical to that of linear dunes formed by saltation, and thus the saltation model is generally preferred for Titan (Lorenz et al., 2006; Radebaugh, 2009; Lorenz, accepted). How the possible range of cohesions may affect the saltation and sand transportation processes is unknown (Lorenz, accepted). Dunes in general are formed by saltation of a narrow range of particle sizes, given that fine particles are either suspended and removed or remain anchored to the bed, and coarse particles are too large to be lofted or rolledby winds. Dune sands on Titan are likely indeed sand-sized, optimally ranging from 0.2–0.6 mm (Lorenz et al., 2006, revisited by Lorenz, accepted). These sizes are able to be saltated on Titan, with gravity 1/7 that of Earth, atmospheric pressure 1.5 bars, and density 4× that of Earth, for cohesionless particles at threshold speeds >0.8 m/s (Lorenz et al., 1995; Tokano, 2010; Lorenz, accepted).

5.1. Sand composition

Material compositions on Titan's surface have been difficult to constrain, not least because spectroscopy is hampered by atmospheric absorptions (Griffith et al. 1991). Titan's dune sands, based on observations and modeling, are thought to be composed of complex hydrocarbons and/or nitriles ultimately derived from atmospheric haze particles (Hunten, 1974; Wilson and Atreya, 2004; Soderblom et al., 2007; Clark et al., 2010). Dune sands are dark to visible and near-IR instruments, and their spectra from VIMS are consistent with organics (Fig. 8; Porco et al., 2005; Soderblom et al., 2007). In addition, radiometry measurements indicate the dielectric constant of dune regions is about 1.7, consistent with that of fine-textured organics of moderate porosity (or internal layering), possibly with a small water ice component (Paganelli et al., 2007a,b; Janssen et al., 2009; Le Gall et al., 2011; Le Gall et al., accepted; Paillou et al., 2013). Such materials would have a density close to 1000 kg/m^3 (Lorenz, accepted). Volume scattering within Titan's dunes is very low, consistent with smooth, homogeneous surfaces with fine-grained, absorbing particles, without cm-scale or larger scattering voids or clasts (Paganelli et al., 2007a,b; Janssen et al., 2009; Le Gall et al., 2011). Titan's lithosphere is modeled to be dominantly composed of water ice, given the high proportions of water present in bulk Titan (Tobie et al., 2005). Some locations, such as eroded mountains, river beds, deltas and impact crater ejecta appear to be enriched in water ice from VIMS spectra (Barnes et al., 2007b; Le Mouelic et al., 2008; Soderblom et al., 2009) and polarized radiometry measurements that yielded a dielectric constant of 2.5 (Janssen et al., 2009). In contrast, dune areas are not bright to V-NIR, they do not contain water ice in their spectroscopic signature, and radiometry measurements there are not consistent with water ice (Janssen et al., 2009), so dune sands must come from a source other than that of erosion of water ice bedrock.

5.2. Sand sources

Most dunes on Earth derive their sediments from fluvial and deltaic deposits, ultimately obtained from eroded bedrock, although other sources can include dry lake bed deposits, beaches, and local interdunes (Glennie, 1970; Lancaster, 1982; McKee, 1966; Kocurek et al., 1991). It is known that a constant organic 'snow' from Titan's atmosphere must lead to vast deposits of organic solids on Titan's surface (Hunten, 1974; Wilson and Atreya, 2004; Clark et al., 2010). These may form sedimentary layers that become hardened, through sintering or diagenesis via an introduced, organic cement, and then eroded by methane rainfall and channel formation into particulate sands (Stofan et al., 2006; Le Gall et al., 2012). These sands may be carried by eolian or fluvial processes to depositional sinks, either regional topographic lows or wind traps, and then blown into dunes by globe-encircling winds (Radebaugh et al., 2008). Another source for sand is seasonally drying lake beds that expose sediments to erosion and transport by wind (Aharonson et al., 2009; Lorenz, 2010). Dry lake beds are mainly found near Titan's polar regions, so transportation of these sediments to equatorial dune regions is problematic (Lorenz, 2010). However, the modeled global, tidal and Hadley wind patterns are toward the equator, which would enable transport of sediments from high latitudes (Hourdin et al., 1995; Lorenz et al., 2006). Additionally, analysis of VIMS images has revealed spectra and morphologies consistent with low-latitude dry lake beds in some areas (Barnes et al., 2011a).

If Titan's dune systems are long-lived, then there would be sufficient time to transport particles from many locations across Titan. The sands must be of a composition that is stable over long enough time scales to be transported and saltated into dunes without being dissolved or sintered to other particles. Compositions of dune sands compared with underlying substrate and surrounding materials are under study using VIMS spectra of these regions to determine sources of dune sands (Vixie and Barnes, 2010). SAR modeling reveals characteristics consistent with Titan's dunes having a fine-layered and SAR-reflective structure, perhaps a result of changes in particle sizes or variations in compaction as a result of changing winds, or cementation from rainfall (Paillou et al., 2013). Studies of dune particle compositions and behaviors at Titan conditions are in the early stages.

