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Implications of dune pattern analysis for Titan's surface history

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ABSTRACT

Analysis of large-scale morphological parameters can reveal the reaction of dunes to changes in atmospheric and sedimentary conditions. Over 7000 dune width and 7000 dune spacing measurements were obtained for linear dunes in regions across Saturn's moon Titan from images T21, T23, T28, T44 and T48 collected by the Synthetic Aperture RADAR (SAR) aboard the Cassini spacecraft in order to reconstruct the aeolian surface history of Titan. Dunes in the five study areas are all linear in form, with a mean width of 1.3 km and mean crest spacing of 2.7 km, similar to dunes in the African Saharan and Namib deserts on Earth. At the resolution of Cassini SAR, the dunes have the morphology of large linear dunes, and they lack evidence for features of compound or complex dunes. The large size, spacing and uniform morphology are all indicators that Titan's dunes are mature features, in that they have grown toward a steady state for a long period of time. Dune width decreases to the north, perhaps from increased sediment stabilization caused by a net transport of moisture from south to north, or from increased maturity in dunes to the south. Cumulative probability plots of dune parameters measured at different locations across Titan indicate there is a single population of intermediate-to-large-sized dunes on Titan. This suggests that, unlike analogous dunes in the Namib and Agneitir Sand Seas, dune-forming conditions that generated the current set of dunes were stable and active long enough to erase any evidence of past conditions.

1. Introduction

Linear dunes are the most abundant type of dune by area on Earth and Saturn's moon Titan (Bullard et al., 1995; Lorenz et al., 2006; Radebaugh et al., 2008; Le Gall et al., 2011). They form a major part of the sediment transport system, represent the results of atmospheric and surface processes, and are sensitive to changes in both (Lancaster, 1995; Warren and Allison, 1998). A detailed geomorphologic study of these features can reveal important relationships and processes and illuminate the evolutionary history of the surface. Here we analyze dune width and crest spacing in select regions across Titan to identify variations with location and to reveal details of dune-forming processes on Titan on regional and global scales.

1.1. Dunes on Titan from Cassini SAR

The Cassini–Huygens mission has revealed Titan to have a varied and complex surface. Among other Earth-like features such as river channels (Lorenz et al., 2008), lakes (Stofan et al., 2007) and mountains (Radebaugh et al., 2007), the surface of Titan is covered by vast fields of sand dunes (Lorenz et al., 2006; Radebaugh et al., 2008).

Dune sands on Titan are organic in composition and fine in size. Photochemical reactions in Titan's atmosphere produce complex organics that fall out of the atmosphere and accumulate on the water ice-rich crust (Soderblom et al., 2007). The materials are then perhaps solidified into a sedimentary layer, then eroded by methane rainfall and surface flow into particles of varying sizes, including sand-sized (Lorenz et al., 2006). Eventually, the particles are worked by near-surface winds, with velocities >1 m/s to saltate such particles in Titan's conditions (Lorenz et al., 2006), into large fields of sand dunes (Lorenz et al., 2006; Barnes et al., 2008; Radebaugh et al., 2008). Thick sands are dark to the Synthetic Aperture RADAR instrument (SAR) on the Cassini spacecraft, indicating they are smooth or absorbing at the Cassini SAR wavelength (2.17 cm), and are dark in the visible and near-infrared spectrum, as seen by the Cassini Visual and Infrared Mapping Spectrometer (VIMS) and Imaging Science Subsystems (ISS) instruments (Barnes et al., 2008).

Dunes are abundant on Titan's surface, covering close to 13% of the total surface area, based on SAR observations (350 m resolution, about 35% global coverage to date) and VIMS and ISS analyses (global coverage but lower resolution) (Le Gall et al., 2011; Rodriguez et al., 2014), and found within a belt ±30° latitude of the equator (Lorenz et al., 2006; Radebaugh et al., 2008; Lorenz and Radebaugh et al., 2009; Le Gall et al., 2011). No permanent lakes or seas or large topographic obstacles (with the exception of the Xanadu landmass) are present to disrupt global wind patterns or dune formation (Lorenz and Radebaugh, 2009).

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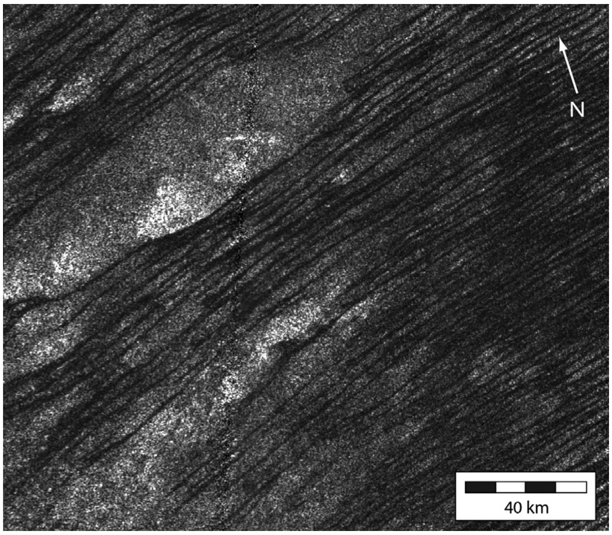

Fig. 1. Example of Titan's linear dunes from Cassini SAR swath T21 centered at about 10.4°N, 279°W. Like similar terrestrial linear dunes, Titan's dunes are slightly sinuous and generally parallel but do not appear to host superimposed or flanking dunes.

The vast majority of Titan's dunes are linear in form and oriented nearly parallel to the equator (Barnes et al., 2008; Lorenz and Radebaugh, 2009). They are up to several km in width and spacing, are up to 180 m high (Barnes et al., 2008; Neish et al., 2010) and can be more than 100 km long (Fig. 1; Lancaster, 2006; Lorenz et al., 2006; Radebaugh et al., 2008). Titan's dunes have been active in the recent geological past, as evidenced by the fact that few, if any, other morphological features overlie dunes at Cassini SAR resolutions. In addition, the interdune area in many of the dune fields is clearly distinguishable by VIMS. This means the substrate is exposed and kept clear of any dune sediments that may have blown or flowed, by mass wasting, into the interdune areas by active winds (Barnes et al., 2008).

Despite the differences in gravity, atmospheric density and sand grain composition on Titan and Earth, the size, morphology, and behavior of Titan's dunes around obstacles are similar to large linear dunes on Earth. Therefore, processes attributed to the evolution of terrestrial linear dunes are applied to dunes on Titan (Lorenz et al., 2006; Radebaugh et al., 2008, 2010; Le Gall et al., 2011).

