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Linear Dune Morphometrics in Titan’s Belet Sand Sea

and a Comparison with the Namib Sand Sea

Robert Corbin Lewis

A thesis submitted to the faculty of Brigham Young University in partial fulfillment of the requirements for the degree of Master of Science

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ABSTRACT

Linear Dune Morphometrics in Titan’s Belet Sand Sea and a Comparison with the Namib Sand Sea

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Master of Science

Despite atmospheric and compositional differences on Titan and Earth, the similarity in the shape and spacing of linear dunes of the Belet Sand Sea of Titan and the Namib Sand Sea of Earth suggests that comparisons will yield a better understanding of the dictating factors of dune-forming processes. We present a methodology for the collection of dune width and spacing measurements representative of the Namib and Belet sand seas. 94,304 locations in Belet from Cassini SAR images and 5,563 locations in the Namib from IKONOS images are used for measurements. The average width and spacing of linear dunes in Belet are 1,235 m and 2,776 m, respectively, with a standard deviation of 422 and 859 respectively. In the Namib, the average linear dune width and spacing is 736 m and 2,203 m, with a standard deviation of 204 and 592. We also analyze these morphometrics according to potential dictating factors such as elevation and distance to sand sea margins. We establish significant trends according to distance to margin, which confirms that the largest and most widely spaced dunes are generally found in the center of the sand sea. We also observe increasing dune width with increasing elevation. The strongest trend we observe is distance to the western margin in the Namib Sand Sea. In Belet, none of these trends were found to be significant. Analysis of width vs. spacing is significant in both sand seas. The disparity in results of the two sand seas suggests factors such as age, sand sea size, or proximity to source may influence linear dune morphometrics.

Keywords: [Belet, Cassini, Linear Dunes, Namibia, Titan, RADAR]
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1 Introduction

In 2004, the Cassini spacecraft reached Saturn, providing new insights into the character of the planet and its satellites. One of the more surprising (Lorenz et al., 1995) finds was abundant sand dunes found across Titan’s equatorial regions (Fig.1; Barnes et al., 2008; Elachi et al., 2006; Lorenz et al., 2006; Radebaugh et al., 2008).

Figure 1. Global Map of Titan from Cassini Image Science Subsystem (ISS) data. The sand dunes and sand seas, appearing dark in ISS data, cover Titan’s entire equatorial region, with the exception of the Xanadu region. NASA/JPL-Caltech/Space Science Institute/USGS

Titan’s dunes are linear in form (Lorenz et al., 2006), which means they are long (often greater than 20 km), straight, parallel, and regularly spaced (Lancaster, 1995). Large linear dunes on Earth and Saturn’s moon Titan are strikingly similar in morphology, which has drawn increasing interest in the aeolian science community to the surface of Titan (Lorenz et al., 2006; Radebaugh et al., 2010; Telfer et al. in revision). However, there are still many unknowns about these aeolian features on both bodies. One major unknown about linear dunes in sand seas
includes the influence of elevation and proximity to the sand sea margin on dune forming processes. Some work has been done regarding the role of elevation in dune formation on Titan (Lorenz et al., 2013; Le Gall et al., 2012).

Titan’s dunes are collected together into regions determined to be sand seas (Lorenz et al., 2006; Radebaugh et al., 2010), which are enormous sedimentary bodies that consist of varied assemblages of depositional features. Little is known about the sources or movement of sand on Titan (Le Gall et al., 2012; Barnes et al., 2015; Malaska et al., 2015). Based on studies in the Namib Sand Sea of southwest Africa, sand seas that are minimally affected by external changes and have a single primary sediment source typically have well-organized dune patterns, allowing for morphologic changes to be primarily a result of regional wind regime changes (Lancaster, 1995). Therefore, comparing one of Titan’s sand seas, the Belet Sand Sea (Fig. 1; 2) to the Namib Sand Sea (Fig. 3) may illuminate our understanding of the nature of sources and transport of sand. This study aims to better identify shared dictating factors of the dune-forming processes that are independent of the different environments and conditions found on Earth and Titan.
Figure 2. The Belet Sand Sea of Titan. Belet is located along the equatorial belt of Titan’s trailing hemisphere at approximately 220° - 280° W longitude. Arnold (2014) determined the sand sea margin represented in green from ISS comparisons with SAR data. ISS background overlain with Synthetic Aperture Radar (SAR) and HiSAR (High-altitude SAR) through T92.
Figure 3. The Namib Sand Sea, SW Africa. It is bounded by the Kuiseb River to the north, the Great Escarpment elevational plateau to the east, and the Atlantic Ocean to the west. The Namib Sand Sea margin as we determined from the presence of large dunes is in purple. Image courtesy of Google Earth.
1.1 Titan Setting, Dunes and Sand Seas

Titan’s atmosphere is approximately 95% nitrogen, with the remainder methane and other hydrocarbons that prevent various wavelengths, including visible wavelengths, from reaching to or from the surface. Because of this, the Cassini orbiter had a RADAR instrument that operated in Synthetic Aperture RADAR (SAR) mode to obtain images of the surface (Elachi et al., 2004). Cassini SAR operated in the Ku band, with a wavelength of 2.17 cm), and obtained images with a resolution of ~350 meters per pixel near the center of each long image “swath” and at least 1 km near swath edges (West et al., 2009), sufficient to allow us to broadly view the geomorphology of Titan’s surface (Elachi, et al., 2004).

The landscape of Titan is of particular interest, given that Titan’s surface features are morphologically similar to those found on Earth. River systems carved into the surface transport liquid methane (Lorenz et al., 2008a) and methane and ethane-filled lakes dot the polar regions (Lorenz et al., 2006; Stofan et al., 2007; Aharonson et al., 2009). Cassini revealed plateaus and mountain belts that have undergone erosion by surficial fluids (Radebaugh et al., 2007; Mitri et al. 2010; Moore and Pappalardo, 2011; Liu et al. 2014; Radebaugh et al. 2016).

