A Geomorphological Study of Yardangs in China, the Altiplano/Puna of Argentina, and Iran as Analogs for Yardangs on Titan

Dustin Shawn Northrup
Brigham Young University

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ABSTRACT

A Geomorphological Study of Yardangs in China, the Altiplano/Puna of Argentina, and Iran as Analogs for Yardangs on Titan

Dustin Shawn Northrup
Department of Geological Sciences, BYU
Master of Science

Collections of straight, RADAR-bright, linear features, or BLFs, on Saturn’s moon Titan are revealed in Cassini SAR (Synthetic Aperture RADAR) images. Most are widely distributed across the northern midlatitudes SAR on SAR swaths T18, T23, T30, T64, and T83 and in swath T56 in the southern midlatitudes. To understand the origin of these features, we compare them with terrestrial yardangs in Dunhuang, China, the Altiplano/Puna of Argentina, and the Lut Desert of Iran and with a similar morphological landform, linear dunes in the Namib Sand Sea, Namibia and on Titan.

We apply a statistical classification model developed through random forests, a type of decision tree classification system, grown with terrestrial and titanian training data to the BLFs. To develop the classification, we measured sinuosity, width, spacing, and length for all of the BLFs and their possible terrestrial analogs. We interpret the features in T18, T64-1, and T83 as yardangs based upon morphological similarities between them and features in Iran and Argentina, such as overall SAR brightness, straightness, and lack of branching. Similarities exist between the BLFs and terrestrial yardangs in sinuosity and spacing—sinuosity values range from 1.00 to 1.04 for all the BLFs, and terrestrial yardangs in Iran range from 1.00 to 1.001. A generated statistical model classified a large number of yardangs in T18 and T64-1.

In contrast, we interpret the BLFs in T23 and T30 as stabilized linear dunes due to similarities in sinuosity, spacing, and scale with linear dunes in the Namib Sand Sea and Titan swath T3. Stabilized linear dunes may be slightly brighter than the SAR-dark dunes due a change in dielectric constant from introduction of liquids and subsequent stabilization or from the formation of a crust over the top the feature. Sinuosities range from 1.00 to 1.37 in T23 and T30 whereas dunes in the Namib and in T3 range from 1.01 to 1.05. Branching behavior similar to dunes are also observed in BLFs in swaths T23 and T30.

The BLF features in T56 in the southern hemisphere we interpret to be dune-related, likely SAR-bright (rough) inter-dune areas. We base this interpretation on the presence of SAR-dark lineations between the BLFs that may be linear dunes. The statistical model classifies few yardangs in T23, T30, and T56.

We conclude that statistical classification of these features can be performed. We also show that yardang orientations may aid in the development of global climate and wind models as both current and paleo wind direction indicators.

Keywords: Titan, Yardangs, Linear Dunes, Cassini, RADAR
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1 INTRODUCTION

A thick, N$_2$-rich atmosphere made optically opaque by hydrocarbon hazes envelops Saturn’s largest moon, Titan, making observations of the moon’s surface difficult. With the arrival of the Cassini spacecraft to the Saturnian system in 2004 and the use of its Cassini Titan RADAR Mapper in Synthetic-Aperture RADAR (SAR) mode that produces long, thin image swaths, Titan’s thick atmosphere was penetrated. Dynamic processes and landforms similar to those on Earth were discovered (Elachi et al., 2006; Porco et al., 2004), including aeolian dunes encircling Titan’s equator (Lorenz et al., 2006; Soderblom et al., 2007; Barnes et al., 2008; Lorenz and Radebaugh, 2009; Radebaugh 2013, Savage et al., 2014), fluvial networks scattered across the moon (Lorenz et al., 2008; Burr et al., 2009; 2013; Langhans et al., 2012), cryovolcanoes (Lopes et al., 2007; 2013, Soderblom et al., 2009), tectonic processes (Radebaugh et al., 2007, 2011; Solomonidou et al., 2013, Liu et al., 2016a; 2016b), and polar lakes filled with liquid hydrocarbons (Stofan et al., 2007; Hayes et al., 2008; Aharonson et al., 2009).

Collections of straight, linear, SAR-bright features, named here Bright Linear Features or BLFs, have been observed in a few locations on Saturn’s moon Titan. They are found distributed across the northern midlatitudes in Titan SAR swaths T18, T23, T30, T64, and T83 and are in the Titan SAR swath T56 in the southern midlatitudes (Paillou et al., 2013; Radebaugh et al., 2011; Paillou et al., 2016). It has been proposed that some of these features are yardangs (Paillou et al., 2016); however, it has also been suggested that some of these features are stabilized linear dunes (Radebaugh, 2011). These features appear to differ from linear dunes on Titan in their levels of sinuosity, SAR brightness, and defect density (Paillou et al., 2016). The goal of this study is to understand the origin of the BLFs on Titan by analyzing their morphology and
morphometry and comparing them with various yardang fields across Earth and dunes in the Namib Sand Sea in order to determine which are the best analogs.
1.1 Yardangs

Yardangs are relatively straight, elongate ridges that form as wind erodes unconsolidated sediment or rock (Fig. 1) (McCauley et al., 1977). They can be found in many deserts across Earth (Goudie, 2007), Mars (Ward, 1979; Greeley et al., 1992; Bridges et al., 2007; Zimbelman et al., 2010; Kerber et al., 2011;), and perhaps Venus (Greeley et al., 1995, Greeley, 1999) and, recently,
possibly Titan (Paillou, et al., 2016). They generally form in soft sediments such as lake-bed clays and nonwelded volcanic ash, but can form in resistant layers such as sandstone or dolomite and crystalline basement rock (Inbar et al., 2001; Goudie, 2007; de Silva et al., 2010). These features develop across a large range of scales from microyardangs (centimeter scale), to mesoyardangs (meters scale in height and up to hundreds of meters in length), to megayardangs (tens of meters high and kilometers long), also known as ridge and swale systems (Halimov and Fezer, 1989; Livingstone and Warren, 1996; Goudie, 2007; Laity, 2009). Yardangs typically form in regions characterized by arid conditions, lack of vegetation, and are thought to form by a persistent, unidirectional wind, oriented along the long axis of the yardang (Goudie, 2007). However, some mega-yardangs have been found to have formed in a cooler, and possibly wetter climate, which means a hyperarid paleoclimate cannot be uniformly assumed (Sebe et al., 2011; Li et al., 2016).

Terrestrial yardang formation appears to be driven mainly by eolian abrasion and deflation with fluvial erosion, mass movement, and weathering possibly playing significant roles in the evolution of the landforms (McCauley et al., 1977; Ward and Greeley, 1984; Goudie, 1999; de Silva et al., 2010). Aeolian sands and gravels typically fill the interyardang corridors, serving to erode the lower meter or so of the yardangs (Grolier et al., 1980; Halimov and Fezer, 1989). Abrasion causes fluting and polishing of the yardang surface as well as undercutting the windward face and lateral slopes and streamlining the features (Peel, 1966; Grolier et al., 1980, Goudie, 2007). Deflation serves to remove the loose and unconsolidated sediments from the yardang surface. It is likely that deflation is of greater importance in yardang fields found in softer sediments such as lacustrine clays and siltstones (Goudie, 2007; Laity 2009). Fluvial incision due to occasional intense rain storms can serve to develop channels, subsequently enlarged and modified by wind, that play a key role in early yardang formation in some locations (Xia, 1987; Goudie, 2007; Laity, 2009; Dong et al., 2012). Large slump blocks are common next to yardangs, where abrasion has undercut the nose or base of the yardang or where the feature is strongly jointed (Hörner, 1932; Goudie, 2007; Laity, 2009; de Silva et al., 2010).
Although not well documented, weathering likely plays a role in preparing material for removal by the wind, particularly in playa environments (Hörner, 1932; Goudie, 2007; Laity, 2009).

Significant work has been done regarding terrestrial yardang morphologies and the relationship between yardang length and width (Goudie et al., 1999; Jihan et al., 2016; Dong et al., 2012). Ward and Greeley (1984) noted yardang length to width ratios of 4:1; Halimov and Fezer (1989) observed length, to width to height ratios of 10:2:1; and Goudie (1999) noted volume, length, width, and height ratios of 18.7:9.9:2.7:1. Carling (2013) looked at overall yardang shape as well as rock hardness and rock recession rates to provide a model for yardang erosion. Some work has been done to understand yardang spacing (Li et al., 2016; Dong et al., 2012); however, little has been done to understand what differentiates yardang morphologies from other similar landforms, such as linear dunes, of particular interest here.