2. Parametric analysis of Titan dune width and spacing

2.1. Dune morphometric study

Titan's dune widths and crest spacings were measured in five Cassini SAR swath images, T21, T23, T28, T44, and T48 (Fig. 2). These image regions were chosen because they all span a range of latitudes and cross the equator, enabling changes with latitude to be readily observed, they have easily identified dunes and interdunes (unlike the more challenging T8 Belet region, for example) and they are located across many different Titan longitudes. Measurements were made using the USGS ISIS program at regular 5 km intervals along dune long axes. Since most dunes on Titan are many times longer than 5 km, this spacing provides an adequate sampling to capture significant variations along each dune. Tests using smaller measurement intervals of 1.8 and 0.8 km did not yield significantly different results than those obtained using the 5 km interval. Dune widths were measured perpendicular to the long axis and taken to be the width of the SAR-dark streaks, which are interpreted as dunes (Fig. 3). Interdune spacing was obtained in similar fashion except the widths of the SAR-light areas between the dark streaks were measured. Since dune crests are not commonly visible in the SAR images the crest-to-crest spacing, a common measurement in terrestrial dune analysis (Breed and Grow, 1979; Lancaster, 1989, 1995; Ewing et al., 2006) was approximated. This was accomplished by pairing the average dune width

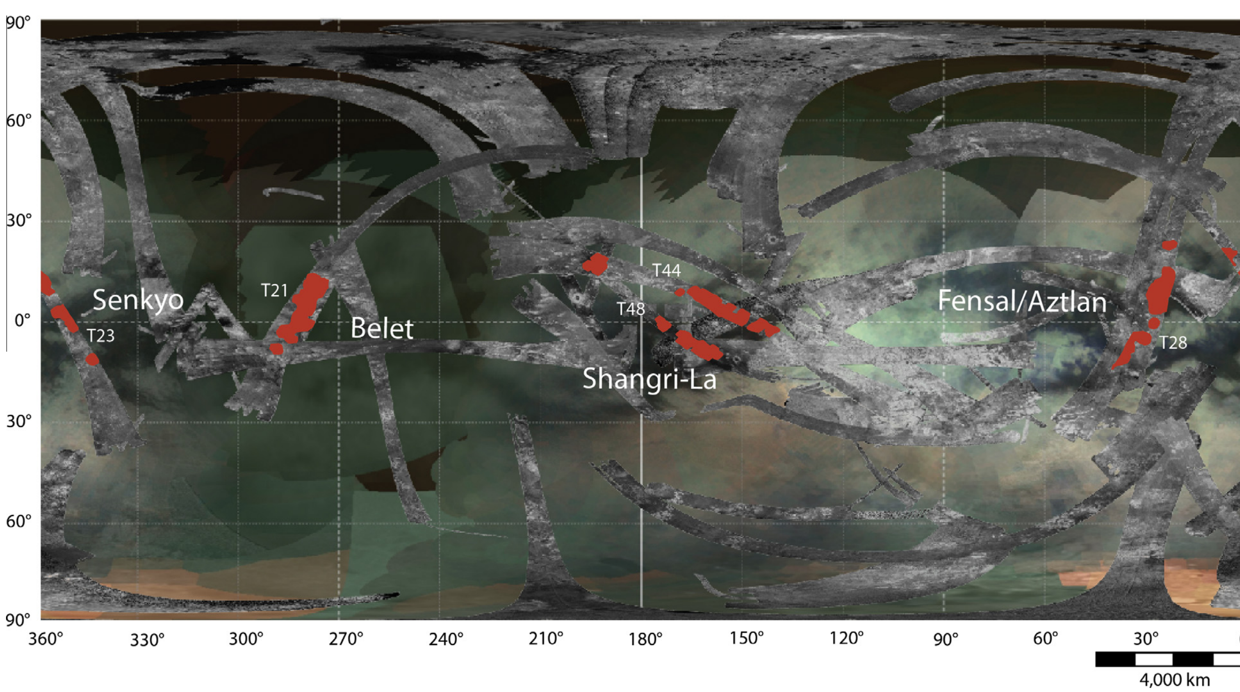

Fig. 2. The approximate location of each measurement made in this study (in proportionately large symbols, and thus overlapping) is marked in red on a global mosaic of 36 of Cassini's SAR swaths, shown as grayscale strips, on a Cassini VIMS/ISS basemap. The five swaths sampled for this study are labeled, as are the major sand seas on Titan. The red points roughly outline the dune fields observed in these swaths. Swaths vary in width from 150 km to nearly 400 km. SAR coverage across Titan's equatorial latitudes at the time of writing is approximately 35%.

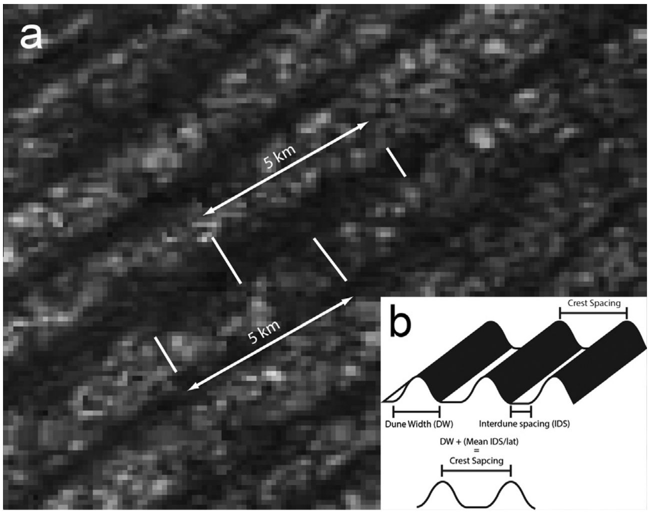

Fig. 3. (a) Section of Cassini SAR swath T23 showing dunes (dark streaks) and interdune areas (lighter areas). Measurements were taken approximately every 5 km across the dune long axis, from one light/dark boundary to the next across the dark dune. Interdune spacing is measured from one light/dark boundary to the next across the light area between dunes. Crest spacing was not directly measured, but approximated by adding the average interdune spacing per degree latitude/longitude to dune width in the same degree latitude/longitude. (b) (inset) Cartoon depicting dune pattern parameters and their measurements. Average dune width and interdune spacing were added to obtain average crest spacing for a given region.

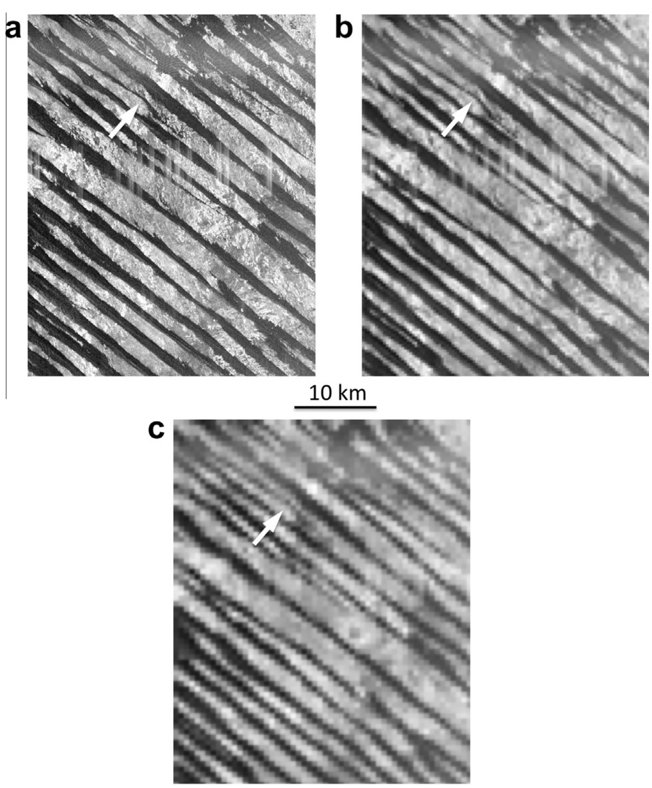

Fig. 4. (a) SIR-C X-band (3 cm) image of linear dunes in the Great Sand Sea of western Egypt. Small, flanking features, small offshoot linear dunes and crestlines are clearly visible in the high-resolution image. (b) The same SIR-C image as in (a) but resampled to 350 m/pixel similar to Cassini SAR image resolution at the center of the swaths. Some small features, such as crestlines and offshoot dunes are still visible. (c) The same SIR-C image as in (a) but resampled to 700 m/pixel, similar to Cassini SAR resolutions near swath ends. Many small features are lost in this image, but a small flanking dune with maximum width 1000 m and minimum width 200 m (white arrow) is still visible. SIR-C/X-SAR image courtesy of NASA/JPL, pr16158_9_16160_1_Lhh_flip, in west-central Egypt, at 25°16′N, 26°50′E.

with the average interdune width for each degree of latitude. Since crest locations would have been approximated, this method, and the resulting "crest-to-crest average" spacing, was found to be more accurate. In all, 14,050 individual dune width and interdune width data points were collected.