2.1.1 Linear dunes on Titan

A linear dune morphology dominates the dunes of Titan (Radebaugh, 2013). The majority of dunes observable at SAR resolutions are ~1 km wide, spaced 1-3 km apart, and tens to hundreds of km long (Lorenz et al., 2006; Radebaugh et al., 2008; Lorenz and Radebaugh, 2009; Savage et al., 2014; Fig. 4). The Cassini RADAR image resolution is considered to be ~350 m (each pixel is ~175 m across), equating to half of the smallest resolvable large linear dunes. The dunes are 100-150 m high as measured by radarclinometry, or slopes obtained from SAR brightness (Neish et al., 2010). Similarly, terrestrial linear dunes are 0.2-2 km wide, spaced
0.2-3 km, and are over tens of kilometers long (Lancaster, 1995). Small linear dunes, flanking
dunes or small domes or barchans are not visible at Cassini SAR resolutions, though moderate-
sized superimposed forms should be visible and are not present (Savage et al. 2014). More
sinuous linear dunes near the edges of sand seas may represent a change in sediment availability,
as in Australian dunes (Fitzsimmons, 2007; Radebaugh, 2013). Titan’s dunes are SAR-dark,
while the interdunes have a range of SAR brightnesses (Radebaugh et al. 2008). This is
comparable to how dunes appear in X-band (3 cm) SAR images in the large sand seas on Earth
(Lancaster, 1995; Rodriguez et al., 2014). The sand-sized particles absorb the SAR signal, and in
addition, the surface is smooth at the Cassini SAR wavelength, which means the dunes appear
SAR-dark. Dunes on Titan remain visually distinguishable from surrounding materials despite
SAR resolutions nearly at the limit of dune detection because of their contrast with surrounding
materials and because their linear form allows for sub-resolution identification (Elachi et al.,
2006; Lorenz et al., 2006; Radebaugh et al. 2010; Savage et al. 2014).
Figure 4. Linear dunes of the Namib and Titan's Belet Sand Sea. The bright patches in the Belet image are relatively sand poor topographic highs that act as obstacles in the sand sea. In the Namib image we notice arcuate crestlines but an overall straightness in the linear dunes. The Belet image (Top) is SAR data collected by Cassini. (Bottom) Image credit Esri, Digital Globe, GeoEye, Earthstar Geographics, CNES-
The presence of dunes suggests one or more processes have acted on the surface of Titan for a long enough period to produce thousands of morphologically consistent, mature landforms (Radebaugh, 2013). There are sediment sources, areas of collection or deposition, and winds strong enough to entrain sand-sized particles (Le Gall et al., 2011; Lorenz et al., 2006; Lorenz et al., 2008; Radebaugh et al., 2008; Radebaugh et al., 2010; Reffet et al., 2010). Proposed dune-forming wind regimes include an obtuse bimodal wind regime with noncohesive sediment (Tsoar 1985; Tokano, 2008), a unidirectional wind regime with noncohesive (Radebaugh et al., 2008) and cohesive (Rubin and Hesp, 2009) sediment, and dominant, slightly off-axis winds mingled with minor shepherding winds to cause down-axis transport, known as the fingering mode growth mechanism (Courrech du Pont et al., 2014; Lucas et al., 2015). These finger-like structures extend in the direction of the resultant sediment flux, when there is limited sediment supply and the dunes propagate across a nonerodible bed (Courrech du Pont et al., 2014; Lucas et al. 2015).

Dune morphologies and terminations around topographic obstacles reflect an eastward propagation (Lorenz et al., 2006; Radebaugh et al. 2010), while global circulation models predict eolian transport should be to the west (Tokano, 2008). However, other models predict that gusts moving eastward occurring during the equinox and storms may be strong enough to accomplish much of the sediment transport (Tokano, 2010; Charnay et al., 2013). Thus, based on global climate models of Titan and the morphology of dunes adjacent to topographic obstacles, or inselbergs, it is concluded that sediment transport occurs from the west to the east (Radebaugh et al., 2008; Tokano, 2010; Charnay et al. 2013; Lucas et al. 2014).

The dune material on Titan differs greatly from that of Earth. Most of the sand on Earth is
composed of quartz that is primarily sourced by the erosion of quartz-rich igneous and metamorphic rock and recycled from older sedimentary rocks (Bagnold 1941; Lorenz and Zimbelman, 2014; Barnes et al. 2015). Because terrestrial sands are composed of a major mineral in Earth’s continental crust, it was expected that Titan’s sands, like Titan’s crust, would be largely composed of water ice (Lorenz et al., 1995; Lorenz and Mitton, 2002). However, the dunes are dark in Imaging Science Subsystems (ISS) and brown in Visual and Infrared Mapping Spectrometer (VIMS), suggesting the composition is water ice-poor (Soderblom et al., 2007). Dune sand on Titan appears to originate in the atmosphere as hydrocarbon polymers (Jaumann et al., 2009; Soderblom et al. 2007) that then rain, snow, or fall down to the surface. Just how the particles then become sand-sized and ready for saltation is not yet known. One theory requires sintering, or vapor phase transport to lead to particle growth, which, because sand-free interdunes suggest the dunes are still active (Barnes et al., 2008), needs to be countered by physical abrasion or erosion to keep particles in a saltatable size range (Barnes et al., 2015). Another theory requires the haze particles to be fluvially transported and deposited in lakes or deltas where they are eventually buried, lithified, and later eroded (Barnes et al. 2015). This theory requires Titan to have a structurally complex subsurface and sufficient geologic time to exhume and erode the material. If the source were evaporites, like the dunes in White Sands, New Mexico, then the sand would be produced from discrete evaporitic lakebed sources (Barnes et al., 2015). However, if the haze material makes up a considerable portion of the crust, then fluvial erosion could produce sand particles without a discrete source (Barnes et al., 2015). Another model calls for the haze materials to be regionally or globally deposited into sedimentary layers, and then eroded into different particle sizes and transported by aeolian and fluvial processes (Radebaugh, 2013; Barnes et al. 2015).
2.1.2 Sand Seas

Sand seas are found on all solid surface planetary bodies with significant atmospheres. Strong, global atmospheric and surface processes form sand seas, which are dynamic sedimentary bodies (Lancaster, 1995). They are part of sand transport systems that move wind-carried particles from source areas to depositional sinks, where wind energy available to transport sand greatly decreases (Lancaster, 1995; Ritter et al., 2011). Sand seas contain an enormous volume of sand and consist of varied assemblages of depositional features including complex dune fields, sand sheets, and interdune zones (Wilson, 1971; Lancaster, 1995; Ritter et al., 2011). The accumulation and development of sand seas are controlled by sediment supply, wind transport capacity, and wind regime. These variables are determined by tectonics, climate, and sea level change (Kocurek and Lancaster, 1999; Lancaster, 1999). The character of the sand distribution and the features in sand seas that accumulate over thousands, perhaps millions (Barnes et al., 2015), of years is influenced by climatic cycles (Holliday 1989a, 1989b; Blount and Lancaster, 1990; Forman et al., 1992; Lancaster, 1999).