2 GEOMORPHOLOGY

2.1 Methods

Measurements of yardangs and dunes on Earth were made using images acquired from ESRI World Imagery, taken using the IKONOS instrument, with an image resolution up to 1 m panchromatic and 4 m multispectral, with a wavelength range of 0.445-0.853 µm. (Dial, et al., 2003; Esri, 2016; Sefercik et al., 2013). Measurements on the SAR-bright possible yardang features and SAR-dark dunes on Titan were made using Cassini SAR data from the Cassini Titan RADAR Mapper. This instrument is a multi-beam sensor with four modes, three active and one
passive, that allow for the imaging of Titan’s surface: the altimeter, scatterometer, and synthetic aperture RADAR imaging (SAR), and radiometer (Elachi et al., 1991, 2004, 2005, 2006; Soderblom et al., 2007). The Titan RADAR Mapper produces SAR swaths with a resolution of up to ~350 m on the Ku-band wavelength of 2.17 cm (Porco et al., 2004; Elachi et al., 2006). The brightness in Titan SAR swaths is controlled by surface properties such as roughness, material composition, surface topography, and volume scattering (Elachi et al., 2006). Roughly 61% of Titan was imaged using the SAR mode on the Cassini Titan RADAR Mapper (Birch et al., 2016).

Because of the low resolution of the Cassini SAR images, mesoyardangs (meters in height and length) or smaller are not visible in SAR data for Titan. However, the larger megayardangs (tens of meters in height and kilometers in length), as well as multiple yardangs grouped together in a single ridge, could be visible in the highest resolution images on Titan. This allows for direct morphological comparisons of the BLFs seen on Titan with the

Fig. 2. SAR image of BLF in T64-1. The yellow lines are crest length measurements, green is straight length measurements, red is width measurements, and purple is spacing measurements.
largest yardangs found on Earth. For this reason, we have chosen to group aligned, smaller yardangs on Earth and measure these as an individual yardang.

Using ArcGIS, measurements were made of the length, width and spacing of the yardang ridges on Titan and Earth, as well as of selected terrestrial and titanian dunes. Crest length was measured by tracing a line, not necessarily straight, down the center of the main crest of each yardang or dune (Fig. 2). Straight length was obtained by digitizing a straight line from the commencement of the upwind margin of the yardang to its terminus on the downwind margin. Dune length and straight length were measured in a similar fashion. Sinuosity was calculated as the ratio of the crest length to the straight length. Width was obtained by digitizing straight lines across the yardang or dune at regular intervals (several kilometers, varying from feature to feature) and then averaging down the feature length for an average width. Yardang and dune spacing were measured from crest line to crest line of the adjacent feature at regular intervals, and averaged to obtain the spacing of a pair of features (Fig. 2).

2.2 Terrestrial Measurements

Landforms from four yardang fields on Earth were measured. The yardang fields were chosen based upon field attributes such as scale and bedrock properties. It is difficult to determine the material properties of the BLFs formed on Titan; it is therefore valuable to compare terrestrial fields with varying lithologies to BLF fields. We may be able to relate similarities in size, shape, and apparent erodibility to these features to test the idea that Titan’s BLFs may be made of similar materials from an erosion standpoint.

Yardangs in Dunhuang, China were chosen because of lithology, which contains lacustrine clays and cross-bedded aeolian sandstones. Yardangs in Argentina were selected from
two separate locations in the Altiplano/Puna. A field of megayardangs was selected based on having a scale similar to that of the features seen on Titan as well as the moderately soft lithology of the yardangs, formed in the Cerro Galan ignimbrite. A mesoyardang field in Argentina south of the megayardangs was selected due to being made of a somewhat different lithology, having formed in a young, weakly indurated ignimbrite that erupted from the Cerro Blanco Caldera approximately 70 ka (de Silva, et al., 2010). In addition, yardangs in this field show no evidence of modification by fluvial erosion, which helps isolate the contribution to erosion by wind. A yardang field located in the Lut Desert in Iran was selected due to having a similar scale as the features on Titan, and they formed in a similar lithology to the yardangs in China, having formed in Pleistocene basin fill deposits. We also measured a set of linear dunes in the Namib Sand Sea, Namibia as a point of morphological comparison between yardangs and dunes. Linear dunes in the Namib Sand Sea are long and relatively straight, like yardangs, and they have nearly the same scale as the BLFs and linear dunes on Titan.
2.2.1 Yardangs in Dunhuang, China

Located at 40°30’ N 93°06’ E, the yardangs in the Dunhuang field of western China are formed in interbedded, horizontally bedded fluvial and lacustrine clays, some fine sands, and inclined and cross bedded loose aeolian deposits (Goudie, 207; Jiyan et al., 2012; Wang et al., 2016). The field has two distinctive orientations, which have been subdivided into two fields, Dunhuang and Dunhuang South (Fig. 3). The majority of the yardangs are oriented NE-SW and form the northern section of the field while the others are oriented E-W and form the southern section. A set of linear dunes runs through the center of the field and is oriented NE-SW (Fig. 3). The yardangs have a blunt upwind margin with streamlining downwind around steep hills, which are up to 40 m high and are divided down their lengths. They are generally more discontinuous,
longer and more widely spaced in the southern section of the field than in the northern section. Grey limestone gravels surround the yardangs; clasts are 0.5-1.0 cm and form large ripples (0.5 m), indicative of high wind speeds or reptation. Some evidence of fluvial erosion is present in the form of rills and gullies found on and between the yardangs (Jiyan et al., 2012; Wang et al., 2016).

The majority of lengths range from 250 m to 2,500 m. The majority of yardang widths range from 25 m to 125 m and yardang spacing ranges from approximately 50 m to 500 m. Also note the low degree of sinuosity of the yardangs, ranging from 1 to 1.01. Extremely low sinuosity appears to be a defining characteristic of yardangs.

Fig. 4. Cumulative frequency plots of length, width, and spacing for yardangs in the Dunhuang field of western China. Notice that the majority of lengths range from 250 m to 2,500 m. The majority of yardang widths range from 25 m to 125 m and yardang spacing ranges from approximately 50 m to 500 m. Also note the low degree of sinuosity of the yardangs, ranging from 1 to 1.01. Extremely low sinuosity appears to be a defining characteristic of yardangs.
note the low degree of sinuosity of the yardangs, ranging from 1 to 1.01. Extremely low sinuosity appears to be a defining characteristic of yardangs.

The majority of lengths range from 250 m to 2,500 m. The majority of yardang widths range from 25 m to 125 m and yardang spacing ranges from approximately 50 m to 500 m. A low degree of sinuosity of the yardangs is observed, ranging from 1 to 1.01. Extremely low sinuosity appears to be a defining characteristic of yardangs.

Table 1. Summary of yardang length, width, spacing, and sinuosity for yardangs in the Dunhuang field. Note the very low mean and median sinuosity values demonstrating the characteristic low degree of sinuosity found in yardangs.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length</td>
<td>3,890</td>
<td>149</td>
<td>991</td>
<td>817</td>
<td>6</td>
</tr>
<tr>
<td>Width (m)</td>
<td>230</td>
<td>8</td>
<td>48</td>
<td>41</td>
<td>4</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>1,790</td>
<td>28</td>
<td>133</td>
<td>101</td>
<td>10</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.08</td>
<td>1.00</td>
<td>1.009</td>
<td>1.005</td>
<td>.004</td>
</tr>
</tbody>
</table>

Yardang lengths in the Dunhuang field range from 149 m to 3,890 m, with an average of 992 m in length. Widths range from 8 m to 230 m, with an average yardang width of 48 m. Yardang spacing ranges from 28 m to 1,790 m, with an average yardang spacing of 137 m. Sinuosity ranges from 1.00 to 1.08, with an average sinuosity of 1.01 (Fig. 4; Table 1).
Table 2. Summary of yardang length, width, spacing, and sinuosity for yardangs in the Dunhuang South field. Note the very low mean and median sinuosity values demonstrating the characteristic low degree of sinuosity found in yardangs.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length (m)</td>
<td>7,760</td>
<td>290</td>
<td>1,836</td>
<td>1,536</td>
<td>5</td>
</tr>
<tr>
<td>Width (m)</td>
<td>214</td>
<td>25</td>
<td>77</td>
<td>69</td>
<td>4</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>2,090</td>
<td>47</td>
<td>341</td>
<td>209</td>
<td>7</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.05</td>
<td>1.01</td>
<td>1.012</td>
<td>1.009</td>
<td>.007</td>
</tr>
</tbody>
</table>

Fig. 5. Cumulative frequency charts of length, width, spacing, and sinuosity for yardangs in the Dunhuang South field. Note the greater range in yarding lengths between the Dunhuang field (Fig. 4) and the Dunhuang South field. Yardang lengths range from approximately 500 m to 4,000 m. The majority of widths range from 50 m to 150 m. The majority of yardang spacing values range from 150 m to 750 m. Sinuosity generally ranges from 1 to 1.03, similar to other yarding fields.
Yardangs in the Dunhuang South field range from 290 m to 7,760 m long, with an average of 1,840 m (Fig. 5). Widths range from 25 m to 214 m, with an average value of 76 m. Spacing ranges from 47 m to 2,090 m, with an average of 290 m (Fig. 5). Sinuosity ranges from 1.01 to 1.05, with an average of 1.02 (Fig. 5; Table 2).