The distribution of dune morphologies across the five study swaths appears to be broadly homogeneous. All of the dunes observed and measured for this study are linear in form as observed at Cassini SAR resolutions of 350 m. Linear dunes on Titan are generally slightly sinuous, yet parallel, like many linear dunes on Earth. Unlike terrestrial dunes of similar size, however, such as those found in the Namib Sand Sea in southern Africa, they do not appear to have intermediate-sized, superimposed flanking dunes that would be visible to Cassini SAR. Rather, there appears to be a clean distinction between dunes and interdunes, in some cases with very high contrast, and in other cases with low contrast, but lacking variability at the dune/interdune boundary that might indicate large, flanking features are running into the interdunes. This is supported by a SAR image of terrestrial linear sand dunes in the Great Sand Sea of western Egypt (Fig. 4a) that has been degraded to 350 m/pixel (Fig. 4b), similar to the effective resolution at the center of Cassini SAR swaths. In this region, there is high contrast between dunes and substrate, similar to many Cassini dune areas. While details become lost with progressive degradation, many features are still visible, such as small flanking or offshoot dunes, sometimes visible at subpixel widths because averaging retains their signature. Cassini SAR images become more degraded in resolution toward the far ends of the image swaths (e.g. see West et al., 2009), and the 350 m resolution images are plagued by noise (see also Neish et al., 2010, for a detailed resolution discussion), so we further degraded this image to 700 m for a

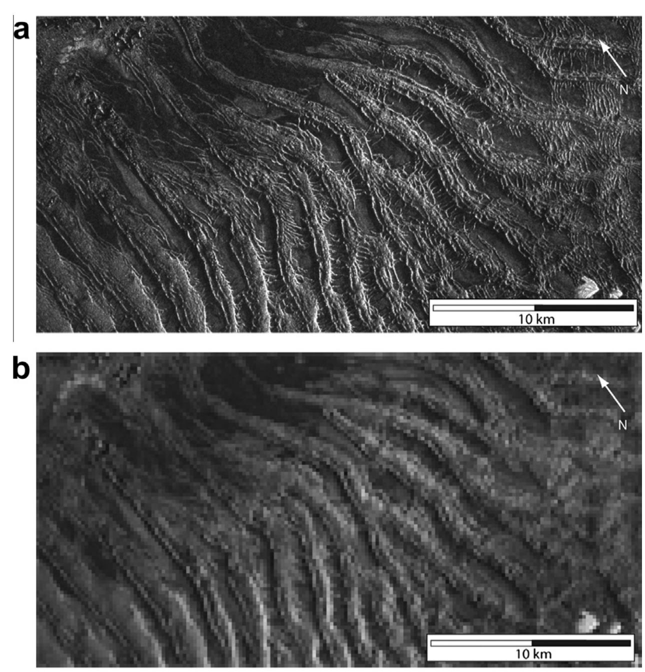

Fig. 5. (a) C-band SAR image of dunes in the Namib Sand Sea, Namibia. Radar-facing dune surfaces are bright in this image and smooth interdunes are dark, which is the reverse of the X-band-SAR-absorbing dunes in Egypt (Fig. 4) and Cassini SAR images of Titan dunes. Some dark bands parallel to dunes are shadows from SAR illumination (Neish et al., 2010). Many superposed forms, flanking features and multiple crests can be observed on these dunes. (b) Top image is resampled to 350 m/pixel, similar to Cassini SAR image resolution at the center of the swaths. Small flanking and superposed features have been lost, but many intermediate features in the interdunes and multiple crestlines are still retained. SIR-C/X-SAR image courtesy of NASA/JPL, pr44422, in the Namib Sand Sea, 24°3′S, 15°46′E.

more conservative example (Fig. 4c). Crestlines completely disappear in this image, as well as most fine features, yet some flanking/offshoot dunes are still visible, including one feature (arrows) that is 300 m at the widest and 150 m at the narrowest. These images demonstrate that high-contrast linear features are visible down to 350 m, and in select cases smaller than this. Thus, we conclude that many intermediate-sized (350 m) flanking features should be visible on Titan's dunes, particularly in the high-contrast areas selected for this study, yet they are not observed.

A C-band SAR image of dunes in the Namib Sand Sea (Fig. 5a) shows an area of compound/complex linear dunes, compound because they have multiple crestlines, up to five per dune in some cases, and complex because they have many intermediate flanking and superposed features (Lancaster, 1995). The image shows dune faces as bright, directly reflecting the SAR signal, while interdunes are smooth and dark to C-band SAR. Degradation to 350 m per pixel (Fig. 5b) demonstrates that while many fine features are lost, intermediate flanking features and multiple crestlines are retained. Moreover, the general morphology of these large, compound/complex linear dunes, the product of many overlapping generations of dune forms, is vastly different from the general morphology of Titan's much straighter, more uniform dunes (Fig. 1).

2.2. Width and spacing trends

Titan's linear dunes measure from 0.4 km to about 3.6 km in width with a mean width of 1.3 km (Fig. 6a). Dune spacing ranges from 1.4 km to almost 5.3 km with a mean spacing of 2.6 km (Fig. 6b). Dune width and crest spacing averages for each individual study swath are all within one standard deviation (0.4 km and 0.5 km respectively) of the global Titan mean. Titan dunes are slightly larger on average than linear dunes in the Namib Sand Sea, whose mean width is 0.9 km and mean spacing is 2.2 km (Lancaster, 1995).

Dune width decreases toward higher northern latitudes, across Titan and in individual regions (Fig. 7a–c; Table 1). Dune spacing may generally decrease toward higher northern latitudes in several locations, but the overall average spacing does not show a significant trend with latitude (Fig. 7a and c). Le Gall et al. (2011) established a latitudinal dependence in the microwave electromagnetic signatures of the dune fields. The dune terrains are less emissive and brighter toward the north, likely because the interdune fraction (ratio of interdune width to dune width) increases toward the north.