Sand seas may accumulate where sand transport from all directions converges, sand transport from two opposite directions converge, or where transport pathways cross the sand sea and local convergence and deceleration of the wind allows for deposition (Wilson, 1971). Sand seas have mostly accumulated in tectonically stable desert regions like the Sahara, Arabian Peninsula, Australia, and southern Africa and the enclosed basins of central Asia (Wilson 1971; Lancaster, 1995). Wind data and satellite imagery indicate that the deposition of sand and the accumulation of sand seas occurs downwind of the sediment source where sand transport rates are reduced due to changes in climate or topography (Wilson 1971; Fryberger and Ahlbrandt,
1979; Lancaster, 1995). The Sahara, Arabian Peninsula, Mojave, and Namib deserts all exemplify long-distance wind transport of sand (Lancaster and Ollier, 1983; Mainguet and Chemin, 1983; Fryberger et al., 1984; Zimbelman and Williams, 1990), while local sources appear to feed Australian sand seas and many North American dune fields (Norris and Norris, 1961; Sharp, 1966; Wasson et al., 1988; Blount and Lancaster, 1990). Some sand seas accumulate in the lee of obstacles due to the convergence of sand transport pathways while other sand seas form on the upwind side of topographic obstacles when the obstacle checks the wind (Lancaster, 1995). Regional wind changes, such as decreased wind speeds and increased directional variability, can result in reduced sand transport rates (Lancaster, 1995). The Namib Sand Sea accumulated due to both regional decreases in wind energy and an increase in directional variability (Lancaster, 1985). Sand is transported from areas of low directional variability and high wind energy, the southern and western coastal areas, to depositional areas of higher directional variability and lower wind energy in the northern and eastern parts of the sand sea (Lancaster, 1989; 1995).

Within sand seas, dune patterns such as spatial variations in dune size, spacing and orientation are the surface expressions of factors that control the accumulation of sand and dune-forming dynamics (Lancaster, 1995). Distinct spatial patterns of dune type, size, spacing, and sediment thickness manifest in many sand seas reveal the factors that have affected sediment accumulation (Breed et al., 1979; Porter 1986; Ewing et al. 2006). Topographic obstacles or regional topography may play a role in dune formation, but regional patterns of dune-forming winds appear to be the primary factor influencing occurrence, size, and morphology of sand seas (Fryberger and Ahlbrandt, 1979; Mainguet, 1978; Wilson, 1971).
2.1.3 Sand Seas of Titan

Dune sands on Titan are found in sand seas that cover 17.5 ± 1.5% of Titan’s surface area or 14.6 ± 1.2 million km² (Rodriguez et al., 2014). Dunes cover close to 13% of the surface (Lorenz et al. 2006; Arnold 2014) and form a greater fractional area on Titan than on any other planetary body (Lorenz, 2014; Zimbelman et al., 2013). On Earth, dunes only cover up to 4% of the surface (Lancaster, 1995; Bourke et al., 2010). The largest sand sea on Earth, the Rub’ al Khali, covers an area of ~560,000 km² (Wilson, 1973), similar in size to ~17% of the Belet Sand Sea, one of five major sand seas on Titan (Le Gall et al. 2012).

On Titan, sand seas are concentrated in the equatorial belt between 30°N and 30°S, except for the Xanadu region, which does not appear to have significant thicknesses of sand or dunes (Radebaugh et al. 2011). The locations of Titan’s sand seas are likely determined in part by the circulation of Titan’s atmosphere and consequent climate. General atmospheric circulation models and data from the Huygens probe indicate the presence of a global Hadley circulation cell that moves warm atmospheric gases back and forth from the southern pole to the northern pole, changing directions with the seasons (Lorenz, 2007; Tokano, 2007). Additionally, modeling of the Hadley circulation on Titan explains the removal of humidity from the equator (Mitchell, 2008). Deserts and sand seas on Earth vary in position latitudinally much more because of a more complex atmospheric Hadley circulation.

The Belet Sand Sea, located between 30°N and 30°S longitude, is approximately 3.3 ± 0.6 million km², equivalent to ~6 Rub’ al Khali Sand Seas (Arnold, 2014). Cassini SAR swaths T8, T21, T49, T61, T91 and T92 cover the region that contains the Belet Sand Sea, to ~60% coverage (Fig. 2; Le Gall et al. 2011; Radebaugh, 2013). Titan’s dune field extents were first mapped based on Cassini VIMS (Visual and Infrared Mapping Spectrometer) data (Rodriguez et
al., 2014), which covers the entire equatorial belt with an average spatial resolution of ~15 km
(Le Mouélic et al., 2012). Rodriguez et al. (2014) based the dune field extents on the Cassini
VIMS “dark brown” unit, accounting for 72% of Cassini SAR-imaged dunes (Rodriguez et al.,
2014). In addition to Cassini SAR data and Cassini VIMS, Cassini ISS (Imaging Science
Subsystem) visible to near-infrared data was used to establish sand sea margins because ISS data
provide 100% coverage at observable dune latitudes (Arnold, 2014).

1.2 Namib Desert Setting, Dunes and Sand Sea

The Namib Sand Sea reaches south to the town of Luderitz, to the Kuiseb River to the
north, to the Atlantic Ocean to west, and to the Great Escarpment to the east (Fig. 3; Goudie,
1972; Lancaster, 1989). The Namib Sand Sea is located in an area of relative tectonic stability,
resting on erosional surfaces consisting of schists, quartzites, and granites (Breed et al., 1979;
Lancaster, 1989). Multiple dune types, including barchans, crescentic dunes, star dunes and
transverse dunes, are found in the Namib Sand Sea, but large linear dunes that roughly trend
north-south dominate the region (Besler, 1980; Breed et al., 1979; Ewing, et al., 2006; Lancaster,
1989; Livingstone et al., 2010; Livingstone, 2013). Despite compositional and climatic
differences, the Namib Sand Sea is a good analog for the Belet Sand Sea (Lorenz et al., 2006;
Neish et al., 2010) because the general morphology of their dunes indicates the presence of
commonalities in conditions such as wind regime.

1.2.1 Linear Dunes of the Namib

Linear dunes are often divided into the morphological subcategories of simple linear,
compound linear or linear dunes with superimposed linear dunes (Mainguet and Callot, 1978;
Lancaster, 1983b), large complex linear (50-150 m high; Holm 1960; Lancaster, 1983b), and
wide (1-2 km) complex linear with superimposed crescentic dunes on their crests, the latter three being classes that are found in the Namib Sand Sea (Lancaster 1983b). Typical complex linear dunes (linear dunes with different superimposed dunes) found in the Namib have a spacing of ~2,000 m and a migration rate of 0.05 m/yr in the azimuth direction of ~25° (Lancaster, 1995).

One theory for the development of compound and complex dunes suggests that dune development occurs in response to temporal changes in flow conditions (Allen, 1968; 1984). It is suggested for dune areas in the Namib that compound and complex dunes formed as a product of Quaternary climatic changes, the large dunes forming during times of strong wind conditions during Pleistocene glacial periods and that weaker modern winds form the smaller, superimposed dunes (Glennie, 1970; Besler, 1980). An alternative theory suggests that two or more scales of bedforms can coexist in equilibrium when steady flow conditions are present (Smith and McLean, 1977; Rubin and McCulloch, 1980; Courrech du Pont et al. 2014). Superimposed bedforms being the product of contemporaneous eolian environments is supported by the prevalence of compound dunes in active modern sand seas and the rock record (Lancaster, 1995). In areas of compound crescentic and linear dunes in the Namib Sand Sea, there is a strong correlation between the mean spacing of superimposed dunes and the large, underlying dune they are on. However, no such relationship exists for the superimposed forms on complex linear and star dunes (Lancaster, 1988). In this case of compound dunes, this means that superimposed dunes scale with major dunes (Lancaster, 1995).