A greater range in yarding lengths between the Dunhuang field (Fig. 4) and the Dunhuang South field is observed. In general, Dunhuang South field is longer, wider, spaced further apart, and slightly more sinuous than the Dunhuang field (Fig. 5).

### 2.2.2 Yardangs in the Altiplano/Puna, Argentina

Two fields were selected for study in the Puna high plateau of northwestern Argentina. The region is characterized as hyper-arid with prevailing NW-SE winds (Inbar and Risso, 2001; de Silva et al., 2010). NW-SE oriented mega- and mesoyardangs form in ignimbrites at 25°39'S, 66°47'W, and 26°36'S, 67°28’W respectively (Goudie, 2007; de Silva, et al., 2010).
Puna North
(Megayardangs)

Similar to the Dunhuang field, both kinds of yardangs in the Puna of Argentina display a blunt upwind margin with a streamlined form downwind (Fig. 6). The tops of both the mega and mesoyardangs are somewhat flat. The older megayardangs, which are significantly larger than the mesoyardangs, are in the more coherent Cerro Galan ash-flow tuff (de Silva, et al., 2010). Cooling fractures are present and appear to contribute to the morphology through aiding in the collapse of the yardang walls to streamline the feature (de Silva et al., 2010). Interyardang troughs are typically vegetated and sandy with some gravel. Fluting is visible; generally, the wind sculpting is visible in the large-scale

Fig. 6. (Upper) Satellite image showing megayardangs located in the Puna/Altiplano of Argentina. (Lower) Satellite image of megayardangs of the Puna North field with yellow lines denoting yardang crests.
morphology. Some evidence of fluvial activity, such as interyardang channels, is present in certain areas of the mega-yardang field.

Yardang lengths range from 190 m to 12,530 m, with an average length of 2,420 m. Widths range from 620 m to 2,880 m, with an average width of 1,690 m. Yardang spacing ranges from 72 m to 1,940 m, with an average spacing of 276 m. Sinuosity ranges from 1 to 1.06, with the majority of sinuosity values ranging from 1 to 1.035 and an average value of 1.01 (Fig. 7; Table 3). The megayardangs in the Puna North field are larger than the mesoyardangs in both Dunhuang fields (Figs. 4 & 5).

Table 3. Summary table for yardang lengths, widths, spacing, and sinuosity values for the Puna North field. Note the very low sinuosity of these features.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length (m)</td>
<td>12,530</td>
<td>190</td>
<td>2,422</td>
<td>1,657</td>
<td>42</td>
</tr>
<tr>
<td>Width (m)</td>
<td>2,880</td>
<td>620</td>
<td>150</td>
<td>134</td>
<td>42</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>1,940</td>
<td>72</td>
<td>276</td>
<td>224</td>
<td>8</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.06</td>
<td>1.00</td>
<td>1.011</td>
<td>1.008</td>
<td>.013</td>
</tr>
</tbody>
</table>
Fig. 7. Cumulative frequency diagrams of yardang lengths, widths, spacings, and sinuosity for the Puna North megayardangs. Note the larger scale between these megayardangs and the yardangs in Dunhuang (Figs. 4 & 5). The majority of lengths range from 500 m to 7,000 m. Widths generally range from 50 m to 300 m. Spacing generally ranges from approximately 75 m to 500 m. Note again the low degree of sinuosity found in yardangs displayed here. The majority of sinuosity values range from 1 to 1.035.
Puna South (Mesoyardangs)

The mesoyardangs of the Puna plateau are more discontinuous than the megayardangs and are much more closely spaced and smaller in size (Fig. 8). Similar to the megayardangs, cooling fractures in the young, weakly indurated ignimbrite that makes up the mesoyardang materials...

Fig. 8. (Upper Left) Map showing the location of the Puna South field. (Upper Right) Satellite image showing mesoyardangs of the Puna South field. Note the high degree of discontinuity along feature lengths similar to the Dunhuang South field. (Lower) Satellite image of mesoyardangs in the Puna South field with crest lengths (red), widths (black), and spacing (blue) measurements included.

The mesoyardangs of the Puna plateau are more discontinuous than the megayardangs and are much more closely spaced and smaller in size (Fig. 8). Similar to the megayardangs, cooling fractures in the young, weakly indurated ignimbrite that makes up the mesoyardang materials...
may contribute to yardang formation and overall morphology through mass wasting along the fracture blocks, while extreme fluting and rounded faces evidence high wind speeds and abrasion from saltating particles. Gravel deposits similar to those found in Dunhuang, China are also present, as well as large gravel ripples. There is no evidence for fluvial activity in the region of the mesoyardangs.

Table 4. Summary table of yardang lengths, widths, spacing, and sinuosity values for the Puna South field. Notice that the features are significantly smaller than the other (Tables 1-4) fields but still display the low degree of sinuosity.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length (m)</td>
<td>1,860</td>
<td>37</td>
<td>509</td>
<td>202</td>
<td>3</td>
</tr>
<tr>
<td>Width (m)</td>
<td>26</td>
<td>8</td>
<td>18</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>103</td>
<td>15</td>
<td>57</td>
<td>58</td>
<td>1</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.08</td>
<td>1.00</td>
<td>1.017</td>
<td>1.009</td>
<td>.009</td>
</tr>
</tbody>
</table>

Mesoyardang lengths range from 37 m to 1,860 m, with an average crest length of 510 m. Widths range from 8 m to 26 m, with an average yardang width of 18 m. Spacing ranges from 15
m to 103 m, with an average yardang spacing of 57 m. Sinuosity ranges from 1.00 to 1.08, with an average sinuosity value of 1.02 (Fig. 9; Table 4).

The Puna South field has a significantly greater spread in lengths greater than 250 m while the remaining 50% of lengths are less than 250 m (Table 4) and display less spread. There is not as strong a cutoff in the parametric values as seen in the other features so far as well. This

Fig. 9. Cumulative frequency chart of yardang lengths, widths, spacing, and sinuosities for the Puna South field. Note that these are the smallest yardangs in scale across all of the terrestrial fields. Note that there is a significantly greater spread in lengths greater than 250 m while the remaining 50% of lengths are less than 250 m (Table 4) and display less spread. Most of the widths range from 15 m to 25 m. Spacing is relatively well spread between 30 m and 90 m. Note again the very low degree of sinuosity with most of the yardangs ranging between 1.00 and 1.03.

The Puna South field has a significantly greater spread in lengths greater than 250 m while the remaining 50% of lengths are less than 250 m (Table 4) and display less spread. There is not as strong a cutoff in the parametric values as seen in the other features so far as well. This
may be due a smaller sample size or our methodology for measurements, in particular, grouping yardangs to form ridges.

### 2.2.3 Yardangs in the Lut Desert, Iran

Located in the eastern portion of Iran, the Lut desert is Iran’s second largest desert, lies in the Dasht-e Lut basin (Arian and Khodabakhshnejad, 2015), and is the lowest and hottest desert in the region (McCauley et al., 1977). Surrounded by mountain ranges that can exceed 3,000 m in height, the Lut desert receives less than 150 mm of annual precipitation. It is a region of intense wind erosion, with hot dry winds from the north in the summer and winds from the south in the winter that carry large quantities of dust and sand (McCauley et al., 1977; Zehzad et al., 2002). The Dasht-e Lut basin bedrock is composed of volcanic and turbidite successions from the Eocene overlain by up to 200 m of Pleistocene basin fill (McCauley et al., 1977; Goudie, 2007).
Located at 30°09′N and 57°41′E, the yardangs in the Lut Desert are formed in the 135 to 200 m thick Lut Formation which is composed of Pleistocene silty clays and gypsiferous sands (McCauley et al., 1977; Goudie, 2007). The yardang field is bound to the north by a salt marsh and to the southeast by a large dune field. The yardangs trend northwest to southeast (Fig. 10) with ridges attaining heights up to 80 m (McCauley et al., 1977; Goudie, 2007). The individual ridges that form the yardangs are closely spaced and less sinuous than other fields. Each yardang is composed of many smaller segments that form the whole ridge line (Fig. 10). Gravels surround the yardangs and form large ripples, indicative of high wind speeds or reputation.
similar to what was observed in Dunhuang and the Puna. Some evidence of fluvial erosion is present in the form of rills and gullies found on and around the yardangs. The presence of linear dunes at the southern margin of the yarding field, and voluminous sands in the west central interyardangs, show there is sediment transport through the yardang corridors.