Exceptions to the trend of decreasing width with increasing latitude can be attributed to local factors. For example, the dunes

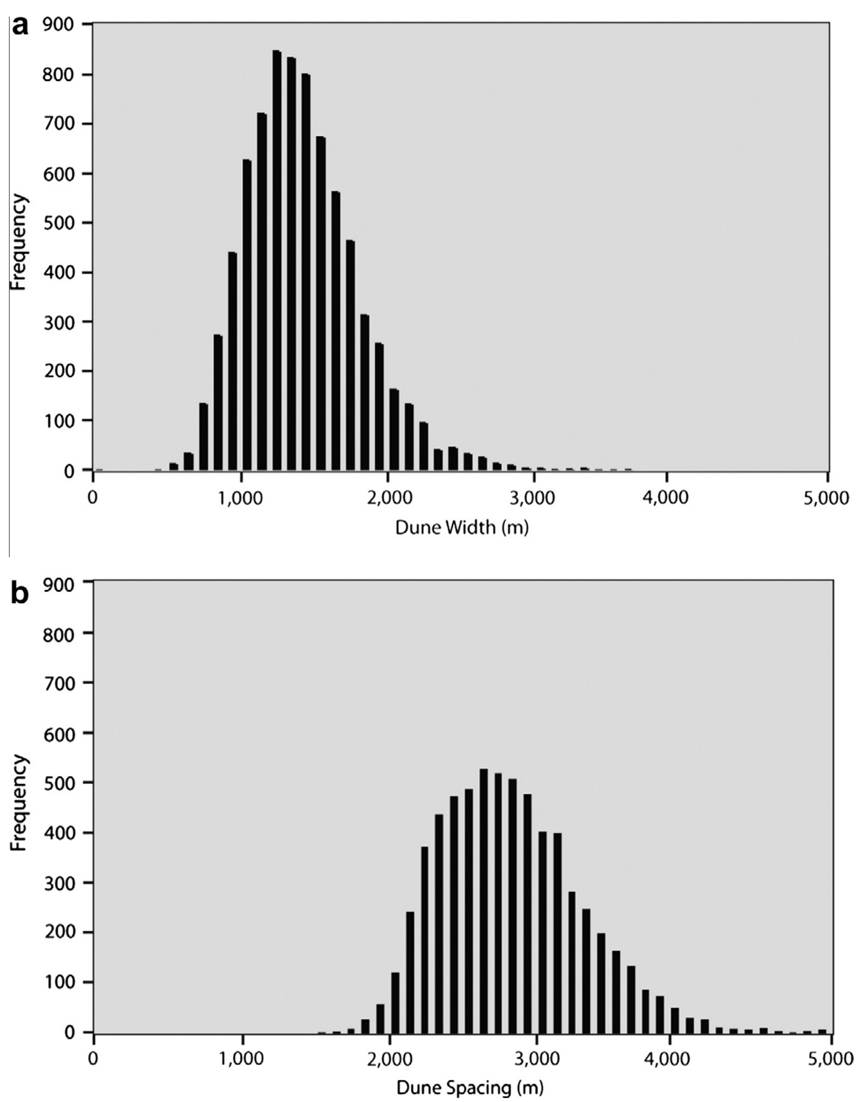

Fig. 6. (a) Titan dune widths for all measured locations (Fig. 2). Mean width is 1300 m. (b) Titan dune spacing for all measured locations, mean spacing is 2600 m.

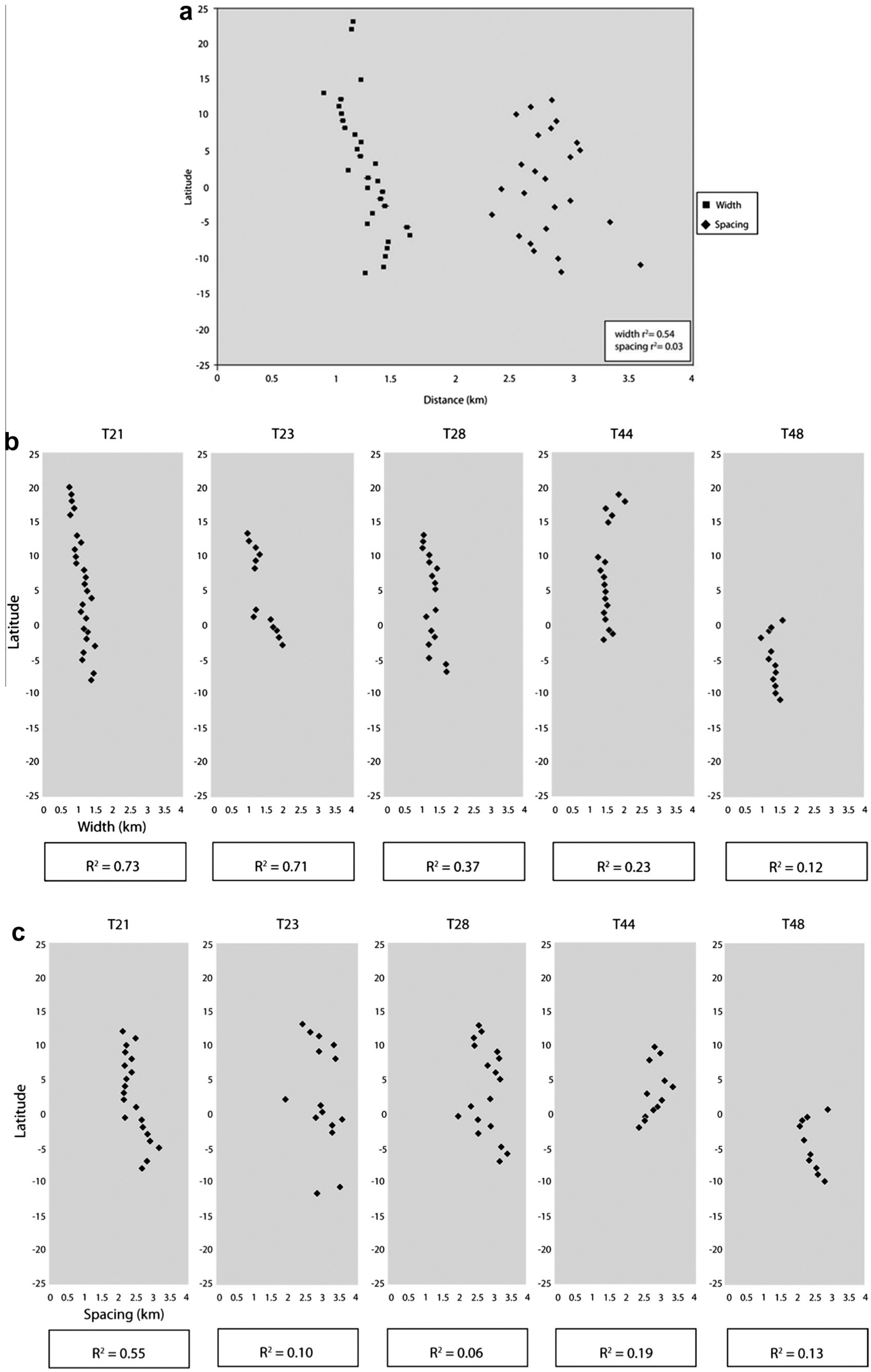

Fig. 7. (a) Mean dune width and crest spacing per degree latitude for all dune measurements across Titan. Dune width decreases to the north while dune spacing shows no significant correlation with latitude. Error bars are 1-sigma, in most cases smaller than the symbols used. (b) Mean dune widths per degree latitude for each study swath. Note that the trend of decreasing width with increasing latitude is visible in most of the study swaths. (c) Mean dune crest spacing per degree latitude for each of the study swaths. Note that the trend of decreasing dune crest spacing with increasing latitude may be present in a few of the swaths.

Table 1
Average width and spacing for all measured dunes across Titan for each degree of latitude. SD is standard deviation, SE is SD/$n^{1/2}$, n is number of measurements, Ave. ID is average interdune width. All measurements are in meters.