The size of compound and complex linear dunes is not thought to be a direct function of grain size (Lancaster, 1988), as was previously suggested (Wilson, 1972); rather, it is the result of long-continued growth in systemic conditions associated with abundant sand supply and under atmospheric boundary layer thickness constraints (Lancaster, 1995; Andreotti et al. 2009).
Compound and complex dunes experience little influence from seasonal or longer-term changes in local wind conditions and can persist for 1 to 100 ka (Lancaster, 1995).

1.2.2 Namib Sand Source and Movement

The presence of differently colored sands in the Namib Sand Sea led to the development of several hypotheses regarding their origin. These included variables such as weathering duration and variability, dune activity, and the possibility of multiple sources (Besler, 1996; Livingstone, 2013; White et al., 2007). Besler believed that three sources – coastal sands, fluvial sands eroded from the Great Escarpment, and sands from the underlying Tsondab sandstone that largely formed during the Miocene – provided the sand for the Namib Sand Sea (Besler, 1996). In contrast, White et al. (2007) only found two sand sources, represented by western coastal and eastern Escarpment sand that mixed in the middle (Livingstone, 2013). White et al. (2007) focused on the presence and nature of an Fe-oxide coating on the grains and the resultant color. Basing classification on color did not reveal influence from the fluvial source discussed in other studies. Another hypothesis suggests the Orange River is the sole sediment source of the Namib Sand Sea (Ewing et al., 2006; Lancaster, 1989). Longshore drift and SSW and SW winds deliver the source sediment (Ewing et al., 2006).

1.2.3 Namib Wind Regime

Some of the most complex and spatially variable terrestrial dune patterns are found in the Namib Sand Sea (Ewing et al., 2006). Although studies of the Namib disagree over dune classifications and the boundaries, there is a gross distribution of varying dune forms, namely transverse dunes to the west, linear dunes in the central belt, and star dunes to the east, that has been attributed to the wind regime rather than sediment sources (Lancaster, 1985; Lancaster,
The coastal transverse dunes are influenced by a strongly unimodal south-westerly wind regime; the influence of these winds is also observed north of the Namib in the dunes of the Skeleton Coast and south of the Namib in the coastal dunes on the west coast of South Africa. These features are also under the influence of a thinner, coastal atmospheric boundary layer, which would affect their size (Andreotti et al. 2009).

Onshore SSW and SW winds and N and NNW plain-mountain winds contribute to the majority of eolian sand transport, which occurs during the summer; additional transport occurs during the winter due to E and ENE mountain-plain wind and southerly winds (Lancaster, 1989). The three elongate zones of dunes, differentiated by morphology, run north-south. According to Breed and Grow (1979), complex transverse dunes in the western belt range 0.3-1.3 km in length and range 0.2-1.9 km in spacing, from Landsat images. The linear dunes found in the central belt average 0.88 km in width, 2.2 km in wavelength (crest-to-crest distance) and 27 km in length. Fields of star dunes, reversing dunes, and complex dunes occur in the eastern belt; complex dunes are described as two different dune types that are superimposed or merged (Lancaster, 1995). The star dunes have a mean diameter of 0.7 km and average spacing of 2.2 km (Breed et al., 1979; Breed and Grow, 1979). According to terminology established by McKee (1979), the linear dunes superimposed by other linear dunes are called compound linear dunes. However, the far more common type of linear dune found in the Namib is the complex linear dune, which is a linear dune superimposed by other, smaller dunes. (Lancaster 1989; Livingstone, 2013). The linear dunes in the center of the northern region of the Namib are predominantly complex (Besler, 1980; Breed et al., 1979; Lancaster, 1989; Livingstone et al. 2010). The linear dunes in the center of the southern region are predominantly compound (Breed et al., 1979; Lancaster, 1989; Livingstone et al., 2010) or transitional forms and longitudinal ridges (Besler, 1980).
Due to a decrease in wind energy inland from the coast, the coastal crescentic dunes are more active than the inland linear and star dunes (Breed, 1979). The coastal dunes are also smaller and therefore move more quickly. Wind energy and sand transport rates experience a general decrease from south to north and west to east, resulting in deposition and accumulation in the northern and central parts of the Namib Sand Sea (Lancaster, 1985). In most of the central parts of the Namib Sand Sea, the equivalent sand thickness is greater than 20 meters and exceeds 30 meters north and northwest of Sossus Vlei. Equivalent Sand Thickness, the measure of sand thickness if it was evenly distributed in a given area, is a measure of the volume of sand contained in the dunes (Rubin, 1984).

1.3 Previous Work - Dune Pattern Analysis and Distributions

The spacing and morphology of dunes reflect sand supply and wind conditions prevalent in the region (Wilson, 1973; Lancaster, 1995). Previous studies of dune width and spacing trends, known as pattern analysis, have provided insights into dune-forming conditions on Earth (Ewing et al., 2006; Lancaster, 1988), Mars (Ewing et al. 2010) and Titan (Savage et al., 2014). The similarity in the shapes and spatial trends of linear dunes on Earth and Titan suggests that the comparative analysis of dunes on both bodies will shed light on the wind and sediment supply necessary to form linear dunes as well as the roles of elevation and distance to the sand sea margin in the dune-forming process.

The Namib is considered a prime example for explaining the relationship of dune patterns to driving variables such as climate (Livingstone, 2013). Patterns in dune morphology, sand thickness, and sediment characteristics suggest the Namib Sand Sea is a single, integrated depositional system (Lancaster, 1995).
Titan’s dunes, while largely confined to the tropics, exhibit a latitudinal trend overall in their morphometric parameters (Le Gall et al., 2011). A previous analysis of dune width and spacing over randomly distributed regions in the sand seas revealed that dune width and crest spacing decrease with increasing latitude (Le Gall et al. 2012; Savage et al. 2014). Dunes tend to have greater spacing, smaller widths, or both in elevated terrains and at higher northern latitudes; additionally, there is less sand cover in the interdune areas (Le Gall et al., 2012).

In general, Titan dune fields tend to be located in the relatively low portions of the regionally high-elevation equatorial belt; ~70% of the observed dune regions that could be correlated with the available SARTopo data, which are elevation profiles along Cassini SAR swaths consisting of estimated surface heights generated through the comparison of overlapping antenna beams, are found below -115 m elevation (Le Gall et al., 2012). Titan’s dune fields are not found where the rate of erosion by aeolian or fluvial processes exceeds the rate of sedimentation, as occurs in the most elevated areas (Le Gall et al., 2012; Turtle et al., 2011).