Table 5. Summary table of yardang length, width, spacing, and sinuosity values for the Lut Desert field in eastern Iran.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length (m)</td>
<td>137,600</td>
<td>9,680</td>
<td>81,997</td>
<td>81,824</td>
<td>431</td>
</tr>
<tr>
<td>Width (m)</td>
<td>2,880</td>
<td>620</td>
<td>1,686</td>
<td>1,532</td>
<td>231</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>6,730</td>
<td>800</td>
<td>2,798</td>
<td>2,120</td>
<td>141</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.006</td>
<td>1.00</td>
<td>1.003</td>
<td>1.002</td>
<td>.0004</td>
</tr>
</tbody>
</table>

Yardang lengths range from 9,680 m to 137,600 m with an average length of 82,000 m. Widths range from 620 m to 2,880 m with an average width of 1690 m. Yardang spacing ranges from 800 m to 6,730 m with an average spacing of 2,800 m. Sinuosity ranges from 1.00 to 1.006.
with an average of 1.003, some of the straightest values measured in this study (Fig. 11; Table 5).

The yardangs found in the Lut Desert are significantly larger in scale than the yardangs observed in China and Argentina, but still display the characteristically low sinuosity associated with yardangs. Similar to the Puna South fields, there are not strong cutoffs in parameters. This

![Cumulative frequency charts for yardangs in the Lut Desert showing length, width, spacing, and sinuosity values across the measured yardangs.](image)

Fig. 11. Cumulative frequency charts for yardangs in the Lut Desert showing length, width, spacing, and sinuosity values across the measured yardangs. The yardangs found in the Lut Desert are significantly larger in scale than the yardangs observed in China and Argentina, but still display the characteristically low sinuosity associated with yardangs. Note that the sinuosity of the yardangs in the Lut Desert are the lowest across all measured terrestrial yardangs (Tables 1-5).

The yardangs found in the Lut Desert are significantly larger in scale than the yardangs observed in China and Argentina, but still display the characteristically low sinuosity associated with yardangs. Similar to the Puna South fields, there are not strong cutoffs in parameters. This
is likely due to a smaller sample size, both the Lut Desert and Puna North field have significantly smaller sample sizes than the other observed yardang fields.

Yardang scale ranges widely across all the terrestrial measured fields. The largest yardangs are located in the Lut Desert, while the Puna South contains the smallest features in scale. Spacing ranges greatly across the various fields. However, sinuosity is consistently low across all measured yarding fields. The median sinuosity values range from 1.002 in the Lut Desert to 1.009 in both Dunhuang South and Puna South (Tables 1-5).

2.2.4 Dunes in the Namib Sand Sea, Namibia

We measured a set of linear dunes in order to compare the general morphology of yardangs with features that have similar geomorphologies, to determine what the quantifiable

Fig. 12. Satellite image of the northern portion of the Namib Sand Sea. The dark region in the map denotes the entire Namib Sand Sea. The measured linear dunes are located primarily in the central portion of the sand sea.
differences are (Fig. 12). Located in Southwestern Africa at 24°14’S 15°5’E, the Namib Sand Sea encompasses approximately 34,000 km² and is dominated by complex north-south trending linear dunes across its 100 to 120 km width, along with includes a variety of other dune forms (Lancaster, 1983; Lancaster, 1989; Livingstone, 2013) (Fig. 10). The sand sea extends over 2000 km from north to south. The town of Luderitz marks its southern border, the Kuiseb River bounds it on the north, the Atlantic Ocean is to the west, and the Great Escarpment is found to the east. Located in an area of relative tectonic stability, the modern dunes, and the underlying Tsondab dune sandstone, rest on the Namib platform, tertiary-aged erosional surfaces cut into schists, quartzites, and granite (Breed et al., 1979; Lancaster, 1989). Dune orientation is controlled by a bimodal wind regime with south-southwesterly winds from the South Atlantic Ocean and easterly winds that move down the escarpment from the interior (Lancaster, 1989). The primary regional sand transport direction is to the north; however, this is more variable in the northern and eastern margins (Livingstone, 2013).

Table 6. Summary of dune lengths, widths, spacing, and sinuosity across the Namib Sand Sea.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length (m)</td>
<td>56,810</td>
<td>9,540</td>
<td>35,307</td>
<td>35,354</td>
<td>679</td>
</tr>
<tr>
<td>Width (m)</td>
<td>850</td>
<td>520</td>
<td>668</td>
<td>650</td>
<td>276</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>2,550</td>
<td>1,300</td>
<td>2,078</td>
<td>2,118</td>
<td>69</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.05</td>
<td>1.00</td>
<td>1.022</td>
<td>1.018</td>
<td>.006</td>
</tr>
</tbody>
</table>

In the center of the sand sea, the measured linear dunes range in length from 9,540 m to 56,810 m, with an average length of 35, 300 m. Dune width ranges from 520 m to 850 m, with
an average width of 670 m. Dune spacing ranges from 1300 m to 2550 m, with an average spacing of 2080 m. Sinuosity ranges from 1.00 to 1.05, and averages 1.02 (Fig. 13; Table 6).

Fig. 13. Cumulative frequency charts of dune lengths, widths, spacing, and sinuosity. Notice that the sinuosity of linear dunes in the Namib Sand Sea is still low similar to yardangs. However, they do range slightly higher as shown in Table 6. Linear dunes in the Namib Sand Sea are also longer than all measured terrestrial yardangs except the Lut Desert, however, the yardangs in the Lut Desert are nearly twice as wide as the dunes. Spacing in the Namib Sand Sea is similar to yarding spacing in the Lut Desert.

The linear dunes in the Namib Sand Sea are closest in length to yardangs in the Lut Desert; however, the yardangs in the Lut Desert are significantly wider than the linear dunes (Tables 5 & 6). Linear dunes in the Namib Sand Sea are also longer than all measured terrestrial yardangs except the Lut Desert. Spacing is similar to that in the Lut Desert (Tables 5 & 6). Sinuosity is generally slightly greater in the Namib Sand Sea than all observed terrestrial yardangs suggesting that sinuosity is a valuable characterization parameter for yardangs (Figs. 3, 6, 7, 8, 10, 12;
Tables 1-6). The greater spacing variability observed in the Namib Sand Sea may be from the higher degree of sinuosity observed in dunes than in yardangs. Length variability may result from the nature of dune fields and dune formation which differs from yardangs since yardangs are erosional features while dunes result from sand transport.
2.3 Morphology of BLFs on Titan

Collections of BLFs have been observed on Saturn’s moon Titan in the northern midlatitudes in Titan SAR swaths T18, T23, T30, T64, and T83 as well as in the Titan SAR swath T56 in the southern midlatitudes (Fig. 14) (Paillou et al., 2013; Radebaugh et al., 2011; Paillou et al., 2016).
It has also been suggested they are stabilized linear dunes (Radebaugh, 2011). It has been proposed that some of these features are yardangs since they appear to differ from linear dunes on Titan in their levels of sinuosity, SAR brightness, and defect density (Paillou et al., 2016).

Both northern and southern BLFs have a basically west-east orientation, broadly but not exactly similar to dune orientations found nearby (Fig. 14b; Paillou et al., 2013; Radebaugh et al., 2011; Paillou et al., 2016). Initial differences and similarities in morphology are readily apparent between many of the BLF fields examined on Titan and between dunes seen elsewhere on Titan. Dunes on Titan’s surface are SAR-dark due to their smooth surfaces and low dielectric constants, and because sand preferentially absorbs RADAR at Cassini’s 2.17 cm wavelength (Radebaugh et al., 2011) (Fig. 11). Since the substrate does not have the same SAR characteristics, the SAR-dark dunes contrast with the exposed substrate in the interdune areas (Radebaugh et al., 2008; Le Gall et al., 2011; Radebaugh et al., 2011) (Fig. 11). It should be noted that the interdune area can be relatively SAR-dark; in such instances, it is assumed to be covered in sand (Radebaugh et al., 2008, Barnes et al., 2008; Le Gall et al., 2011; Radebaugh et al., 2011).

We argue that some BLFs are stabilized linear dunes, even though they are SAR-bright. Stabilized linear dunes may become SAR-bright due to a change in the dielectric constant from the introduction of liquids, such as methane, perhaps carrying cements, into the stabilized dunes, or from the formation of a crust across the top of a stabilized linear dune from atmosphere-derived tholins.

The SAR-brightness of BLFs can result from scattering due to roughness or if there are conditions where reflections occur off the lineations, revealing they are elevated ridges or dune crestlines (Paillou et al., 2013).
Dunes were also examined in Titan’s SAR swath T3, north of the Fensal and Aztlan Sand Seas between the equator and 30°N. They were examined as a control on dune morphology and chosen to be outside of the one of the five large equatorial sand seas in order to determine the viability of the hypothesis that the BLFs are stabilized dunes as suggested by Radebaugh (2010).