Lat.	Ave. width	SD	SE	Min.	Max.	*n*	Ave. ID	SD	SE	Min.	Max.	*n*	Ave. spacing	SD	SE	Min.	Max.	*n*
−12	1240	393	82	581	2164	23	1854	541	150	954	2668	13	3094	541	150	1998	3712	13
−11	1390	314	52	715	2151	36	2342	463	119	1538	3223	15	3732	463	119	2752	4437	15
−10	1414	344	19	698	2618	312	1520	395	114	880	2020	12	2934	395	114	2290	3429	12
−9	1426	354	11	518	3280	643	1212	232	37	904	1982	39	2638	232	37	2309	3387	39
−8	1443	378	17	633	2630	487	1287	376	188	852	1727	4	2730	376	188	2192	3068	4
−7	1630	348	13	774	2961	686	1327	338	102	817	1722	11	2957	419	126	2231	3403	11
−6	1601	393	20	596	3200	399	1514	568	61	693	3033	87	3115	646	63	2102	4703	61
−5	1249	307	16	580	2277	362	2131	547	146	1616	3273	1.1	3380	54S	147	2726	4472	14
−4	1314	311	19	526	2169	283	1438	525	103	732	2359	26	2752	390	104	2025	3511	14
−3	1415	355	28	780	2991	158	1324	345	51	576	2161	46	2739	161	61	2109	3632	35
−2	1381	372	20	678	3072	351	1392	449	32	589	3109	200	2773	584	41	1588	4399	200
−1	1394	346	17	715	2536	399	1270	515	40	522	3290	103	2664	623	49	1766	5042	163
−0.5	1267	347	27	635	2492	169	1063	241	21	580	1796	137	2330	310	26	1745	3421	137
0.5	1353	376	25	436	2739	219	1342	287	22	616	2186	166	2695	343	26	1844	3563	168
1	1275	440	26	290	3590	293	1204	379	25	475	2128	728	2479	439	12	1567	3616	194
2	1101	377	16	434	3129	523	1165	494	40	251	2402	152	2266	141	50	2077	3804	127
3	1333	442	27	508	508	270	984	266	28	553	553	93	2317	336	40	1566	3479	72
4	1210	431	23	363	3446	353	1294	530	41	496	2799	165	2504	531	48	1748	4284	139
5	1183	454	17	364	2406	730	1445	502	51	55S	2518	81	2628	588	71	1817	3897	69
6	1219	476	16	291	3283	835	1464	447	44	746	2803	105	2683	501	49	1965	4180	105
7	1165	449	18	363	3123	633	1283	413	39	635	2377	110	2448	458	44	1796	3667	110
8	1078	402	18	361	2791	523	1669	585	51	832	3507	130	2747	679	63	1840	4790	117
9	1062	408	17	218	3217	586	1555	550	47	771	3779	155	2617	631	55	1740	4988	133
10	1044	354	17	291	2660	443	1529	544	51	633	3265	115	2573	657	63	1568	4571	111
11	1022	260	16	437	1947	268	1624	541	43	0	3634	145	2646	548	46	1656	4830	144
12	1045	260	22	566	1769	146	1772	534	62	608	2896	74	2817	544	63	1652	3982	74
13	888	242	23	460	1837	111	1547	541	96	597	2965	32	2435	547	97	1576	4033	32
15	1203	452	36	377	2680	157	1458	521	92	528	2643	37	2661	521	92	1647	3761	32
22	1121	298	29	452	2129	103	1483	341	50	956	2684	46	2604	141	50	2077	3804	46
23	1139	405	108	512	1697	14	1611	296	148	1300	1973	4	2750	296	148	2439	3112	4

measured in the northern Fensal Sand Sea (swath T28) above 15° latitude all reside in small, isolated fields. This also is the case for dunes in the southern Senkyo Sand Sea (swath T23) between −11° and −12° latitude. In these smaller, isolated dune fields, dunes tend to be wider and more widely spaced than dunes found in larger dune fields, such as those in the middle of the Fensal/Aztlan Sand Sea (T28) between −7° and 13° and those in the central Senkyo Sand Sea (swath T23) between −3° and 13°. The dunes in large fields are more closely spaced and have widths that generally decrease toward higher northern latitudes. In the northern Shangri-La Sand Sea (swath T44), there are outliers beyond this trend, but unlike those already mentioned the outlying dunes in T44 between 15° and 19° latitude are not members of small, isolated dune fields. In this region, it is difficult to accurately differentiate dunes from interdune areas because both are SAR-dark. This region is near the edge of the swath where resolution tapers off and gives way to sandy interdunes, leading to reduced contrast. Measurements here are thus more challenging. Some areas, however, such as the western margin of the Belet Sand Sea (T21), have high contrast between the interdune and dune. If high-latitude dune field parameters are removed from the global averages, the R^2 fit improves from 0.54 to 0.79 for the trend of decreasing dune width toward higher latitudes, but does not improve for dune spacing.

Overall, dune spacing is more variable than dune width because of the variation of interdune widths, likely related to the sinuosity of the individual dunes.

2.3. Population identification

Terrestrial studies of dune parameters have yielded important results concerning dune field maturity, spatial variations and changes over time. We apply the parametric analysis methods utilized by Ewing et al. (2006) in a study of White Sands and the Namib and Agneitir Sand Seas. The study assumes sample sizes are large enough that the distribution of sample means can be approximated by a normal distribution (according to the Central Limit Theorem; Triola, 2004). If this is true, cumulative probability plots of the data can reveal separate populations of dunes if they exist within the total sampled dune field or sand sea. These smaller populations are distinct and display their own log-normal distributions that plot as a single line on a log-normal plot of cumulative probability if the data are the result of a single mechanism or dune-building event (e.g., their White Sands plots). If the data are the result of multiple mechanisms, then multiple lines will be present, separated by breaks or inflection points (Fig. 8). Each population on the plot represents a significant change in conditions, such as wind direction, sediment availability or sediment mobility, and can be identified and separated from other populations to further investigate the formative conditions at specific points in time.

Cumulative probability plots of dune spacing in the Namib Sand Sea and the Agneitir Sand Sea (Fig. 8) show that each contains at least three populations of dunes represented by distinct lines separated by inflection points. The trends in Fig. 8 imply two significant shifts in dune-forming conditions in each location and thus are evidence for three separate dune-forming periods.

The main challenge in applying this method to Titan's dunes is the Cassini SAR image resolution of ~350 m, as discussed above. Linear features with high SAR contrast, such as dunes, however, can be detected at subpixel size. Many of the flanking dunes in the Namib and Agneitir Sand Seas are a couple of hundred meters apart (Breed and Grow, 1979; Lancaster, 1989, 1995; Ewing et al., 2006) and in many place they reach well into the interdune area and would thus be apparent on Cassini SAR imagery (Figs. 4 and 5). Smaller features, such as dunes superimposed on the crestline, which are the third-tier population in the Agneitir (Pop A in Fig. 8b), would not be visible to Cassini SAR.