Le Gall et al. (2012) examined the regional differences of Titan’s dune fields and determined that processes that limit the sand supply, transport capacity or sand availability of Titan’s sand seas do not vary much between the various sand seas, suggesting the sand seas are similar in age. Similarly, a global dune pattern analysis study also suggests the dunes have a similar formation period (Savage et al. 2014).

2 Methodology and Procedures

We collected measurements of dune width and spacing to determine sediment transport and deposition trends from the Belet and Namib Sand Seas. We compared these measurements with maps of underlying elevation and other factors, such as distance from the sand sea margin.
2.1 Dune Width and Spacing Measurements

Measurements of Titan’s dunes made previously were obtained using the U.S. Geological Survey’s Imaging Software for Imagers and Spectrometers (ISIS; Savage et al., 2014). Using ESRI’s ArcMap 10.3 and Cassini SAR data, we developed a new system for measurement of width and spacing across the sand seas. This represented a general improvement over the previous method, which only allowed for collection of one measurement at a time and did not retain a line trace. Our method allows for the collection of large amounts of data, strong spatial correlation across the data and with other datasets across the sand seas, and retention of the line traces as shapefiles.

![Figure 5](image)

Figure 5. Measurement Method Diagram. The dark and light features are dunes and interdunes, respectively. Measurements were made by manually tracing along the dune-interdune boundaries. The automated process included partitioning the lines into 500 m segments and placing a point at the center of each point.

The lines were traced by hand along dark and bright SAR boundaries, representing the dune and interdune boundary (Fig. 5). The remainder of the steps were automated using a Python script that prepares the data for correlation. The automation includes segmenting the traced dune-interdune margins into 500 m intervals, representing each segment with a central point, and
performing a near-distance analysis for each point to the nearest point of an adjacent polyline for width, or to the corresponding margin of an adjacent dune for spacing.

These data were then used to perform near distance analysis in relation to the sand sea margin and correlation with elevation data from the global topography map (Corlies et al. 2017). This new method produced a more representative data set of over 90,000 data points dispersed throughout the Belet region (Fig. 6) and over 5,000 data points in the Namib sand sea (Fig. 7). These measurements represent nearly every possible measured dune in each sand sea (the dunes in Belet being measured only in SAR swath data (Fig. 6). Dunes were not measured in Belet where the dune/interdune boundary was not clear or in the Namib where the dunes were sinuous to the point of not being parallel, and thus not able to generate clear width and spacing (Fig. 7).

Figure 6. Belet Sand Sea Measurements overlain on Fig. 2. Locations of the measurements are indicated in blue with the symbols much larger than the individual measurements. 94,304 measurements were collected throughout the sand sea.
Figure 7. Namib Sand Sea Measurements. The dark lines within the sand sea indicate locations of measurements. Image credit Esri, Digital Globe, GeoEye, Earthstar Geographics, CNES-Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.
For the Namib Sand Sea, satellite images were used in the visual wavelengths (0.445-0.853 micrometers) from the IKONOS satellite, with a resolution of 1 meter panchromatic and 4 meters multispectral (Sefercik and Ozendi, 2013). The resolution of these images is significantly better than the Titan data used, so we could have used the crests of dunes, rather than the dune-interdune margins, to measure spacing. However, the crests of the dunes are far more sinuous than the dune-interdune margins and cause a greater variation in the parametric analyses than intended. For this reason, and to remain consistent in the measurement technique across both bodies, dune-interdune margins were used to obtain spacing instead of dune crests in the Namib.
Sand Sea (Fig. 7).

Figure 8. Namib Measurement Groups. Each point represents the central point of 500 m segments of the dune traces. Both groups are representative of the groups of measurements throughout the Namib and Belet sand seas. Image credit Esri, Digital Globe, GeoEye, Earthstar Geographics, CNES-Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

2.1.1 Details of Python Script

Python was used to automate the calculation of dune width and spacing from ArcGIS measurements. The dune-interdune boundaries were traced by hand, saved as individual polylines, and organized within ascending group folders beginning with ten. For example, the Group_10 folder is the first group and contains six polylines (three dunes) to ten polylines (five dunes). The Group_10 folder is followed by the Group_11 folder that contains six to ten
polylines. The python script selects the polylines within the group folders, cycling through each line pair to generate dune width and spacing and other associated inputs including location and elevation. The script performed eight distinct functions for each group folder. Additionally, the projected coordinate system was redefined as the geographic coordinate system in order to obtain the associated location in decimal degrees for each point.

A primary purpose of the script is obtaining dune width and spacing in a mostly automated manner. This is calculated using the Near (Analyst) tool in ArcGIS. After dividing the hand-drawn polylines into 500 m increments, the script loops through the point shape files, organizing them into pairs. For example, a width pairing (i, i+1) may have the Near tool input of point shapefile “Line_10” and the near feature of Point shapefile “Line_11”. A spacing pairing (i, i+2) may have the Near tool input of point shapefile “Line_10” and the near feature is the point shapefile “Line_12”. The object IDs of the closest near feature associated with the input are recorded in the attribute table as the NEAR_FID. The dune width, spacing, and FIDs are also stored in their respective attribute tables. Odd numbered line pairs represent dune widths and even numbered line pairs represent interdune widths. A separate list is created to which the interdune widths are assigned, effectively separating the dune widths from the interdune widths. The two groups are then merged into two distinct feature classes associated with a particular dataset.

The traced lines often vary in length, resulting in the pairing of multiple points along the near feature to a single point along the Near tool input. This results in the generation of incorrect data. This occurrence manifests in the attribute table as a repeating NEAR_FID. The script identifies attributes that have three or more repeating NEAR_FID and saves the first two data points while reassigning the remaining points as null values. To help mitigate against the
generation of spurious data, we try to make all the polylines within a group similar in length, beginning and ending at similar locations. Most data points have both a width and a spacing value.

2.2 Elevation Data

A topographic map for Titan (Fig. 9) was developed, in its most recent form, by Corlies et al. (2017), building on work by Lorenz et al. (2013). This used multiple datasets from Cassini including RADAR altimetry (Zebker et al., 2008; 2009), radarclinometry or shape-from-shading (Lorenz et al., 2006; Radebaugh et al., 2007; Neish et al., 2010), radargrammetric analysis of stereo image pairs (Kirk et al., 2013; Elachi et al., 2006), and SARtopo, which uses overlapping beam patterns in individual Cassini SAR images to determine relief (Stiles et al., 2009).

Figure 9 Global topographic map of Titan generated from SARTopo and altimetry data. The margin of the Belet Sand Sea is outlined in black and generally occupies a low between two regional highs (Corlies et al. 2017).


Topography Mission) that used a modified SAR system on board the Space Shuttle Endeavour with a resolution of ~90 m (Fig. 10).