5.3. Interdunes

Interdune areas of linear dune fields on Earth are also important for understanding dune environments (Ahlbrandt and Fryberger, 1981; Hummel and Kocurek, 1984). Interdune compositions vary widely, and are of two main types, deflationary or non-depositional and depositional (Ahlbrandt and Fryberger, 1981). Deflationary interdunes consist of non-eolian deposits, like bedrock, or former eolian deposits, while depositional interdunes can be comprised of sand sheets or remnants of flooding, such as organic or lacustrine deposits. Interdunes on Titan are of a wide variety of SAR and near-IR brightnesses and textures (Figs. 2 and 10). Many interdunes are SAR-bright, are regularly interspersed with mountains, and have textures different from the dunes, as viewed at allillumination angles (Le Gall et al., 2012). These are considered to be bedrock interdunes, materials that existed and were shaped before the onset of the sand sea (Radebaugh et al., 2008; Le Gall et al., 2012). Scatterometry measurements indicate many interdunes are flat (Le Gall et al., 2012). Other sand sea regions have SAR-dark interdunes, similar in SAR brightness to the surrounding dunes. Interdunes in these regions are thus considered to be sandy (Radebaugh et al., 2008). VIMS observations of the northern portion of the Fensal/Aztlan Sand Sea revealed some regions in which the interdunes show the same spectral characteristics as the dunes, and other regions where the interdunes are spectrally distinct from the dunes (Barnes et al., 2008). Given VIMS observes surficial deposits, the interdunes in the spectrally distinct areas must be completely free of sand (Barnes et al., 2008). The presence of sand-free interdunes has been used to suggest sands are being actively shaped into dunes, since otherwise erosion from methane rainfall should carry sands from dunes and deposit them into adjacent interdunes (Barnes et al., 2008). In the inactive dune fields of the Australian Simpson, Kalahari, Nebraska Sand Hills and Great Indian Sand deserts, interdunes are sandy, likely as a result of erosion and redistribution of sand. Some active dune regions can have sandy interdunes, as in portions of the Namib Sand Sea, where sand volumes are high (McKee, 1982; Lancaster, 1989).

Sand-free interdunes have avariety of SAR textures and spectral reflectances as seen by VIMS (Barnes et al., 2008) and may thus be comprised of different terrains. Some observed regions match bright materials seen near 25° of the equator, while others match the blue spectral unit, which indicates the presence of some water ice (Barnes et al., 2008). Both of these units may be eroded bedrock of varying proportions of organic and water–ice-rich sedimentary layers. Yet another interdune unit is similar to 5-um bright terrains, which have been described as cryovolcanic (Barnes et al., 2006; Nelson et al., 2009; Wall et al., 2009) and as evaporitic lakebed sediments (Barnes et al., 2011a). Sand-free interdune regions generally appear to be preexisting terrains of various origins onto whichdune sands have been carried.

6. Dunes and Titan's winds

Dunes on Earth and other planets have been used as air flow indicators or indicators of wind direction, given their direct morphological relationship with dominant winds. The utility of this relationship depends on appropriate classification. Dunes on Titan are classified as linear, based on the similarities in their morphologies compared with this dune type on Earth (Lorenz et al., 2006; Radebaugh et al., 2010a). Linear dunes can form from at least two different wind conditions, wide unimodal winds, coming from one broad direction and blowing down the dune long axis (e.g., Blandford, 1877; Fryberger and Dean, 1979), or bimodal winds, wherein at least two strong winds blow from widely separated (>90°) directions (Tsoar, 1983; Rubin and Ikeda, 1990). A unimodal wind regime in the presence of cohesive particles may create linear dune forms with the long axis oriented parallel to winds (Rubin and Hesp, 2009). Controlled experiments and numerical models (e.g., Reffet et al., 2010) have revealed that bimodal winds separated by at least 130° generate longitudinal dune forms, and that sand transport occurs down the dune long axis. It is generally agreed that even wide unimodal wind regimes have important seasonal winds from different directions (Lancaster, 1981), and that the time-averaged vector sum of winds, weighted by strength, in the bimodal wind model is generally down the dune long axis (Fryberger, 1979; Lancaster, 1995). Thus, it has been assumed that the time-averaged vector sum of winds, weighted by strength, is parallel to Titan's dunes and that sand transport occurs in the direction of mean wind flow (Radebaugh et al., 2008; Barnes et al., 2008; Lorenz and Radebaugh, 2009; Radebaugh et al., 2010a).

6.1. Winds and sand transport

Dunes on Titan have also been classified as longitudinal (Radebaugh et al., 2008), a genetic term (Rubin and Hunter, 1985) that indicates sand transport occurs down the dune long axis. While sand transport has not been observed on Titan, given the low resolution of the *Cassini* SAR, there are indications that sand transport occurs down the dune long axis. Dunes adjacent to topographic obstacles have morphologies consistent with winds transporting sediments from the west to the east (Radebaugh et al., 2008, 2010a). Sands become concentrated at the west side of obstacles, and dune forms reorient around them, similar to flow features around islands in streams (Figs. 2, 3 and 12). Diffuse, moderately bright materials visible in *Cassini* SAR and ISS are oriented similarly to dunes and are more prominent on the east side of obstacles. They are thought to be aureoles eroded from mountains and drawn downwind or bedrock stripped free of sands (Turtle et al., 2007;