2.3.1 Titan SAR Swath T3 – Dunes

Titan’s dunes are morphologically similar in width, spacing, and height with dunes on Earth (Lorenz et al., 2006; Radebaugh et al., 2008; Neish et al., 2010), and their orientations suggest net sand transport from west to east (Radebaugh et al., 2008; Lorenz and Radebaugh, 2009; Radebaugh et al., 2010). At locations outside the main equatorial band, dunes are more closely spaced and lack dark, sandy interdunes (Figs. 14 & 15). These isolated dunes have morphologic characteristics similar to the equatorial dunes, such as branching, though their sinuosity is slightly higher (Figs. 14 & 15).

Lengths of the measured dunes range from 10,760 m to 53,930 m, with an average dune length of 28,140 m.

Fig. 15. (Above) SAR image of linear dunes in swath T3. Yellow lines denote measured crests and the rose diagram shows dune orientations.
Table 7. Summary of lengths, widths, spacing, and sinuosity values across linear dunes in T3. Note similar sinuosity values to linear dunes in the Namib Sand Sea (Table 7).

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length (m)</td>
<td>59,930</td>
<td>10,760</td>
<td>28,138</td>
<td>27,003</td>
<td>350</td>
</tr>
<tr>
<td>Width (m)</td>
<td>1,320</td>
<td>650</td>
<td>958</td>
<td>940</td>
<td>350</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>4,400</td>
<td>1,060</td>
<td>2,597</td>
<td>2,363</td>
<td>350</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.05</td>
<td>1.01</td>
<td>1.023</td>
<td>1.017</td>
<td>.013</td>
</tr>
</tbody>
</table>

Dune widths range from 650 m to 1320 m, and average 960 m. Spacing ranges from 1,060 m to 4,400 m, with an average spacing of 2,620 m. All of these values are broadly similar to other dunes on Titan, except that lengths are typically longer in the centers of the sand seas (Savage et al., 2023).

Fig. 16. Cumulative frequency charts for lengths, widths, spacing, and sinuosity for all linear dunes measured in T3. Dune sinuosity is similar to sinuosity values for linear dunes in the Namib Sand Sea (Fig. 12).
al. 2014). Sinuosity varies from 1.01 to 1.05, with an average sinuosity of 1.02 (Fig. 16; Table 7).

### 2.3.2 BLFs in Swath T18

SAR-bright features can be found at 6°48’9’’ E 47°50’14’’ N, on the western end of Cassini’s T18 SAR swath (Figs. 14 & 17). The region can be characterized as generally more SAR bright than the surrounding areas, signifying rougher terrain. Because some of the reflections are exceptionally narrow, straight and uniform in brightness, it is likely we are seeing reflections off elevated ridges (e.g. Radebaugh et al. 2008). The features trend northwest to southeast, and there are 46 measureable features (Fig. 17). The area surrounding the features appears relatively flat, while to the north and south, possible fluvial channels and topography is visible.

![Fig. 17. (Top) SAR image of BLF in T18. Yellow lines denote crest measurements and the rose diagram shows orientation. (Below) SAR image of features measured in T18.](image)
The features found in swath T18 display no visible branching. There are 46 measured features while the other fields range from 12 to 23 measured features over a similar area, indicating a higher overall density of features. The features have a low degree of sinuosity but with a slight curve in the field orientation toward the southeastern end. Morphologically, the features most closely resemble morphologies of the yardang field in the Lut Desert of Iran, in that they are bright, display a low degree of sinuosity, uniform orientation, and have a slight curve in orientation through the field. While the complexity found within individual yardangs seen in Iran is not visible in T18, this is likely due to SAR image resolution. When compared with a SAR image of Iran that has been degraded to a

Fig. 18. (Top) SAR image of BLF measured in T18. (Bottom) Low resolution radar image of yardangs in the Lut Desert. Note the geomorphologic similarity in appearance between the two fields.
The features in T18 have a low sinuosity and display no branching. They have low sinuosity, and their width aligns best with that in the Namib Sand Sea, while the spacing aligns with both Iran and the Namib, but the distribution more closely resembles the yardangs of Iran (Fig. 11, 13, 19). Compared to Iran, the features in T18 are significantly smaller with a higher degree of sinuosity (Figs. 11 & 19). It is important to note that the difference in average sinuosity between Iran in T18 is still minimal, 1.01 for T18 and 1.003 (Tables 5 & 8).

Table 8. Summary of length, width, spacing, and sinuosity values for all BLF's measured in T18. Sinuosity appears similar to terrestrial yardangs.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length (m)</td>
<td>67,760</td>
<td>4,710</td>
<td>22,140</td>
<td>18,799</td>
<td>350</td>
</tr>
<tr>
<td>Width (m)</td>
<td>1,560</td>
<td>507</td>
<td>850</td>
<td>796</td>
<td>350</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>6,950</td>
<td>1,600</td>
<td>3,129</td>
<td>2,765</td>
<td>700</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.03</td>
<td>1.00</td>
<td>1.01</td>
<td>1.009</td>
<td>.0014</td>
</tr>
</tbody>
</table>

Lengths of the measured features range from 4,710 m to 67,760 m, with an average length of 22,200 m. Width ranges from 507 m to 1,560 m, with an average width of 850 m. Spacing ranges from 1,600 m to 6,950 m, with an average spacing of 3,360 m. Sinuosity ranges from 1.00 to 1.03, with an average sinuosity value of 1.01 (Fig. 19; Table 8).
2.3.3 BLFs in Swath T23

West-to-east oriented, southeast-trending long, linear, SAR-bright features are visible in the northern section of the Cassini T23 SAR swath at 42°6′W 52°56′N (Figs. 14 & 20). The immediate topography of the area containing the features is relatively uniform, and a SAR-bright section is found immediately southwest of the features. The eastern and western margins of the features appear to bounded by a slightly more SAR-bright region than the surrounding area. The

Fig. 19. Cumulative frequency chart show length, width, spacing, and sinuosity values across BLF’s in T18. Note the low degree of sinuosity focused between 1.005 and 1.015.
features have a low sinuosity, and some features display branching morphologies (Fig. 20C). The features have a regular appearance in terms of their spacing.

The features in T23 are long and linear with very low degrees of sinuosity. Feature orientations are northwest-southeast with little variation, indicative of a steady set of wind conditions in that area. The features are coherent and easily identifiable.

BLF median sinuosity values are similar to those of linear dunes in T3 and in the Namib Sand Sea (Table 7 & 9). Median values suggest a greater similarity to dunes rather than yardangs (Tables 1-9).

Table 9. Summary of length, width, spacing, and sinuosity values for BLFs across T23. Note the sinuosity values similar to T3 and the Namib Sand Sea (Tables 5 & 6).

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length (m)</td>
<td>71,000</td>
<td>6,740</td>
<td>22,936</td>
<td>18,042</td>
<td>350</td>
</tr>
<tr>
<td>Width (m)</td>
<td>1,000</td>
<td>650</td>
<td>813</td>
<td>815</td>
<td>350</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>6,790</td>
<td>1,680</td>
<td>3,051</td>
<td>2,640</td>
<td>350</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.03</td>
<td>1.004</td>
<td>1.034</td>
<td>1.018</td>
<td>.025</td>
</tr>
</tbody>
</table>
Feature lengths range from 6,740 m to 71,000 m, with an average feature length of 22,940 m. Feature widths range from 650 m to 1,000 m, with an average width of 810 m. Spacing ranges from 1,680 m to 6,790 m, with an average spacing of 3,660 m. Sinuosity ranges from 1.004 to 1.37, with an average sinuosity of 1.03 (Fig. 21; Table 9).
2.3.4 BLF in Swath T30

Located in the upper midlatitudes at 39°0’W 52°7’N in the western section of the Cassini SAR swath T30, there are some BLFs that have an overall west-to-east trend, with two features trending more northwest to southeast (Figs. 14 & 22). The field can be divided into two separate groups, with the features on the western margin of the eastern group displaying a northwest-to-southeast orientation. The features in both groups appear to be contained in and follow the orientation of a SAR-dark band (Fig. 22). Some branching within the features may be visible, but they are hard to positively identify (Fig. 22). The western group has

![Fig. 22. (Above) SAR image of BLF measured in T30. Note the SAR-dark band containing BLF. (Below) SAR image of BLF in T30 with yellow lines denoting crest measurements and rose diagrams showing orientation. Note the two orientations within the field.](image)
a higher density of features and a closer spacing, while the eastern band has fewer features overall.

The BLFs found on SAR swath T30 have dune-like branching similar to those of T23. They are long and linear, and have a low degree of sinuosity, similar to both dunes and yardangs (Figs. 1 & 22). T30 displays median sinuosity values close to those of linear dunes in T3 and those in the Namib Sand Sea (Figs. 13, 16, 23). The median sinuosity values of the BLFs in T30 suggest a greater similarity to dunes than yardangs (Table 10).