Cumulative probability plots of dune widths and spacings (Fig. 9) of dunes across all five study swaths on Titan form a single

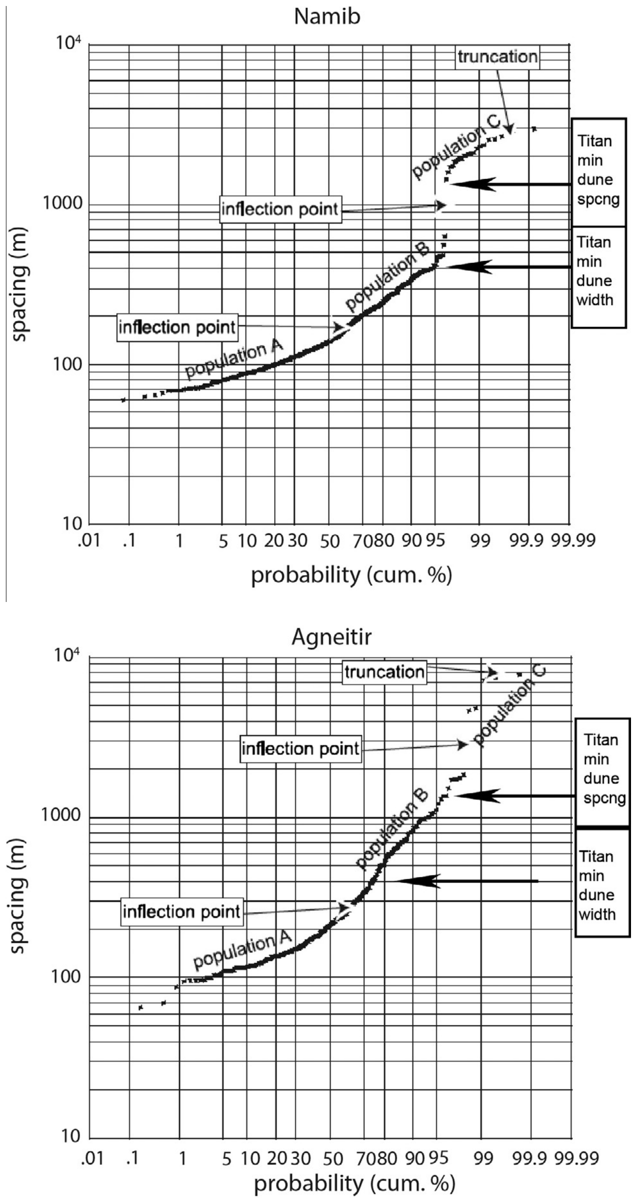

Fig. 8. Cumulative probability plots of dune spacing from (a) the Namib Sand Sea and (b) the Agneitir Sand Sea (from Ewing et al., 2006). Two inflection points separate three different populations in each location. The smallest population (A) would not be visible to Cassini SAR, but at least some of population B and all of population C would be.

curve and suggest the dunes measured are from a single population. Given that swaths are 150 km wide at the narrowest, the datasets for each image swath include at least several dozen dunes. Plots of individual swaths also show single populations (Fig. 10), except dune spacing in the southern Senkyo Sand Sea (T23) has a kink in the curve that may be evidence of more than one population. The slopes of the curves below and above the kink, however, are the same, unlike in the Namib and Agneitir, where different populations have different slopes. A large dune region within the T23 swath (at ~2°N and 350°W) shows overlapping dune forms, generally linear forms that have crossing orientations. These dunes appear downwind of a large, SAR-bright obstacle that has likely disrupted winds and caused the dunes in the lee of the obstacle to have different orientations This is seen in a few other regions on Titan (Lorenz, 2014), and may be the explanation for the kink in the population curve (Fig. 11).

3. Parametric and morphometric constraints on Titan dune type

A proxy for linear dune type (simple, compound, complex) may exist in the ratio of dune width to crest spacing. Breed and Grow (1979) note that there appears to be a linear arithmetic relationship between mean widths and spacings across all linear dune types. This trend is particularly strong ($R^2 = 0.9$) for data taken from linear dune fields on Earth (e.g. Lancaster, 1995, 2006; see Table 2 for locations). There is a similar relationship between widths and spacings of all dunes measured per degree latitude on Titan, and dunes on Titan fit on the plot of Earth dunes where large linear dunes are found (Fig. 12). The correlation of width to spacing for dunes on Titan alone is weaker ($R^2 = 0.37$) when values for dunes are averaged per degree latitude, likely because all dunes studied are large and therefore plot close together, and because there is variation in width with latitude. The width and spacing relationship for all dunes on Earth and Titan, similar to that plotted for limited Titan data by Lancaster (2006), has a correlation $R^2 = 0.89$, when using average values per swath and per terrestrial dune area (Fig. 12). That such a relationship can be correlated across Earth and Titan is further evidence that terrestrial dunes can be used as analogues for understanding Titan's dunes (Radebaugh et al., 2010) and that the essential, dune-forming processes are the same. Breed and Grow (1979) also showed that spacing tends to be about twice the mean width of linear dunes regardless of size (Table 2), a trend also found in Titan's dunes.

Because Titan's dunes do not appear to have multiple crestlines or host intermediate-sized superimposed or flanking dunes, they are different from typical terrestrial compound or complex dunes (Breed and Grow, 1979; Lancaster, 1995; Bourke et al., 2010). Terrestrial dunes of comparable size to Titan's dunes in the Namib Sand Sea and Agneitir Sand Sea nearly all have large, superimposed dunes or multiple crestlines. Titan's dunes are thus more similar to the large linear dunes of the southern Great Sand Sea (in west-central Egypt) and the southern Rub' al Khali, in Yemen, that are large but do not have many intermediate-sized superimposed or flanking dunes. Such dunes, however, do have small superposed features that would not be visible to Cassini SAR resolutions. Thus, we suggest Titan's dunes have the morphology of large linear dunes, and they lack any evidence for being compound or complex at the resolution of Cassini SAR.

4. Linear dune maturity and wind regime stability

Dune size and morphological variety on Earth and Mars are largely functions of dune field maturity, or the length of time a dune field is exposed to a given set of formative conditions (Warren and Allison, 1998; Ewing et al., 2006, 2010). Maturity is expressed by increasing dune similarity (uniform morphology), increased complexity, increased size and crest spacing, and decreased defect density (Kocurek and Ewing, 2005; Ewing et al., 2006). Starting from any number of initial conditions or dune forms, holding wind regimes steady forces sand into dunes that evolve through smaller, less complex morphological stages until they reach the largest, most complex and best ordered form allowed by their environment (Breed and Grow, 1979; Hersen et al., 2002; Ewing et al., 2006, 2010; Andreotti et al., 2009; Kocurek et al., 2010; Lorenz et al., 2010). Thus, dune morphology, size and spacing are all indicators of dune field maturity.

Small dunes form in short periods of time while large dunes form under long-term, consistent wind conditions (Warren and Allison, 1998). Changes in wind patterns eventually lead to destruction of dunes and reconstitution of new dune forms (Warren and Allison, 1998). Thus, large dunes can be interpreted