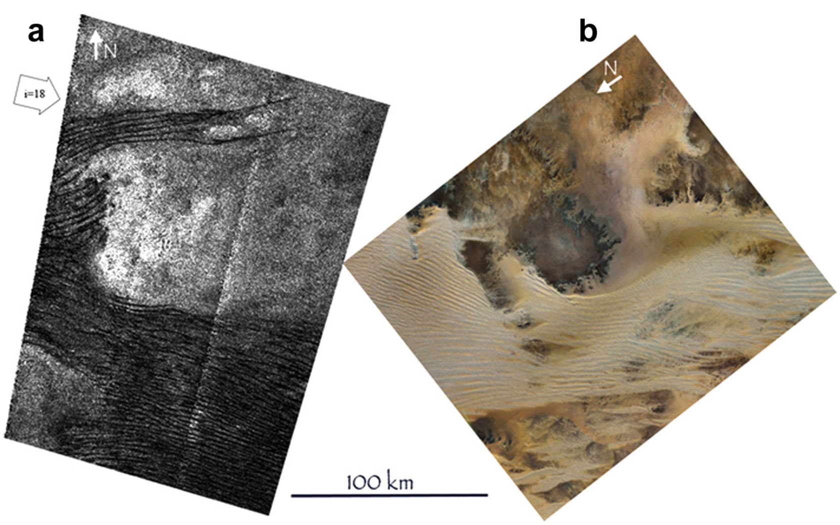

Fig. 12. (a) Dunes on Titan in the Shangri-La sand sea interact with SAR-bright topographic obstacles. Similar to dunes in Libya (b), the sands are halted upwind of the obstacle (dark in Libya image), then are diverted around the obstacle to resume their downwind course. Titan image from T55, 5/09, 4° N 154° W. Libya image from 23° 20 N, 21° 27 E, courtesy of Google Earth. Open arrows demonstrate direction of radar illumination and incidence angle.

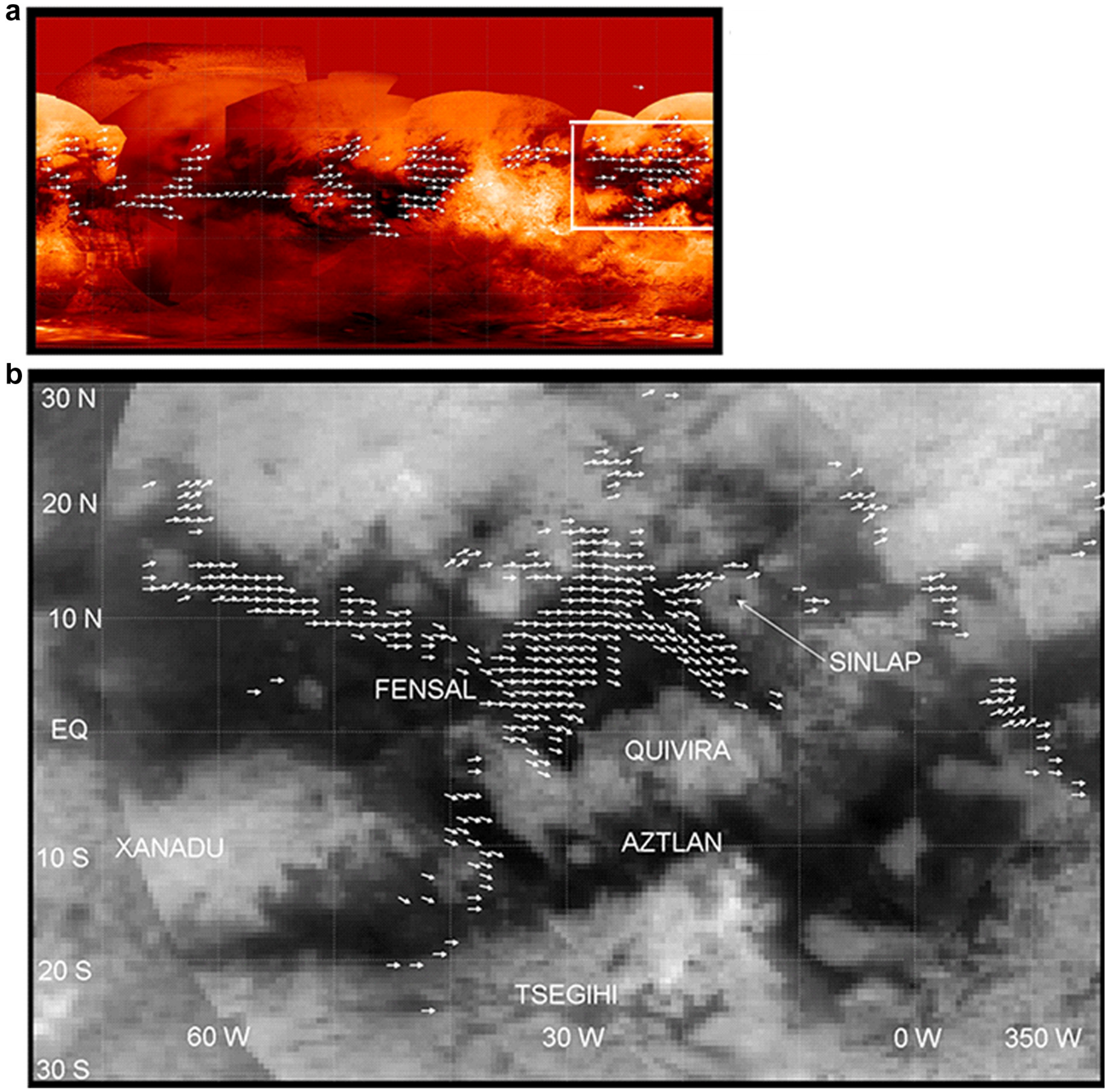

Fig. 13. (a) Orientations of dunes across Titan as a proxy for regional time-averaged wind and sand transport direction. Based on measurements of 16,355 dunes in a roughly global sample. Arrows represent 5° bins with the arrowhead chosen from interactions with topographic obstacles, basemap is colorized *Cassini* ISS image. Courtesy of NASA, PIA11801. From Lorenz and Radebaugh (2009). (b) Closeup view of the Fensal/Aztlan region (white box in global image a). Arrows represent 1° bins; note how dunes divert locally around topographic obstacles, such as Sinlap impact crater. From Lorenz and Radebaugh (2009).