Table 10. Summary of length, width, spacing, and sinuosity for BLFs in T30. Notice the similarities between BLFs in T30 (Table 9).

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length (m)</td>
<td>53,930</td>
<td>10,760</td>
<td>17,865</td>
<td>15,495</td>
<td>350</td>
</tr>
<tr>
<td>Width (m)</td>
<td>820</td>
<td>550</td>
<td>676</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>4,060</td>
<td>1,780</td>
<td>3,092</td>
<td>2,805</td>
<td>350</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.04</td>
<td>1.00</td>
<td>1.02</td>
<td>1.018</td>
<td>.0246</td>
</tr>
</tbody>
</table>

We observed a greater variation in orientation in the BLFs in T23. The features appear to follow the orientation of a SAR-dark band that is bounded to the south by rougher, SAR-bright terrain and what appears to be a topographic high to the north (Fig. 22) indicating this region may be sand covered. The BLFs appear to be contained within the dark band, suggesting a low in elevation that may funnel winds through the SAR-dark depression or valley and collect sand. This could create the unusual range in orientations seen in this swath. While it is possible for yardangs to form with different orientations in nearly the same place (e.g. Dunhuang, China (Fig. 3), this occurrence seems more consistent with sand being transported through a low elevation point. Considering this and the sinuosity values, we interpret the BLFs in T23 to be stabilized, or possibly even active, linear dunes.
Feature lengths range between 10,760 m and 53,930 m, with an average length of 28,140 m between the two groupings. Widths range from 550 m to 820 m, with an average width of 676 m. Spacing ranges between 1,780 m and 4,060 m, with an average spacing of 3,090 m. Sinuosity ranges from 1.00 to 1.04, with an average sinuosity of 1.02 (Fig. 33; Table 10). Note that the features were separately measured, rather than as one long feature, because we could not conclude that they were continuous. If they are continuous, then their sinuosities and lengths would be much higher across the whole field.

![Cumulative frequency charts](image)

*Fig. 23. Cumulative frequency charts of length, width, spacing, and sinuosity for BLFs in T30. Notice the higher sinuosity values with the majority of values ranging between 1.015 and 1.025.*
2.3.5 BLF in Swath T56

Unlike the other fields, the features observed in Titan’s SAR swath T56 are found in the southern midlatitudes at 164°29’W 29°26’S. Similar to the features observed in SAR swath T30, these features appear to be in separate groups (Figs. 14 & 23). Unlike the features seen in the other swaths, these features are wider and the edges are much more ambiguous, terminating against the SAR swath boundary, and they also appear somewhat brighter (Fig. 23). Here, the dark lineations are more readily delineated than the bright lineations; and in fact, it may be that dark overlies light in this case, meaning these features are instead SAR-dark dunes. The features trend from west to east in both groups and become less distinct towards the east. Feature density and spacing appear to be consistent between both groups, and there is a total of thirteen measured features.

The BLFs in swath T56 look distinctly different from the other, high-latitude linear features on Titan. The features are not as wide as the dunes of the Namib or the dunes in T3 and they are more widely spaced than both (Fig. 12, 16, 25; Tables 6, 7, 11). The median sinuosity is higher than all of the terrestrial yardang fields and SAR-bright feature fields T18 (Tables 1-5, 7).
Wider than the terrestrial yardangs in Puna North and South fields, they are, however, narrower than the dunes in the Namib Sand Sea and yardangs in the Lut Desert (Tables 1-6). They are more widely spaced than the dunes in T3 and the dunes in the Namib Sand Sea with a spacing similar to the proposed dunes in T30 (Figs. 12, 16, 25; Tables 6, 7, 11). Linear SAR-dark features are observed between the brighter more diffuse lineations we measured. We suggest they are SAR-dark features or lineations on a brighter substrate. Furthermore, their proximity to the southern margin of Shangri-La and the presence of a large number of dunes to the north of the BLF may suggest these features may be dunes. Coupled with their more dune-like aspects, including the long SAR-dark features that are reminiscent of dunes, and the more diffuse

![Cumulative frequency charts for length, width, spacing, and sinuosity of BLF's in T56.](image-url)
margins we suggest they are dunes with bright inter-dunes. The similarities in spacing with T30 also suggests that these features may be similar to the proposed dunes in T30.

Feature lengths range from 5,220 m to 35,130 m, with an average length of 19,450 m. Widths range between 440 m and 1,070 m, with an average width of 590 m. Spacing ranges from 1,070 m to 4450 m, with an average spacing of 2,780 m. Sinuosity ranges from 1.01 to 1.02, with an average value of 1.01 (Fig. 25; Table 11).

Table 11. Summary of length, width, spacing, and sinuosity for BLFs in T56.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length (m)</td>
<td>35,130</td>
<td>5,220</td>
<td>19,449</td>
<td>17,918</td>
<td>350</td>
</tr>
<tr>
<td>Width (m)</td>
<td>1,070</td>
<td>440</td>
<td>590</td>
<td>565</td>
<td>350</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>4,450</td>
<td>1,070</td>
<td>2,777</td>
<td>2,757</td>
<td>350</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.02</td>
<td>1.01</td>
<td>1.012</td>
<td>1.012</td>
<td>.03</td>
</tr>
</tbody>
</table>
2.3.6 BLFs in Swath T64, field T64-1

Located in the northern midlatitudes at 149°43’E and 41°35’N on the eastern edge of the Cassini T64-2 SAR swath, the features display a prominent northwest-to-southeast trend (Figs. 14 & 26). They are extremely SAR-bright, are fairly wide, and have a high feature density, all morphological characteristics that are different from the other fields discussed so far. They appear to have been crosscut and modified by fluvial channels. The SAR-bright lineations are all relatively closely spaced and appear to fan out to a small degree from a point in the southeastern section of the field. They do not display branching (Fig. 26). The fanning or radial pattern, the accompanying drainages, and the roughness of the terrain indicate that these features may be formed on a topographic high. This has been postulated as a laccolith, or volcanic upwarp by Schurmeier et al. (2018).

The features are closely spaced and densely packed. They appear similar in morphology to the yardangs found in Iran’s Lut Desert when compared to the de-resolved Lut SAR image (Fig. 26).
The features are incredibly straight, having one of the lowest average sinuosities across the measured fields. Median sinuosities compare well with terrestrial yardang sinuosities (Tables 1-5, 12). The width values are significantly larger than those observed in the Namib or T3, more closely aligning with the peak yardang widths in Iran (Figs. 11, 13, 16, 27). They also have a larger overall length, similar to the features seen in Iran (Fig. 11 & 27, Tables 5 & 12).

Table 12. Summary of length, width, spacing, and sinuosity values for BLFs found in T64-1 field, swath T64. Note the similar mean and median sinuosity values with T18 (Table 8).

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length (m)</td>
<td>69,720</td>
<td>11,430</td>
<td>35,340</td>
<td>32,635</td>
<td>700</td>
</tr>
<tr>
<td>Width (m)</td>
<td>2,020</td>
<td>960</td>
<td>1,452</td>
<td>1,431</td>
<td>700</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>5,970</td>
<td>1,290</td>
<td>2,423</td>
<td>2,108</td>
<td>350</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.02</td>
<td>1.00</td>
<td>1.01</td>
<td>1.009</td>
<td>.003</td>
</tr>
</tbody>
</table>

Feature lengths range from 11,430 m to 69,720 m with an average length of 35,340 m. Widths range between 960 m and 2020 m, with an average width of 1450 m. Spacing ranges from 1290 m and 5970 m, with an average spacing of 2420 m. Sinuosity ranges between 1.00 and 1.02, with an average sinuosity value of 1.01 (Fig. 27; Table 12).
2.3.7 BLFs in Swath T64, field T64-2

Located in the northern midlatitudes at 144°34′E 42°29′N on the western section of the Cassini T64 SAR swath, this group has a generally low feature density and wide spacing (Fig. 28). The features are shorter in general than other features discussed, unless they are continuous along their length, which is hard to confirm. Instead, they are divided into three subgroups, all with the same orientations, and with some possible branching (Figs. 14 & 28).

Fig. 27. Cumulative frequency charts of length, width, spacing, and sinuosity for BLFs found in T64-1. T64-1 sinuosities range up to 1.0125 and are very similar to T18 (Fig. 17)
The features in field T64-2 have a wider spacing than those of T64-1 (Fig. 27 & 29; Tables 12 & 13). Both fields in the T64 swath have similar orientations but the radial element is not present in T64-2, and they are not as densely spaced. The features are slightly wider than dunes in the Namib Sand Sea but very similar to the dunes in T3 (Figs. 13, 16, 29). The median sinuosity is larger than T64-1 (Tables 12 & 13). However, due to the branching seen in T64-2 we conclude that these features may be stabilized dunes rather than yardangs.