2.3 Extent of the Sand Seas

Arnold (2014) used Cassini ISS data in conjunction with Cassini SAR data to establish polygons representative of sand sea margins for each of Titan’s equatorial sand seas (Fig. 2). Using Cassini SAR data, Arnold drew polygons around locations that contained linear dunes. After superimposing the polygons on the ISS mosaic, Arnold was able to determine the ISS data values that represent dune material, even though individual dunes were not able to be resolved in lower-resolution (<1 to ~10 km/pixel) ISS data. Using those ISS values, the dune field polygons were carefully extended into regions where only ISS coverage is available. Correlation of the Cassini SAR and ISS data indicates that ISS brightness values lower than ~115, on a scale of 0 to 255, correspond with dune areas. Because of varying solar illumination of the surface and differences among sand seas, ISS values correlating to dune material vary somewhat for each sand sea (Arnold, 2014). This value was chosen to be a conservative estimate, so that some regions brighter than the threshold may still contain smaller dune forms such as barchans, domes or transverse dunes that are not visible to Cassini SAR. This approach results in what is believed to be an underestimation of the total area of the sand sea, as indicated in the total sand sea coverage from this method of 15.4%, compared with the values for sand coverage obtained from VIMS data of 17.5% (Arnold, 2014; Rodriguez et al. 2014).

Determining the sand sea margin of the Namib was far simpler than for the Belet Sand Sea because of the availability of high-resolution, visual wavelength satellite imagery (Fig. 7). The sand sea margin was determined by the presence of dunes, (primarily linear and transverse) and clear delineations between sandy material and the underlying substrate. Furthermore, much
of the sand sea margin is clearly established by coastal boundaries to the west and a river channel to the north. Mountains largely influence the eastern boundary.

2.4. Statistical Analysis Methods

Using the Titan and Namib dune data sets, we examined width and spacing trends in relation to regional elevation and distance from the sand sea margin. The two data sets were analyzed using a multiple spatial regression model, which accounts for the correlation between observations that are geographically close. A regression is a statistical method that is used to examine the relationship between one or more independent variables (e.g., elevation, distance from the sand sea margin, latitude, longitude) and a dependent variable (width, spacing), and that allows for the determination of the strength and direction (positive, negative, zero) of the relationship. The independence of variables is a necessary regression assumption. If the error term, or unexplained variation from the trend, contains spatial dependencies, the model will inaccurately represent the relationships between the independent variable(s) and the dependent variable (Cressie, 1993; Bailey and Gatrell, 1995). Spatial dependence occurs when there is a spatial pattern in values within a geographical area. By accounting for spatial dependence, a spatial regression model is able to reveal the actual influence of the independent variables on the dependent variable. The spatial regression model accounts for spatial dependence by estimating the correlation between each pair of points based on the (Euclidean) distance of the points. The model then accounts for spatial correlation by building the spatial errors as a part of the model so that any “leftover” error actually satisfies the independence assumption (Cressie, 1993; Bailey and Gatrell, 1995).
The $r^2$ values were calculated using linear regressions, and they establish how much of the variability in the dependent variable is explained by the regression model with the independent variables. The smaller the $r^2$, the more unexplained variation in the dependent variable and the less predictive power the trend offers. Relative significance between datasets can be ascertained by the comparing of $r^2$ values. The higher the $r^2$ value, the better the model explains the observed data.

The p-values were calculated using a multiple spatial regression model in R version 3.4.2 (using the package “nlme”). The p-value threshold was set at 0.01. The p-values are the probability of observing the trend in the data under the assumption that there is no relationship between the dependent and independent variable. Small p-values indicate that the probability of observing a trend just by chance, if there was in fact no relationship, is very small. Therefore, when the p-value is smaller than the set threshold, we say that the observed trend is not likely to have occurred by chance if there is no relationship, and therefore there is likely a significant relationship.

2.5 Challenges and Limitations

Because of the different attributes of the imagery used for measurement on Earth and Titan, challenges exist to produce comparable datasets. Gaps in swath coverage of Titan’s surface prevent a complete view of Belet. However, working within the confines of the swaths, we have attempted to obtain a representative data set of widths, spacing, and elevation. Differences in resolution create difficulty in comparing data sets of Earth and Titan. Earth images, with a resolution of 1 meter (Esri, 2016; Sefercik, 2013), allow for more accurate measurements than SAR images of Titan, ~350 meters (Elachi et al., 2004). In an attempt to
mitigate this problem, we have maintained a consistent methodology in producing the two datasets. Additionally, the higher resolution data present the issue of sometimes having too much information and having to decide how to separate flanking and superimposed dunes from the dominant, larger linear dune form. To account for this, we measured the dunes at a display scale of 1:250,000.

3 Results

We collected 94,304 width and 78,072 spacing measurements throughout the Belet Sand Sea representative of its linear dunes. We collected 5,563 width and 4,025 spacing measurements in the Namib Sand Sea. Namib measurements are primarily located in the central north-south belt, representative of compound (south) and complex (north) linear dunes but also include dunes in the eastern belt, representative of anastomosing linear dunes. The Belet dunes have an average width and spacing of 1235 m and 2776 m (Fig. 11A; B) and the dunes of the Namib have mean width and spacing of 736 m and 2203 m (Fig. 12A; B). The standard deviations for width and spacing in Belet are 422.1 m and 859.1 m, respectively. The standard deviations for width and spacing in the Namib are 203.9 m and 591.9 m, respectively (Table 1). The average width and spacing of linear dunes in Belet are ~500 m larger than those in the Namib (Fig. 11; 12). The normal quantile plots demonstrate that the distributions of width and spacing in the Belet and Namib sand seas are not normal. The non-normal distributions are likely due to multiple dune populations being found within the sand seas.
Figure 11. Width (A) and spacing (B) distributions in the Belet Sand seas. (Top) The Belet dunes have average width and spacing of 1235 m and 2776 m (Top). For the box and whisker plots, the box is bounded by 75% with the center line being the median and the floating line being the mean. The ticks mark 90%, 97.5%, 99%, and 100%. The Normal Quantile plots test for normalcy. A normal distribution follows the diagonal line. A non-normal distribution suggests multiple populations.
Figure 12. Width (A) and spacing (B) distributions in the Namib Sand Sea. The dunes of the Namib Sand Sea have mean width and spacing of 736 m and 2203 m. For the box and whisker plots, the box is bounded by 75% with the center line being the median and the floating line being the mean. The ticks
mark 90%, 97.5%, 99%, and 100%. The Normal Quantile plots test for normalcy. A normal distribution follows the diagonal line. A non-normal distribution suggests multiple populations.

Table 1. Width and Spacing Distributions of the Belet and Namib sand seas.