Radebaugh et al., 2008; Barnes et al., 2008). Dune azimuth increasesahead of the 80-km Sinlap impact crater, on Titan's leading hemisphere, so that dunes appear to arc around it as if it were an obstacle to sand transport (Fig. 13b). Similar morphologies occur in dunes at the western margin of the continent-sized Xanadu region. Xanadu does not contain dunes or thick sands, and while it is puzzlingly lower in elevation, on average, than surrounding dune regions (Stiles et al., 2009; Radebaugh et al., 2011a), it has a slightly elevated western margin that may preclude sand transport from the west (Kirk et al., 2013).

Measurements of the long axes of over 16,000 dunes covering ~4% of the surface revealed Titan's dunes are broadly parallel to lines of latitude across the globe, with variations of about 30° on their orientation of 90° from north (Fig. 13; Lorenz and Radebaugh, 2009). The mean direction of wind flow, globally to the east, was determined from the interaction of dunes with topographic obstacles (Radebaugh et al., 2008; Lorenz and Radebaugh, 2009; Radebaugh et al., 2010a).

6.2. Wind directions and dune orientations

Global mean wind directions on Titan, as observed and as calculated in atmospheric models, have been anticorrelated in their early stages (Tokano, 2008; Radebaugh et al., 2008; Lorenz and Radebaugh, 2009). As discussed above, dune morphologies indicate winds blow globally across Titan from the west to the east(Radebaugh et al., 2008; Lorenz and Radebaugh, 2009; Fig. 13). In-situ measurements of Titan's winds from the Huygens Doppler Wind and Descent Imager and Spectral Radiometer (DISR) indicated winds blew toward the SSE near the equator, at the time of the descent of the Huygens probe in 2005 (Karkoschka et al., 2007). In contrast, global circulation models, and simple atmospheric

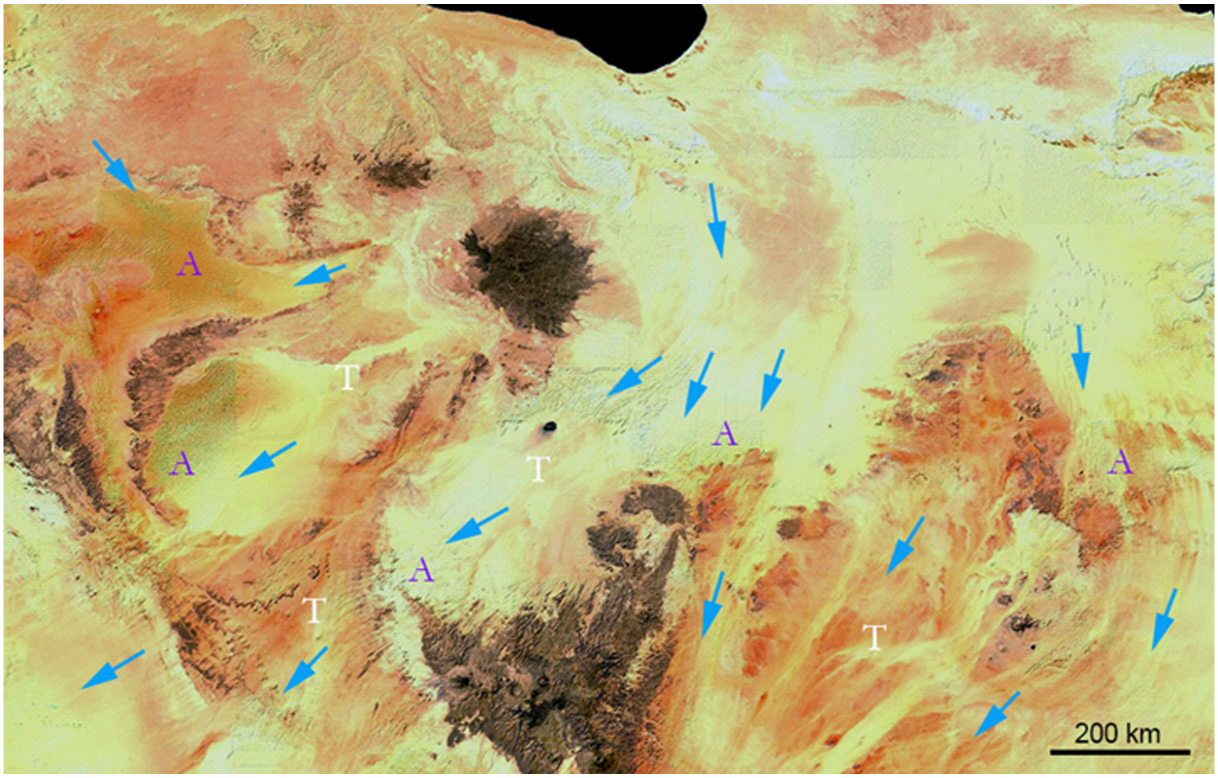

Fig. 14. Distribution of sands (light tan color) and winds (blue arrows) in the NE Sahara. Linear dunes and sand streaks broadly parallel trade winds (Mainguet, 1984). Transport (indicated by white Ts) occurs where sediments are thin and no obstacles exist. Accumulation (indicated by As) occurs ahead of obstacles, where winds decrease in strength (Bowen and Lindley, 1977). From Radebaugh et al. (2010b). MODIS image courtesy of NASA, centered at 26° N, 19° E.