Table 13. Summary of length, width, spacing, and sinuosity for BLFs in T64-2. Note the higher sinuosity values than observed in T64-1 (Table 12).

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest Length (m)</td>
<td>25,510</td>
<td>5,280</td>
<td>14,119</td>
<td>12,832</td>
<td>350</td>
</tr>
<tr>
<td>Width (m)</td>
<td>1,210</td>
<td>760</td>
<td>952</td>
<td>913</td>
<td>350</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>9,280</td>
<td>1,310</td>
<td>4,548</td>
<td>3,682</td>
<td>350</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>1.03</td>
<td>1.01</td>
<td>1.014</td>
<td>1.012</td>
<td>0.0229</td>
</tr>
</tbody>
</table>
Feature lengths range from 5280 m to 25,510 m with an average length of 14,120 m. Widths range between 760 m and 1210 m, with an average width of 950 m. Spacing ranges from 1310 m and 9280 m, with an average spacing of 4550 m. Sinuosity ranges between 1.01 and 1.03, with an average sinuosity value of 1.02 (Fig. 29; Table13).

Fig. 29. Cumulative frequency charts for length, width, spacing, and sinuosity for BLFs in T64-2. Higher sinuosity values are observed in T64-2 than T64-1 (Fig. 25). However, they are less than observed in T23, T30, and T3 (Fig).
2.3.8 BLFs in Swath T83

Located at 163°35′E 39°30′N, in the Cassini T83 SAR swath in the northern midlatitudes, there are some BLFs that are wide, closely spaced, and extremely SAR-bright, similar to those in the T64-1 field (Section 2.3.6). They display a strong northwest-to-southeast trend (Figs. 14 & 30), and a slight difference in orientation occurs between some of the features in the northern section of the field and the remaining features. Multiple channels can be seen near and between the SAR-bright features (Fig. 30). The field itself displays a high feature density with fairly uniform spacing. No branching is visible in this field. As with T64-1,
this field seems to be in an area of rougher, SAR-brighter, terrain.

As noted earlier, the features in T83 appear similar to the features in T64-1 and the yardangs measured in Iran (Figs. 1, 30). The features appear to be in a region of rougher and likely elevated terrain evidenced by the down-cutting, dendritic fluvial systems and SAR-brightness of the regions, which may be evidence of roughness and uneven terrain (Fig. 30). The features also appear to be partially eroded by fluvial activity. BLFs here are wider than observed in the Namib and T3 and spacing is wider than seen in the Namib or T3 (Figs. 13, 16, 31). The median sinuosity is slightly higher than observed terrestrial yardangs (Table 14). However, due to their morphologic similarities to T64-1 and Iran, it is prudent to classify these features as yardangs (Figs. 1, 30).

Table 14. Summary of length, width, spacing, and sinuosity for BLF’s observed in T83.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Error (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Crest Length (m)</strong></td>
<td>52,440</td>
<td>9,680</td>
<td>28,917</td>
<td>25,431</td>
<td>700</td>
</tr>
<tr>
<td><strong>Width (m)</strong></td>
<td>1,210</td>
<td>860</td>
<td>1,014</td>
<td>1,009</td>
<td>350</td>
</tr>
<tr>
<td><strong>Spacing (m)</strong></td>
<td>10,850</td>
<td>1,780</td>
<td>3,443</td>
<td>2,908</td>
<td>350</td>
</tr>
<tr>
<td><strong>Sinuosity</strong></td>
<td>1.04</td>
<td>1.01</td>
<td>1.014</td>
<td>1.012</td>
<td>.0229</td>
</tr>
</tbody>
</table>

Feature lengths range between 9,680 m and 52,440 m, with an average length of 28,910 m. Widths range from 860 m and 1,210 m, with an average width of 1,010 m. Spacing ranges between 1,780 m and 10,850 m, with an average spacing of 3,440 m. Sinuosity varies between 1.01 and 1.04, with an average sinuosity of 1.01 (Fig. 31; Table 14).
Differences between dune and yardang fields are most apparent when examining sinuosity (Table 15). Differences in scale between the terrestrial yardangs are readily visible, with yardangs from the Lut Desert being significantly larger than those in the yardang fields in Argentina and China. The Iranian yardangs are the closest in scale to BLFs on Titan (Table 15). The dunes in the Namib Sand Sea, on the other hand, compare nicely to the dunes measured in T3, with very similar crest length, width, spacing, and sinuosity values (Figs. 13 & 16). It appears that the best discriminator between the dunes and the yardangs is sinuosity, with yardangs displaying a small sinuosity, or high degree of straightness (Table 15).

Fig. 31. Cumulative frequency charts of length, width, spacing, and sinuosity for BLFs observed in T83. Higher sinuosity values were observed in T83 than T64-1 and T18, yet this field was classified as a yardang field. This is due to the morphological appearance where valleys are observed between BLFs and the higher feature density. The slightly elevated sinuosity values are likely due to the yardangs becoming more eroded due to occasional rains that cause intense erosion within the valleys between the yardangs.
Table 15. Summary of length, width, spacing, and sinuosity for all fields.

<table>
<thead>
<tr>
<th>Field</th>
<th>Length</th>
<th>Width</th>
<th>Spacing</th>
<th>Sinuosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field 1</td>
<td>1000</td>
<td>500</td>
<td>200</td>
<td>0.5</td>
</tr>
<tr>
<td>Field 2</td>
<td>1500</td>
<td>700</td>
<td>300</td>
<td>0.6</td>
</tr>
<tr>
<td>Field 3</td>
<td>2000</td>
<td>800</td>
<td>400</td>
<td>0.7</td>
</tr>
<tr>
<td>Field 4</td>
<td>2500</td>
<td>900</td>
<td>500</td>
<td>0.8</td>
</tr>
<tr>
<td>Field 5</td>
<td>3000</td>
<td>1000</td>
<td>600</td>
<td>0.9</td>
</tr>
</tbody>
</table>

...
3 STATISTICS

3.1.1 Decision Trees and Random Forests

Decision trees are a form of machine learning that can be used for regression and classification in statistical methods. A tree is constructed by building a decision path that partitions the data into binary subsets and develops a set of classification rules. The tree branches will then classify the data into distinct groups or classifications (Neeley, 2003; James et al., 2013). The branching or splitting of the data reduces deviance of the data within the tree. Every split is based upon every variable and possible value of the variable, where the splits with the smallest deviance are chosen (Neeley, 2003). While useful for classification, tree-based methods are simple. To improve prediction accuracy, specialized tree models such as random forests can also be applied.

A Random Forest is a tree-based method for classification of quantitative data that improves on a simple tree by building a large number of decorrelated trees and then averaging them. This is done by forcing each split or division to only consider a randomly selected subset of the predictors (James et al., 2013). By de-correlating the trees, very strong predictors are prevented from overruling other moderately strong predictors. If the trees were not de-correlated, it would result in highly correlated trees being averaged together which would not lead to a substantial reduction in variance (Breiman, 2001; Hastie et al., 2009, James et al., 2013). Random forests construct each tree using a different bootstrap sample of the training data, a type of resampling method. Each node within the constructed trees is split using the best division among a subset of randomly chosen predictors at the node, thus allowing for a more substantial reduction in
variance (Breiman, 2001; Liaw and Wiener, 2002; James et al., 2013). Thus, random forests are a powerful classification tool.

Using a function in R, the statistical software used to perform the random forest, it is possible to obtain a general view of the importance of each variable used as a predictor. Two measures of importance are reported. The first measure describes the mean decrease in accuracy when a variable is excluded from the model; this is measured in the test data where the actual classifications are known. The other measure describes the total decrease in node impurity resulting from splits over a specific variable after it has been averaged across all of the trees. For classification trees, node impurity is measured by the deviance (James et al., 2013).

### 3.1.2 Methods

A random forest classification analysis was performed on the features on Titan, since this method relies on similarities between the geomorphic measurements rather than on statistical modeling. The data set was randomly divided where the Dune/Yardang classification is known into a training and a test dataset, with completely separate features in each case. The training data has 327 observations and contains 301 known yardangs (all on Earth) and 26 known dunes (6 on Earth and 20 on Titan). The measured Titan dunes are all SAR dark and come from the isolated set of dunes described above (Radebaugh et al. 2008). The test data has 328 observations and contains 300 known yardangs (all on Earth) and 28 known dunes (14 on Earth and 14 on Titan). A random forest was performed on the training dataset to classify the dune/yardang classification.