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<th>Namib</th>
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Table 2. Regressions of the Belet and Namib sand seas.
We examined the width and spacing trends of linear sand dunes in relation to distance to the nearest sand sea margin. In Belet, there are weak trends in width ($r^2 = 0.0052$) and spacing ($r^2 = 0.0030$) with distance from any margin. The width increases ~30 m and spacing decreases ~40 m for every 100 km increase in distance from the nearest margin, which indicates an overall increase in sand density towards the middle. The graphs visually suggest a trend; however, these trends are not of statistical significance, with p-values of 0.2968 for width and 0.4752 for spacing. In the Namib Sand Sea, there are also trends in width ($r^2 = 0.0172$) and spacing ($r^2 = 0.0610$) with distance from any margin (Fig. 7; 13). The width increases ~220 m and the spacing increases ~1200 m for every 100 km increase in distance from the nearest margin. In contrast with the titanian data, p-values of 0.005 for width and <0.001 for spacing indicate that these trends are significant.
Figure 13. Dune width and spacing according to distance from the sand sea margin. The plots are contoured by 10% quantiles. The clumping of Belet data is likely due to being restricted to measuring on the swaths. A) In Belet, for every 100 km increase in distance from margin dune width increases ~30 m. B) In Belet, for every 100 km increase in distance from margin dune spacing decreases ~40 m. C) In the Namib, for every 100 km increase in distance from the sand sea margin dune width increases ~220 m. The outliers are the anastomosing dunes in the northeast corner of the sand sea. D) In the Namib, for every 100 km increase in distance from the sand sea margin, dune spacing increases ~1200 m.

We examined width and spacing trends of linear dunes according to distance from the western margin in the Namib Sand Sea in an attempt to better understand the role of proximity to source, if the source is the Orange River via longshore drift. The correlation of spacing according to distance from the western margin ($r^2 = 0.0134$) is not significant ($P=0.8915$). However, the correlation of width and distance from the western margin ($r^2 = 0.1768$) is significant.
(P<0.0001), with width increasing ~430 m for every 100 km increase in distance from the western margin (Fig. 7; 14).

Figure 14. Dune width and spacing versus distance to the western margin in the Namib Sand Sea. The plot is contoured by 10% quantiles. The dune width increases ~9 m for every km increase in distance from the western margin.

We examined trends of linear dune width and spacing according to elevation (Fig. 15). In Belet, there are weak positive trends in width ($r^2 = 0.0123$) and spacing ($r^2 = 0.0226$) with elevation. Dune width increases ~29 m and spacing decreases ~80 m for every 100 m increase in elevation, though these are not of statistical significance, with p-values of 0.33 for width and 0.43 for spacing. In the Namib, there are also weak trends in width ($r^2 = 0.1215$) and spacing ($r^2 = 0.0002$) with elevation. Dune width increases ~32 m and spacing decreases ~4 m for every 100 m increase in elevation. P-values for width (<0.001) and spacing (0.157) suggest that the trend in width is significant, but the trend in spacing is not.
Figure 15. Dune width and spacing according to elevation. The data are contoured by 10% quantiles. A) In Belet, dune width increases ~29 m for every 1 m increase in elevation. B) In Belet, dune spacing increases ~80 m for every 100 m increase in elevation. C) Binomial analysis was performed to establish a potential inflection point at approximately -300 m. D) An inflection point doesn’t appear to exist in
spacing vs. elevation. E) In the Namib, dune width increases ~33 m for every 100 m increase in elevation. F) In the Namib, dune spacing increases ~4 m for every 100 m increase in elevation.

We examined width relative to latitude to compare with the results of previous studies that found that width decreased with increasing latitude with maximum width at approximately -7° (Le Gall et al. 2012; Savage et al., 2014). Measurements by Savage et al. (2014) were collected in an area potentially representative of a dunefield within Belet. We considered latitude north of -7° and south of -7°, where the previous trend turnaround location was determined (Le Gall et al. 2012; Mills et al. 2013; Fig. 16). These have weak negative trends to the north ($r^2 = 0.04$) and a weak trend to the south ($r^2 = 0.0008$). However, the p-values are not significant to the north (0.081) or to the south (0.533). Because this trend runs perpendicular to the long dune axis in Belet, we decided to examine width and spacing in the Namib according to longitude (Fig.
17). Both width and spacing with longitude were significant with p-values of $<0.001$ (Table 2).

Figure 16. Dune width and spacing versus latitude in the Belet Sand Sea. (A) The Belet Sand Sea has a trend of decreasing dune width north of $-7^\circ$ with a p-value of $<0.05$. (B) The dunes of northern Belet do not exhibit a significant trend in spacing with a p-value of 0.14. (C) Binomial analysis of width vs. latitude indicates the maximum width occurs at approximately $-13^\circ$. (D) Binomial analysis of spacing vs. latitude indicates the maximum spacing occurs at approximately $-5^\circ$. The data density is contoured by 10% quantiles.
Figure 17. Dune width and spacing vs. longitude in the Namib Sand Sea. The dunes in the Namib Sand Sea have significant correlations of (A) width and (B) spacing with longitude with p-values of <0.001 and <0.001, respectively. The trend in width is weak. Binomial analysis of (C) width and (D) spacing vs. longitude was performed to determine an inflection point as was previously established on Titan.
Dune width vs. spacing was analyzed (Fig. 18). Dune width vs. spacing in Belet has a positive trend ($r^2 = 0.1174$) with a significant p-value of 0.002. The same analysis in the Namib has a positive trend ($r^2 = 0.7747$) with a significant p-value of <0.001. In Belet, the spacing increases ~70 m for every 100 m increase in dune width. In the Namib Sand Sea, the spacing increases ~77 m for every 100 m increase in dune width.

4 Discussion

Improving the method for collecting dune width and spacing measurements has enabled us to closely examine their variations across the Namib Sand Sea and compare them with those of the Belet Sand Sea. Measurements in the Namib Sand Sea yield significant correlations of width and spacing versus distance from the closest sand sea margin (Fig. 13) as well as in width according to elevation (Fig. 15; Table 2). Wider linear dunes that are more widely spaced are found in the center of the Namib and diminish in width the closer they are to the nearest sand sea margin. This trend seemingly correlates with sediment thickness, especially in the northern half of the Namib Sand Sea, in which sands are thickest in the center of the sand sea and thin as
distance from the sand sea margin decreases (Lancaster, 1995). These results also corroborate results of previous studies, which show the widest dunes are generally in the center of the sand sea (Lancaster, 1989). In the Namib, this suggests influence by variables other than, or in addition to, elevation, such as being located in the center, away from the sand sea margin, where sand can collect and dunes can form unobstructed (Lancaster, 1989).

Linear dunes measured along the eastern margin of the Namib Sand Sea are uncharacteristically wide (Fig. 13) according to the overall trend of width vs. distance to the nearest margin and appear to be outliers. This may result from additional sediment accumulation caused by increased wind direction volatility brought about by topographic obstacles that bound much of the eastern margin of the Namib Sand Sea. Lancaster (1989) classifies these abnormally wide dunes as anastomosing linear dunes, which differ from the compound and complex linear dunes that make up the rest of the dataset.