angular momentum constraints, require time-averaged zonal winds near the surface to blow from east to west (Tokano and Neubauer, 2005; Tokano, 2008; Newman et al., 2011). However, new general circulation modeling (Tokano, 2010; Lorenz, 2010) that follows wind history with high time resolution throughout the year shows that although easterly winds are generally in effect, balancing Titan's atmospheric angular momentum constraints, strong westerly winds occur briefly at equinox, during the passage of the intertropical convergence zone (ITCZ). These seasonal winds are strong at Titan's surface, and may be the only winds that reach saltation velocities, of >0.8 m/s from models (Lorenz et al. 1995, 2006; Lorenz, accepted) and Huygens observations (Tomasko et al., 2005). These constraints allow them to shape Titan's dunes (Tokano, 2010). Thus, wind directions on Titan from dune morphologies and general circulation models may finally be in accord.

The large sand seas of Earth have dune forms that broadly parallel the anticyclonic flow resulting from the Coriolis Effect, or Earth's rotation (Mainguet and Canon, 1976; Wasson et al., 1988; Fryberger, 1979; Thomas and Shaw, 1991; Fig. 14). In the northeastern Sahara, these winds enter the desert from the Mediterranean and then sweep south and west towards the Atlantic, generally transporting sand in this direction (Mainguet and Canon, 1976). Linear dunes in the Sahara trace the pattern of these winds, curving over length scales consistent with the changing direction of winds in the current anticyclonic cells, indicating dune forms may be in equilibrium with current tradewinds (Mainguet and Canon, 1976). These patterns indicate the importance of dominant winds on the linear dune forms. Similar tradewind correlation patterns are seen in the now vegetated dunes of the Central Australian deserts (Wasson et al., 1988). This pattern of dunes paralleling dominant regional winds is considered to be an analog for the relationship between dunes and winds on Titan (Radebaugh et al., 2010b). Similar morphologies are seen, in which dunes arc over several hundred-kilometer scales, consistent with regional wind models (Fig. 13; Lorenz and Radebaugh, 2009; Tokano, 2010).

6.3. Atmospheric controls on size

The spacing of linear dunes has been the subject of much research, with one model requiring helical flow of wind in interdunes and another requiring disturbance of air flow in the lee of the crest. The helical roll vortex model suggests sheared flow in thermally unstable conditions will result in roll vortices that can sweep through interdune areas and carry particles up onto dune plinths (e.g., Bagnold, 1953; Folk, 1970; Brown, 1980). The air flow disturbance model suggests the spacing is related to how far air flow is disturbed downwind of the crest, and how high the crest is (Tsoar, 1978; Lancaster, 1983). A new study of the atmospheric boundary layer and its effect on capping the growth of dunes has yielded an idea for explaining the spacing of large linear dunes (Andreotti et al., 2009). This model suggests the elementary dune form size is dependent on the distance over which a given particle can be accelerated to wind velocities (Claudin and Andreotti,2006). These elementary dunes can coalesce to become larger features, if atmospheric conditions are stable and the dune is unrestricted. However, there is an upper limit to the size dunes can attain that is dependent on the atmospheric boundary layer, or the cap of the convective boundary layer in the atmosphere (Andreotti et al., 2009). Much like the flow of water over sediment in a river, increased shear at the top of the boundary layer prevents continued growth in spacing beyond the limit, which for Earth in coastal regions is only a few hundred meters but can reach ~3.5 km inland (Andreotti et al., 2009). This relationship can be seen in the Namib Sand Sea, where dunes are small and spaced by 200–300 km near the coast and grow to spacings of several kilometers inland. Lorenz et al.(2010) show that Huygens data support an estimate of ~3 km for the thickness of the boundary layer on Titan, which appears to be consistent with the spacing observed for dunes (Section 3). If dune size and spacing is indeed controlled by the boundary layer thickness, this would explain the remarkable similarity in size of the largest terrestrial dunes and those on Titan, despite differences in gravity and other parameters. An additional implication (Lorenz et al., 2010) is that the generally consistent dune spacing suggests that the boundary layer is uniform in thickness across the equatorial regions of Titan.

7. Dunes and Titan's climate

The distribution of dunes across Titan's equator coupled with the distribution of lakes at Titan's polar regions (Stofan et al., 2007; Lopes et al., 2010) leads to initial assumptions about Titan's climate based solely on landforms. Deserts are assumed to be found at equatorial regions (Lorenz et al., 2006), while the poles must be humid and slightly cooler (Stofan et al., 2007). Models of Titan's atmospheric circulation also demonstrate dry conditions near the equator and humid conditions at the poles (Rannou et al., 2006). Modeling of the Hadley circulation on Titan calls for transport of humidity away from the equator (Mitchell, 2008). Other modeling shows that an asymmetric circulation regime on Titan causes upwelling of humid air at the summer pole and dry downwellingeverywhere else, except during brief intervals at equinox, when the change in upwelling from one pole to the other results in a symmetric circulation regime (Hourdin et al., 1995). This regime may allow for higher-than-normal volumes of methane rainfall and accumulation in the equatorial deserts at equinox (Radebaugh et al., 2008). Away from equinox, however, conditions at the equatorial regions are consistent with desert environments. This may result in greater availability and mobility of sand, having not been transported to lakes or been wetted by continual methane rainfall. Thus, the observation of dunes at equatorial regions is correlated with models that suggest desert conditions generally prevail in those locations. Although dunes can be found on Earth in relatively humid environments, perhaps the presence of dunes at Titan's equatorial regions could be attributed in large part to the desert conditions that persist there (Radebaugh et al., 2008).