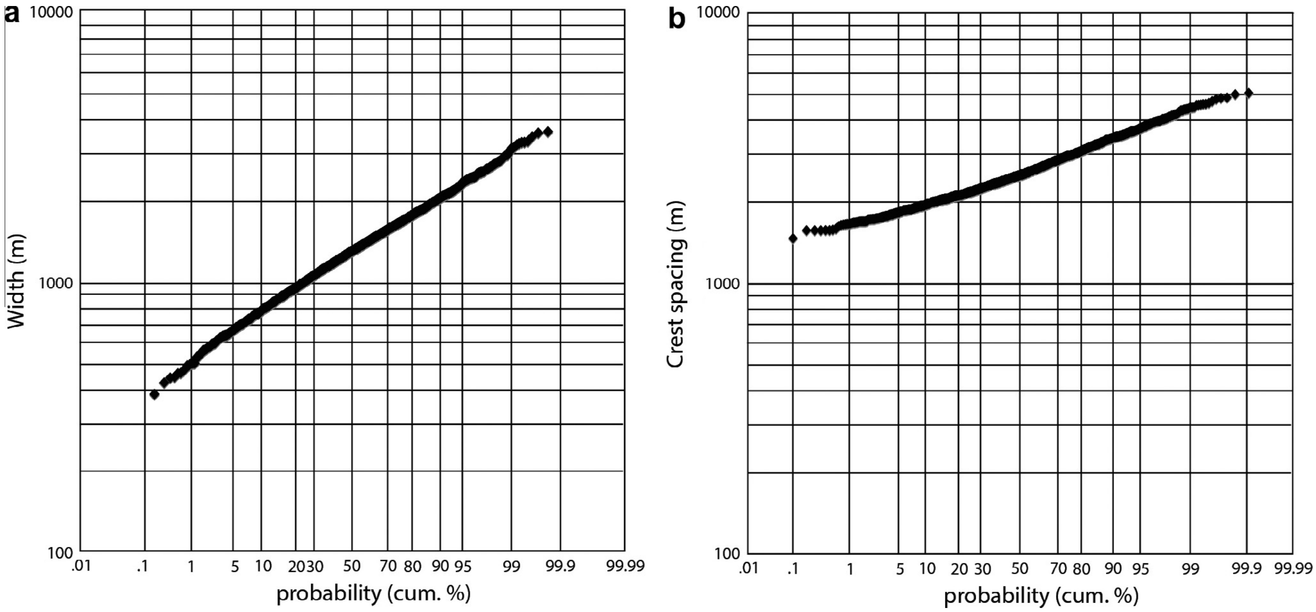

Fig. 9. Cumulative probability of (a) all widths and (b) all crest spacings measured for Titan's dunes in this study. The lack of inflection points or breaks in the data suggests that all the dunes measured are from a single population.

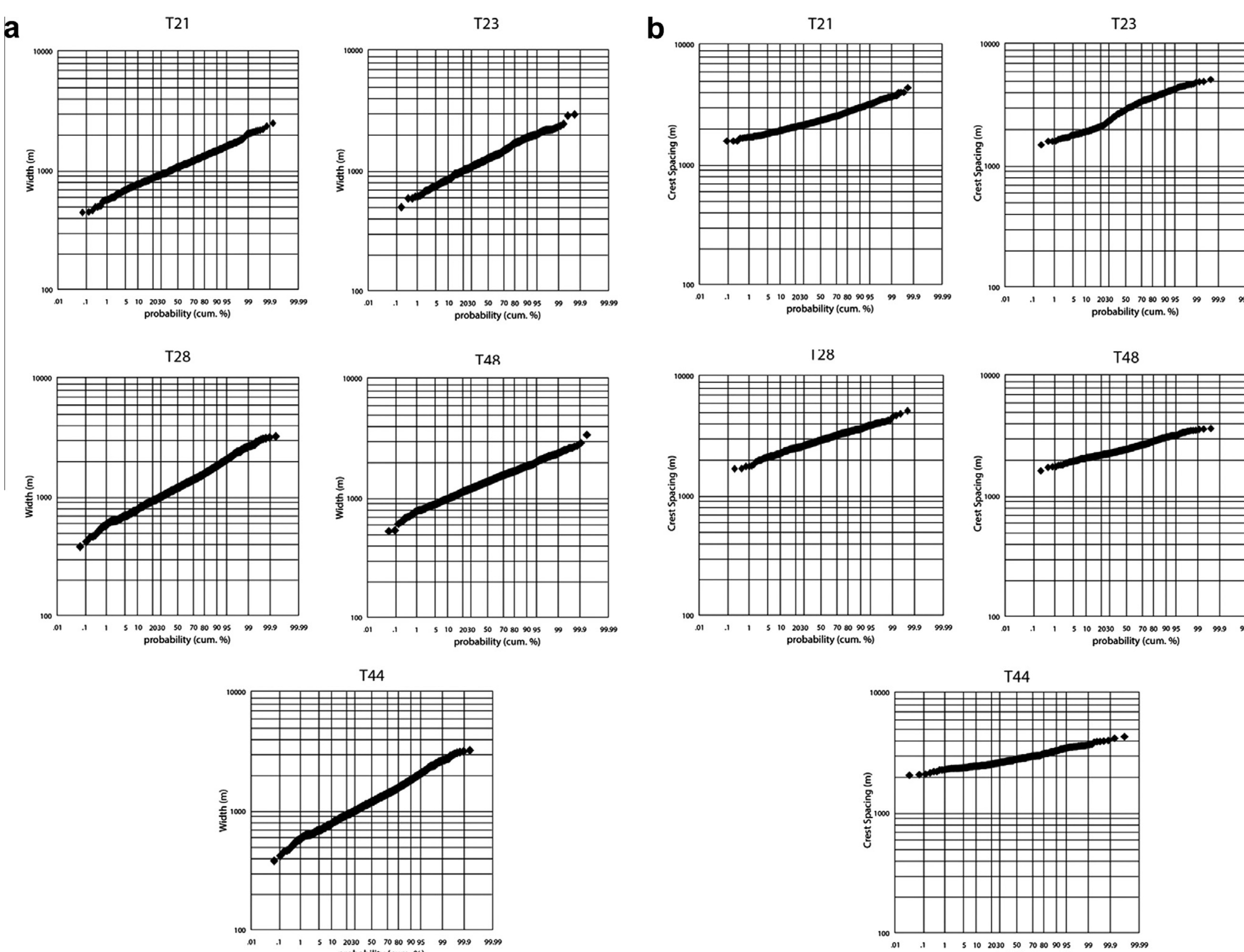

Fig. 10. (a) Cumulative probability of dune width for each of the study swaths. Each plot shows that the dunes measured for each swath belong to single populations. (b) Cumulative probability of dune crest spacing for each of the study swaths. Each plot shows that the dunes measured for each swath belong to single populations with the possible exception of T23.

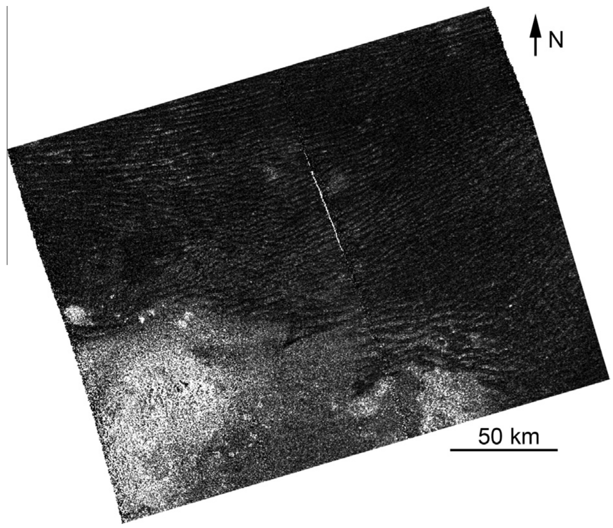

Fig. 11. Dunes in the T23 region have overlapping, or interfering, forms. These may be caused by wind disruption around the SAR-bright obstacle upwind, to the west. The deviated forms may have resulted in the kink seen in dune spacing in Fig. 10 for T23. Dune field at ~2°N and 350°W.

Table 2
Mean width and spacing for various terrestrial dune fields (from Breed and Grow, 1979; Lancaster, 1995).