However, when analyzed alone, dune width in the Namib according to elevation ($r^2 = 0.1215$; Fig. 15) has a stronger relationship than width vs. distance to the nearest margin ($r^2 = 0.0172$; Fig. 13). This is potentially contradictory to the result suggesting dunes are wider near the sand sea center. It also contradicts Le Gall’s (2012) conclusion that Titan’s dune-interdune ratio increases with elevation. No significant correlation of spacing with elevation is observed in the Namib.

A separate analysis indicates that linear dune width increases with distance from just the western coastal margin (Fig. 14). This suggests a relationship with proximity to the sediment source. However, it is important to note for trends of width that it is difficult to distinguish between the influences of distance from the western coastal margin and elevation, as both increase from west to east. Both trends have small p-values (<0.0001 and <0.001) indicating
statistical significance. Additionally, there are significant trends in the Namib Sand Sea in spacing according to latitude and longitude (Fig. 17), as well as in width according to longitude, with width and spacing increasing from the west to the east and width increasing from the south to the north.

The previous studies in Belet that indicated dune widths decrease with increasing latitude (Le Gall et al., 2012; Savage et al., 2014) could have resulted from proximity to sand sea margin. However, in our new analysis no significant correlation of width to proximity to margin was found (Fig. 13; Table 2). Previous studies also suggest dune widths decrease with increasing latitude, perhaps a result of climatic positioning, being more humid at high latitudes and thus anchoring sands, as suggested in Le Gall et al. (2012).

New analyses of width and spacing according to elevation reveal no statistically significant trends in the Belet Sand Sea as a whole. Additionally, width and spacing according to distance from the closest sand sea margin exhibit no significant trends. This new analysis of dune width according to latitude does not reveal a strong trend within the Belet Sand Sea north or south of -7° (Fig. 16). Previous measurements were collected in the western extreme of Belet (Savage et al., 2014), perhaps confined to a single smaller dune subfield, while for this study, measurements were collected throughout the sand sea. Perhaps the presence of a latitudinal trend found in Belet in previous studies, and in global comparative studies of all sand seas, suggests a need to divide the large sand seas into smaller fields for a more effective comparative analysis with terrestrial sand seas. Because Titan’s Belet Sand Sea is 97 times larger than the Namib Sand Sea, smaller fields within Titan’s sand seas are still comparatively large and exhibit many geomorphological variations between them, and thus may serve as better analogs to terrestrial sand seas.
Increasing dune size, crest spacing, and crest length characterize pattern development in aeolian systems (Werner and Kocurek, 1997, 1999; Ewing et al., 2006). In the Namib Sand Sea, the largest linear dunes were previously found to be located near the center of the sand sea with the size of the linear dunes increasing with distance to the sand sea margin (Lancaster, 1989; 1995). This is corroborated by this study, which demonstrated that the largest dunes are generally located at the center of the Namib Sand Sea. The conclusion reached in part by the presence of the largest dunes in the center is that the greatest sediment accumulation in the Namib Sand Sea occurs in the center of the sand sea, along the south-north dune long axis alignment largely due to the dominant wind regime in this part of the Namib (Lancaster, 1995).

Close correlations between dune height, width, and spacing across the Namib from previous studies suggested that it is a mature sand sea (Chorley and Kennedy, 1971; Tsoar, 1978); our data are consistent with this notion (Fig. 18). The consistently large, linear morphology of the dunes on Titan, as well as the large dune widths and spacings, suggest that Belet is a mature sand sea (Savage et al., 2014; Radebaugh, 2013; Table 1). The large, linear dune morphology examined within the Belet Sand Sea is also indicative of a large amount of sediment accumulation throughout the sand sea and a stable wind regime. Lancaster (1995) suggests the mode of sand sea accumulation is controlled by sand supply and accumulation rate. Saturation levels of the sediment stream in relation to changes in sediment transport rates determine where erosion, deposition, or bypassing of sand take place within a sand sea (Lancaster, 1995). Equivalent sand thickness increases with width and spacing of linear dunes, as observed in the Namib Sand Sea by Lancaster (1989). Thus, perhaps large sand thickness within a sand sea indicates relative maturity. There is a large Equivalent sand thickness in the Belet
Sand Sea, matching the distribution of larger dune widths, further confirming the maturity of the sand seas on Titan.

The strongest relationship observed in this study is dune width vs. distance from the western margin in the Namib Sand Sea (Fig. 14; Table 2). This analysis reveals there may be an influence of proximity to source on dune parameters. Because the primary sediment transport direction in Belet is west to east, perhaps Belet is largely sourced by Senkyo, the sand sea directly to the west of Belet. Examining width and spacing according to distance from Belet’s western margin, which has not yet been performed, may reveal a similar trend. Finally, Belet may need to be divided into smaller dune fields before the existence of such a trend, or any other trends, may be established. Further analyses of dune parameters in relation to elevation, distance to margin, and proximity to source will allow for a better understanding of sediment transport and deposition patterns in sand seas on Earth and Titan.

5 Conclusion

In this study, we demonstrated that linear dune width and spacing correlate significantly with distance from the Namib Sand Sea margin, confirming that the largest and most widely spaced linear dunes generally exist in the center of the sand sea. We observe increasing linear dune width with increasing elevation. However, the strongest trend we observe is of increasing linear dune width with increasing distance from the western coastal margin of the Namib Sand Sea. These trends contrast from the lack of significant correlations of linear dune width and spacing with either elevation or distance from margin in the Belet Sand Sea on Titan (Table 2).

The similarity in individual linear dune morphology within the Namib and Belet sand seas suggest the two sand seas are fitting analogs. If true, an explanation needs to be found for
the lack of comparable parametric trends in the two sand seas. Factors such as age or maturity may explain the trends or lack thereof observed in the two sand seas. Perhaps the difference in size of the Namib and Belet sand seas is a factor; Belet is significantly larger than the Namib. A potential solution may be found by dividing Belet into smaller fields to serve as more contained analogs for the Namib Sand Sea. Another factor requiring further exploration that may bear partial responsibility for these results may be proximity to source. Our lack of understanding of the source(s) of Titan’s sand makes it difficult to analyze this factor as part of an analog to terrestrial sand seas. Perhaps the geographic constraints influence the different morphometric trends we observe. The extent of the Namib is constrained by the Atlantic Ocean to the west, the Great Escarpment to the East, and the Kuiseb River to the North. In contrast, Belet appears relatively unconstrained by topographic or hydrographic constraints. The examination of the influence exerted on dune width and spacing within sand seas will also be further clarified by the analysis of other sand seas on both Earth and Titan. This will aid in the identification of planetary body-specific trends as well as the trends that transcend the different conditions of Earth and Titan.
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