7.1. Dune maturity and migration on Earth

The question of longevity of individual dune forms, dune fields, and sand seas is intricately linked with the persistence of climate, locally and globally. Dune morphologies are strongly tied to wind properties, so dunes can reveal past and present wind and climate conditions in dune regions (Savage et al., in revision; Ewing et al., 2013). On the individual dune scale, the rate of dune bedform movement is inversely correlated with bedform size (Rubin and Ikeda, 1990). Centimeter-sized ripples can move at several centimeters per hour (e.g., Allen, 1984; Lorenz, 2011), while small barchan dunes can move at several tens of meters per year, for example in central Tunisia (Allen, 1984; Lorenz et al., in press).

Because linear/longitudinal dunes have several kilometer sizes, they require thousands of years to respond to wind regime changes (Warren and Allison, 1998; Livingstone et al., 2006). These dune forms thus require longer-term monitoring to unravel their histories. Combined studies using Optically Stimulated Luminescence (OSL) dating and ground penetrating radar (GPR) to probe exposure ages of sediments and pair them with bedding planes are yielding valuable results (Bristow et al., 2005). These studies have revealed most dune systems undergo periods of concentrated dune-building when conditions areconsiderably dryer and windier, such as during the Last Glacial Maximum (Lancaster, 1990; Fitzsimmons et al., 2007). These are followed by periods of relative inactivity, when reworking of surface sediments prevails (Lancaster, 2008). For example, linear dunes in the Rub al Khali of the UAE experienced rapid growth at a rate of 3.3 m/ky at 10 kyr, followed by relative inactivity, then by growth again at 74 m/ky in the last 1 ky (Goudie et al., 2001). Studies of linear dune morphologies reveal superposed forms, such as transverse or star dunes, that indicate wind conditions have changed since the linear forms were built (Fig. 15; Ewing et al., 2013). Studies of a linear dune on the eastern margin of the Namib Sand Sea revealed this is a composite feature with different episodes of construction dating from 5700 years ago through the present (Bristow et al., 2007). Substantial migration of the dune occurred through 140 years ago, and most recent activity mainly involves building superposed transverse dunes and shifting of the crestline (Bristow et al., 2007). Monitoring of the dune forms in this region over the last 30 years, however, did not reveal any substantial movement (Livingstone, 2003). More field studies of this nature are needed to continue to unravel histories of big linear dune fields.

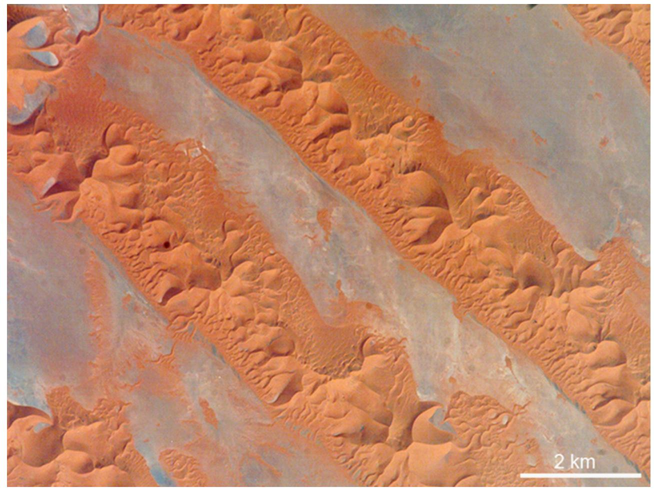

Fig. 15. Linear dunes in Algeria with superposed star dunes. Wind conditions must have changed since the formation period of the linear dunes, as these dune types have different wind regimes. Dunes are 2 km wide, north is to the upper left. Visible image taken from the International Space Station, 2006, 28.9° N, 4.8° E, image ISS013-E-75141, courtesy of NASA.

7.2. Dune maturity and migration on Titan

In-situ analyses of dunes is not yet possible on Titan, so researchers rely on remote sensing data. Morphological studies, in the form of pattern analysis of various dune parameters (see Section 3) are starting to yield important results concerning dune field maturity. The strength in these studies for planetary surfaces is that many characteristics of a region can be determined from spatial analyses alone. Given the lack of in situ data for most planetary surfaces, especially Titan, pattern analyses are proving to be of great value. On Earth, in the Namib Sand Sea, for example, there are three superposed sets of linear dunes of different sizes, with each progressively smaller size being of a more recent age (Lancaster et al., 2002; Ewing et al.,2006; Fig. 16). The existence of these sets indicates that climate conditions have changed, but not with enough severity or duration to erase the preexisting forms. If Titan has undergone a recent change in climate or wind direction, superposed forms or variations in overall size would be evidence of this change. At *Cassini* SAR's resolution of 350 m at best (capable of resolving intermediate to large forms; see Savage et al. in revision), with the exception of disrupted or cross-cutting forms seen