Type	Location	Spacing (m)	Width (m)
Simple	Great Sandy Desert (Australia)	900	290
	Kalahari Desert (southern Africa)	700	290
	Navajo Reservation (northern Arizona)	150	43
	NE Rub' al Khali (Saudi Arabia)	1410	380
	Simpson Desert (Australia)	648	290
	Simpson Desert (Australia)	900	220
	SW Kalahari (southern Africa)	435	220
Compound	Namib (SW Africa)	1724	650
	S Sahara (Niger)	1900	1060
	SW Rub' al Khali (Saudi Arabia)	2180	1210
	SW Sahara (Mauritania – Agneitir)	1930	940
Complex	N Sahara (Algeria)	3240	1090
	Namib (SW Africa)	2163	880
	Namib (SW Africa)	2200	880
	Rub' al Khali (Saudi Arabia)	3170	1480
	S Sahara (Niger)	3280	1280
	W Rub' al Khali (Saudi Arabia)	3170	1480

as being older or having been present in the wind regime under which they grew for a longer period of time than smaller dunes (Warren and Allison, 1998; Bristow et al., 2007). Large, linear dunes can have construction times of several thousand to tens of thousands of years (Lancaster, 1988; Warren and Allison, 1998).

Dunes will seek a new equilibrium under changed wind conditions by either completely realigning themselves according to the mean wind direction or by forming superimposed dunes (e.g. Fig. 11), a process that tends to be faster than complete realignment (Ewing et al., 2006). Superimposed forms are useful in reconstructing the history of dune fields. Multiple sets of superimposed dunes can be taken as an indication of the minimum number of constructional episodes or, more specifically, significant changes in wind regime (Kocurek and Ewing, 2005; Ewing et al., 2006). That Titan's dunes have evolved toward large linear dunes, which lack evidence for intermediate-sized superimposed features indicates the presence of a consistent wind regime over long time scales.

The trend of decreasing width with latitude for Titan's dunes could in part be explained by the maturity of the dunes. Since dunes just south of the equator are larger and more widely spaced than their northern counterparts, it may be that these southern, low-latitude dunes have been evolving for a longer period of time under dune-favorable conditions. These conditions have gradually expanded over time so that higher northern latitude dunes are still evolving to their limiting sizes (see also Le Gall et al., 2011). Dunes across Titan reflect the steady state condition of ~3 km spacing as dictated by Titan's 3 km atmospheric boundary layer (Andreotti et al., 2009; Lorenz et al., 2010).

Le Gall et al. (2011) also suggest that the net transport of moisture from the south to the north discussed by Aharonson et al. (2009) is a possible explanation for the trend of decreasing dune width with latitude. Sediments farther north remain wetted for longer periods of time, reducing their mobility and effectively restricting sediment supply and, consequently, dune size (Kocurek, 1999; Kerr and Nigra, 1952; Le Gall et al., 2011).

Recent global circulation models indicate that the saltation threshold for Titan (~1 m/s; Lorenz et al., 2006) is only reached during a brief season every 14 Earth years, near the Titan equinox (most recently in 2009), when the zonal component of near-surface winds reverses briefly from westward to eastward during the passage of the intertropical convergence zone (ITCZ; Tokano, 2010; Lorenz, 2010). During the rest of the Titan year, eastward winds blow at around 0.5 m/s and westward winds remain near 0.2 m/s, as do any winds from other, variable directions. This leads to a dune condition likely dominated by depositional hiatus. New calculations based on the frequency of predicted wind velocities

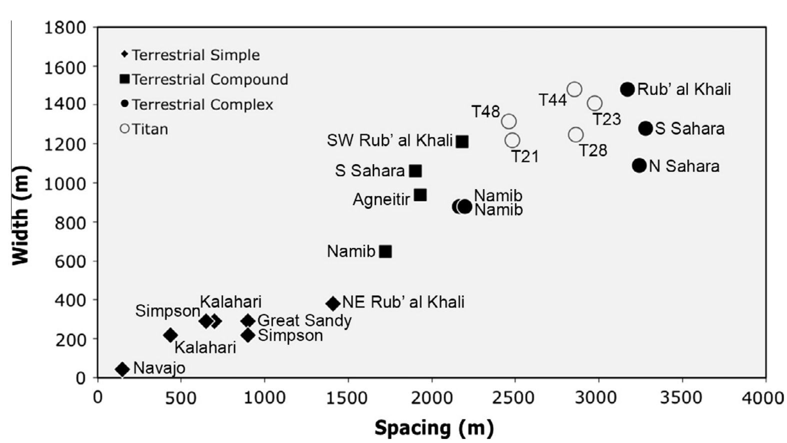

Fig. 12. Scatter diagram (similar to Lancaster, 2006) showing the correlation between mean dune crest spacing and mean dune width in relation to dune form for various linear dunes around the world and for each measured swath on Titan (data from Breed and Grow, 1979; Lancaster, 1995). Note that most of Titan's dunes plot in the upper right where terrestrial linear dunes are compound or complex.

needed to enact saltation among dune sands on Titan reveal rates of sand movement of 5 cm/Earth year, resulting in construction or reorientation times for Titan's dunes of 50,000 Earth years (Lorenz, 2012, 2014).

5. Implications of a single population of dunes on Titan

The cumulative probability plots of width and spacing of Titan's dunes indicate that, with some notable exceptions of superimposed or reoriented dunes (in isolated patches occupying less than 1% of the dune area, see Lorenz, 2014; Hayes et al., 2012), there is a single population of intermediate-to-large-sized dunes across the satellite. Thus, even if there have been previous dune-building events on Titan, perhaps under different wind conditions, the current dune-forming conditions have been present and uniform across the entire moon long enough to erase any evidence of previous periods at the scale of features visible to Cassini SAR.

On Earth, data from dune fields separated by long distances, and indeed even from within the same dune field, reveal several populations (as in the Namib and Agneitir). Cumulative probability plots of data from widely separated regions across Titan, with the exception of T23 dune spacings, show a single population. This is evidence that the conditions that led to the formation of the large, linear dunes were (or are) mostly uniform across Titan. A recent study of dune orientations (Lorenz and Radebaugh, 2009) supports this through demonstration that the vast majority of crest orientations, with the exception of those interacting with local topography, are aligned roughly parallel to the equator.

6. Conclusions

Parametric analysis of dune width and spacing on Titan constrains the effects of past and present conditions on dune formation and evolution. Linear dunes measured across five widely spaced regions on Titan have an average width of 1.3 km and an average crest spacing of 2.6 km, similar to values for large linear dunes on Earth. Based on their size alone, Titan's dunes are similar to terrestrial compound or complex dunes, which host multiple crestlines or superimposed or flanking dunes, but no such features are visible on Titan's dunes at the resolution of the available images. Rather, their morphologies are simple, similar to large linear dunes in the south-central Great Sand Sea of Egypt or the south-western Rub' al Khali.

Titan's dunes show characteristics indicative of being mature and long-lived, given their uniform morphology across Titan, their large widths and spacings and the general absence of abundant intermediate-sized flanking features. Since dunes are the result of interactions between the atmosphere and sediments, all of these attributes are evidence of long-term stability of the wind regime and/or growth of the dunes toward a steady state. The trend of decreasing spacing with increasing northern latitude may be the result of southern dunes having been stabilized by liquids or by being more mature.

Finally, it is compelling that given the current data, all dunes of intermediate-to-large size measured at different locations across Titan comprise a single population. This suggests that dune-forming conditions have been stable long enough to erase any evidence of past conditions. These studies of Titan's dunes also have implications for their sister features in Earth's large deserts, most of which have superimposed dunes. Such observations lend evidence to the idea that large terrestrial desert dunes may have actually formed under different conditions in the past and are now undergoing change.

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