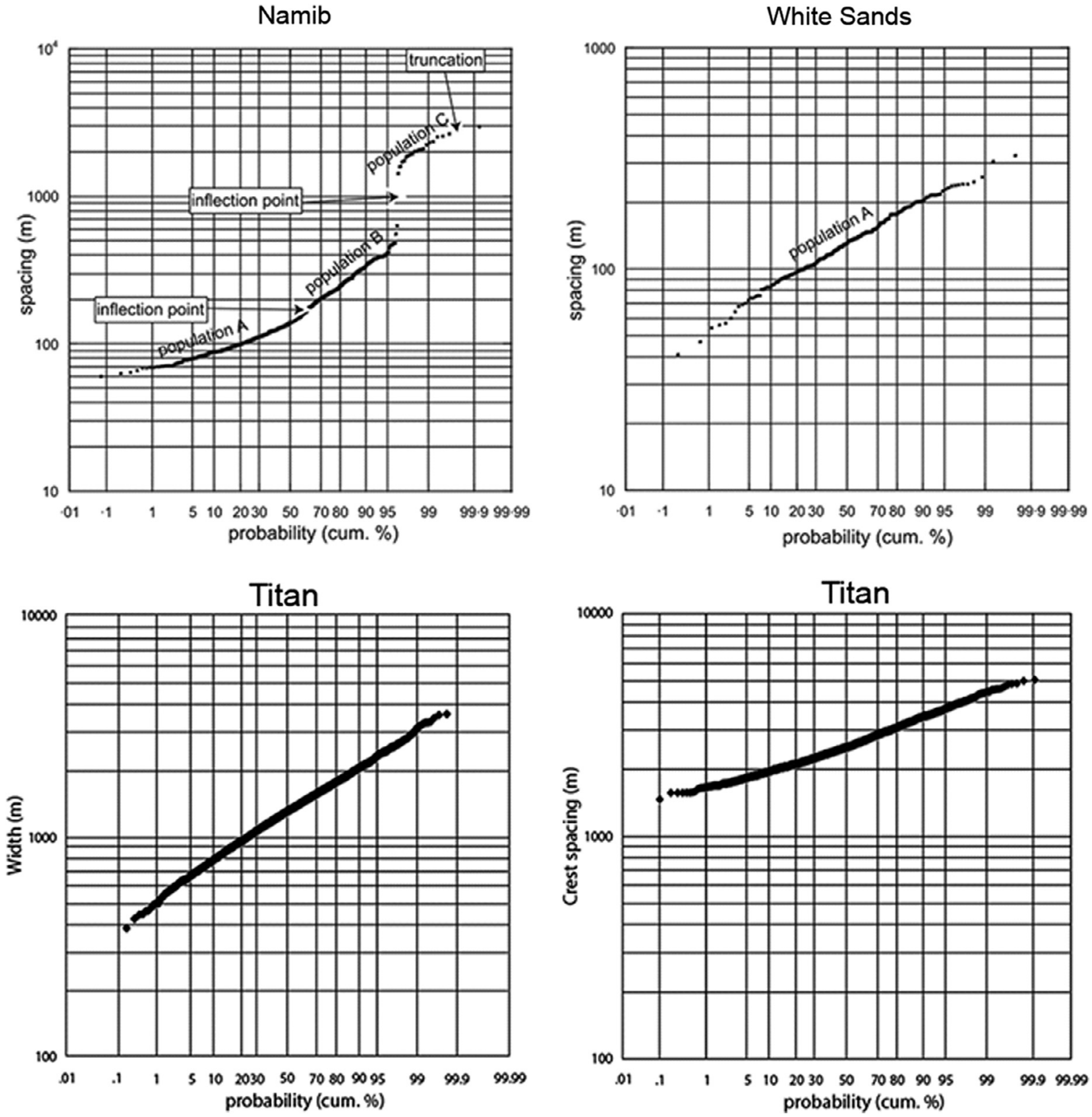

Fig. 16. Cumulative probability distributions of dune crest spacings for the Namib and White sands deserts (top) (from Ewing et al., 2006). Two inflection points separate three different populations in the Namib dunes indicating three different dune-building episodes, while a single population only is visible in White Sands. For the Namib dunes, the smallest population (A) would not be visible to *Cassini* SAR, but at least some of population (B) and all of population C would be. Bottom row shows dune width and crest spacings from 7000 each dune width and spacing measurements made across Titan (T21, T23, T28, T44, T48). From Savage et al. in revision. Like for White Sands, the lack of inflection points or breaks in the Titan data suggests that all the dunes measured are from a single population.

upwind of some obstacles, very few superposed forms are evident in dune fields on Titan (Fig 16). Preliminary studies of dune parameters numerically corroborate this observation, that Titan's dunes belong to a single population, and that the most recent dune-building conditions were sufficient to erase evidence of prior different conditions (Savage, 2011; Savage et al., in revision).

The uniformity of dune type across Titan, coupled with emerging pattern analysis results, indicate dunes on Titan may reside in an equilibrium condition that has persisted for a long time. Sand seas are relatively long-lived on Earth, as the transport and accumulation of sand can occur over tens of thousands of years in some regions, in many cases episodically (Lancaster, 1995). Just how these processes might scale to Titan conditions of lower atmospheric energies and other parameters is the subject of current modeling (e.g. Aharonson et al., 2009; Lorenz, accepted; Ewing et al., 2013). Titan's regional climate is expected to change seasonally, as methane evaporation and precipitation change location on Titan (Stevenson and Potter, 1986). In addition, climatic variations resulting from orbital eccentricity and spin variations are likely to occur over time scales of ~50,000 years, causing modification of features such as polar lake basins (Aharonson et al., 2009). It could be expected that such variations would also cause changes to the equatorial wind field and resultant dune forms. The reorientation or reconstitution time is how long it takes for a bedform to migrate its length, which is also related to the flux of sand (Allen, 1984). Migration rates of complex dunes in the northern Namib Sand Sea are 0.1 m/y, leading to a reconstitution time of ~6000 years, similar to the oldest OSL ages found for the dune (Bristow et al., 2007). Based on wind speed estimates, Lorenz (accepted) found a 10 m-high dune should migrate 1 m per Earth year, under continuous winds. However, saltation-speed winds are likely only seasonal, as on Earth. Thus, sands should only move at 1–5 cm/yr

(Lorenz, accepted), which is not likely to be observed in *Cassini*'s lifetime. This rate yields a reorientation timescale for Titan's large dunes of ~50,000 y (Ewing et al., 2013; Lorenz, accepted), similar to the climate forcing period (Aharonson et al. 2009).

7.3. Activity of Titan's dunes

The determination of whether or not dunes on Titan are active is valuable in terms of what it reveals about dune sands, current wind strengths, and rates of planetary processes (Radebaugh, 2009). On Earth, "active" can indicate anything on the continuum from mobilization of the whole dune form to reworking of sands along the crest of an otherwise stabilized dune (Lancaster, 1995). Methane rainfall is theorized to occur on Titan at least seasonally (Lorenz et al., 2008a; Griffith et al., 2005) and has been observed to occur at Titan's equatorial region in clouds (Schaller et al., 2009) and a rain-darkened surface (Turtle et al., 2011). Channels carved by methane precipitation and erosion of bedrock can be found in great abundance across the surface of Titan (Collins 2005; Lorenz et al., 2008a; Burr et al., 2009; Burr et al., 2013) and may even exist in a global network below the resolution of *Cassini* SAR (Radebaugh, 2009; Burr et al., 2013). Even on Earth in the Namib Sand Sea, where sand is abundant and actively moving (Bristow et al., 2007), large vlies, or dominantly dry river beds, gouge through giant dune forms, indicating fluvial activity morphologically dominates eolian activity. No rivers cut through dunes on Titan, except for one small channel observed by VIMS winding its way through several dune forms (Barnes et al., 2008; Radebaugh et al., 2010a). Studies of the SAR characteristics of Titan's dunes are consistent with superposed features larger than the SAR wavelength (2.1 cm) but smaller than the SAR image resolution (350 m), such as ripples or superposed dunes (Le Gall et al., in press), which indicates very recent activity, though another SAR modeling study and theory demonstrates if ripples are present, they must be small (Paillou et al., 2013; Lorenz, accepted). Dunes cover impact craters, channels, and other buried bedforms, they onlap mountains, and they are not cut by any other feature. They are thus among the youngest geological features on Titan (Radebaugh et al., 2008; Barnes et al., 2008), and if they are not cut by river channels, when methane rainfall is postulated to presently fall on Titan's surface (Turtle et al.,2011), there is a strong argument in favor of current dune activity on Titan (Lorenz, accepted). What is the nature of the activity of Titan's dunes, and how fast the dunes change or advance, remain unknown.

That Titan's dunes are uniformly linear may in fact be a result of their longevity and maturity (Tsoar, 1978; Lorenz, accepted). Thus, dunes on Titan may be simultaneously long-lived and actively forming, and so could be valuable analogs for understanding the more complicated dunes of Earth's sand seas.

8. Conclusion

Dunes are a dominant landform on Titan, and are the result of a long sequence of processes in the atmosphere and on the surface, including atmospheric chemistry, formation of sedimentary layers, erosion by rainfall, fluvial transport, and finally, wind action. Sand seas encircle Titan's equator, and morphologies indicate that global, eastward sand transport is halted only by large landmasses or diverted on a local scale by topographic obstacles. The dune forms are dominantly linear, and indicate bimodal, likely seasonal, winds that average over time and strength at Titan's surface near the equator as westerlies. Sands are likely composed of complex organics derived from atmospheric photochemistry, perhaps deposited into sedimentary layers, and then eroded by methane rainfall into saltatable particles. Dunes highlight some of the most recent, and perhaps even current, processes on Titan's surface. However, the dunes appear to be from a single population and highly mature, so erosion, transportation, and accumulation processes could operate over long time scales.

Dunes on Titan have been a topic of vigorous studysince they were first seen using *Cassini* data in 2005. The spacecraft is slated to operate at Saturn until 2017, during which it will obtain more images and data of Titan relevant to our understanding of dune systems. Dunes have been considered a possible landing site for future Titan spacecraft because of their safety (Leary et al., 2009; Lockwood et al., 2008); despite the presence of large-scale slopes, dunes are free of lander-scale rock and gully hazards. They would also represent a region of concentration of atmospheric and erosional processes and would thus be good sites for sampling and analysis. Plans for in situ balloons and aircraft (Barnes et al., 2011b) include targeting the dunes for imaging analysis to elucidate the composition, relative age, and dynamics of these features.

Ongoing studies of dunes and sand seas on Earth, their dynamics, and the conditions required to form and sustain them will increase our knowledge about large linear dunes on Titan. Conversely, studies of dunes on Titan, which form in the absence of vegetation or equatorial oceans and appear to erase evidence of ongoing precipitation at available resolutions, should also advance our understanding of Earth's dunes. Combined studies will help resolve questions about solar system dune formation, sand transport, wind and climate now and in the past.

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