Models 1 & 3:
Classification = Crest Length + Straight Length + Width + Spacing + Width to Spacing + Sinuosity + Crest Length to Width + Crest Length to Spacing

Model 2:

Classification = Crest Length + Straight Length + Width + Spacing + Width to Spacing + Sinuosity + Crest Length to Width + Crest Length to Spacing + Located on Titan

The ability of the random forest model to classify features was checked by running the prediction on the test data set. Both models gave the same predictions on the test data. The correct classification rate of yardangs was 99.67% (299/300) and the correct classification rate of dunes was 89.29% (25/28). This approach demonstrates the ability of the model to distinguish dunes from yardangs based on the measurements provided.

Next, a random forest model based on all of the data where the dune/yardang classification is known (essentially, the sum of the training and test datasets) was created. This model was used to predict dune/yardang classification for the unknown features on Titan. Those results are described and discussed below.

We examined all three generated models and will focus primarily on the third model, since it most closely aligned with geomorphological observations and interpretations.
3.1.3 Results

Table 16. Summary of results from statistical classification model applied to all BLFs on Titan. Models 1 and 2 were preliminary and used to develop model 3 which is discussed further.

<table>
<thead>
<tr>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Morphological Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Features</td>
<td>Dunes Yardangs</td>
<td>Dunes Yardangs</td>
<td></td>
</tr>
<tr>
<td>T18</td>
<td>46</td>
<td>44</td>
<td>2</td>
</tr>
<tr>
<td>T23</td>
<td>24</td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>T30</td>
<td>16</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>T56</td>
<td>13</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>T64-1</td>
<td>18</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>T64-2</td>
<td>14</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>T83</td>
<td>17</td>
<td>17</td>
<td>0</td>
</tr>
</tbody>
</table>
Models 1 and 2 were both test models, while Model 3 is the used model. Model 1 was generated using data from crest length, straight length, width, spacing, width to spacing, sinuosity, crest length to width, and crest length to spacing as variables in order to generate classifications (Fig. 32). Model 1 predicted that at least a few BLFs were yardangs in all of the fields on Titan, but T83 and T64-1 contain the largest fraction of predicted yardangs. Model 2 used all of the same variables as Model 1 with the addition of the feature locations, Earth or Titan, as a deterministic variable. Model 2 predicted yardangs in only fields T18, T21, and T64-1. Model 3 was generated by using

\[\text{Fig. 32. Charts showing the average decrease in accuracy (left) and the average decrease in deviance across the various generated decision trees (right).}\]
only the known terrestrial measurements in the training data and then applying it to the Titan data. Model 3 predicted some BLFs were yardangs in each field, with all the features of T64-1 being predicted as yardangs (Table 16).

Variables of greatest importance varied between the three models. Sinuosity and length were the variables that contributed most toward accuracy and decrease in deviance for Model 1. In Model 2, sinuosity and length contributed most toward accuracy; however, length and spacing contributed the most towards a decrease in deviance. Accuracy was most driven by width and sinuosity in Model 3, with width and length driving the decrease in deviance (Fig. 32).
Fig. 3: Cumulative frequency graph showing number of features on the x-axis and crest length in meters on the y-axis. Terrestrial fields are denoted by a dashed line while fields located on Titan are a solid line. Notice the grouping of terrestrial fields at lower length values while the BLF's, dunes in T3, dunes in the Namib Sand Sea, and yardangs in the Lut Desert are much longer with a greater spread in lengths. Also note that T64.1 is the BLF field that most closely resembles the Lut Desert on Titan; however, its more closely matches the Namib Sand Sea indicating that yardangs in the Lut Desert are significantly larger than any BLF observed on Titan.
Fig. 34. Cumulative frequency graph with width on the x-axis and frequency on the y-axis for features measured on both Earth and Titan. The titanian features, Lut Desert, and Namib Sand Sea are wider than the remaining terrestrial features. T64-1 and the Lut Desert are similar in width, and T18, T30, and the Namib Sand Sea are similar in width. T64-2 and T83 have similar widths as well.
Fig. 35. Cumulative frequency graph of yardang, dune, and BLF spacing across the x-axis and frequency on the y-axis for all measured fields. Similar to Fig. 34, the terrestrial yardang fields, with the exception of the Lut Desert, are significantly smaller in width than the terrestrial fields. T23 and T3 are similar in width and T18, 30, and the Namib Sand Sea are similar in width. The widest features on Titan are found in T64, which are similar in width with the Lut Desert.
Fig. 36. Box plot showing yardang, dune, and BLF sinuosities across all measured fields. The blue zone denotes the interquartile range (IQR) of yardang sinuosities of both the Namib Sand Sea and T3. The orange denotes the IQR of all measured terrestrial yardangs. The purple denotes the overlap of the yardang and dune IQR values. The dark lines in the center of the IQR box show the mean sinuosity value for the given field. Notice that the IQR for both field T18 and T641 align predominantly within the yardang zone and their median values are similar to those of Punu North, Punu South, and Dunhuang South. While the IQR for T23 and T30 strongly resemble the IQR for both the Namib Sand Sea and T3 with similar median values of both the Namib Sand Sea and T3. The orange denotes the IQR of all measured terrestrial yardangs. The purple denotes the overlap of the yardang and dune IQR values.
4 DISCUSSION

Similarities between yardangs in SAR images of Iran’s Lut Desert and the BLFs in T18, T164-1, and T83 are readily apparent (Figs. 1 & 18). The lack of observed branching (Figs. 17, 24, 28), low sinuosity (Fig. 34; Table 15), high SAR-brightness (Figs. 17, 24, 28), being located on domes, elevated terrains or prominent layers (Figs. 24 & 28), and similarities in lengths, width, and spacing led us to interpret these features as yardangs (Figs. 31, 32, 33; Table 15).

The similarity in morphology is particularly striking when comparing the SAR image of BLFs in T18 and the SAR images of the Lut Desert when the resolution is degraded and noise is applied to simulate Cassini SAR images (Fig. 18). When examined morphometrically, we find BLFs in T18 have higher sinuosity values than those in Iran, but the interquartile range still comfortably lies within the orange yardang band in Fig. 34 (Table 15), which confirmed our classification of these BLFs as yardangs. The median sinuosity is similar to both Puna fields and the mesoyardangs in Dunhuang, South (Fig. 34; Table 15). However, these fields, both Puna and Dunhuang fields, are smaller in scale, than the yardangs of the Lut Desert (Fig. 33 & 34), however, BLF’s in T18 space farther apart than all terrestrial yardangs and dunes (Fig. 35). This may be a result of the substrate, which is unknown, or from atmospheric conditions.

When the statistical model was applied to the BLF parameters, it classified 7 yardangs and 39 dunes, we classified these features as yardangs (Table 16). The discrepancies between our morphology-based classification and the various model classifications is likely due to the lack of yardang training data on Titan. By including BLFs from T64-1, where both our morphology-
based classifications and model classifications align, it is expected that the statistical models would more readily classify BLFs in T18 as yardangs.

The striking similarities in appearance between the yardangs in T18 and the yardangs in Iran may also shed light on possible materials the features in T18 formed in. Since the features are not located on or near a dome, we suggest it is unlikely that these features formed in volcanically-related strata. Rather we suggest that yardangs in T18 may have formed in loosely cemented basin fill deposits, in a similar manner as yardangs in the Lut Desert.

Similar to BLFs in T18, the BLFs in T64-1 are not as long as yardangs in the Lut Desert (Fig. 33); however, they are similar in length, width, and spacing as the interpreted yardangs in T18 (Figs. 33-35). The entire IQR for T64-1 BLFs reside within the orange yardang band of Fig. 36 with a median sinuosity similar to T18, Puna North, Puna South, and Dunhuang South (Table 15). With the application of the statistical model to T64-1, the model classified 18 yardangs and no dunes (Table 16).

As noted earlier, the BLFs in T64-1 are located atop a dome (Fig. 26). It was suggested by Schurmeier et al., (2018) that this dome is a volcanic upwarp. We suggest that these yardangs formed in materials similar to yardangs in the Puna fields of Argentina, which are associated with explosive volcanism. The deposits could have formed as liquid water was expelled and fragmented as an explosive cryovolcano, forming a type of “ash” which would have fallen to the surface and formed the deposit the yardangs formed in. It is also possible that the lithology was deposited as flows moving across the landscape from a cryovolcanic eruption, as long as this material retained an erodible texture.
BLFs in T83 have a higher IQR for sinuosity in Fig. 36. However, the spread of the IQR is significantly smaller than any dune or yardang field except the Lut Desert. Furthermore, the IQR lies within the yardang and dune yardang bands. BLFs in T83 are the closest in width to the Lut Desert and BLFs in T64-1 (Fig. 34), but are greater in spacing and lesser in length than the Lut Desert (Fig. 33 & 35). BLFs in T83 are distinctly similar in morphological appearance to yardangs in T64-1 (Figs. 26, 30, 36), which, coupled with similarities in width with the Lut Desert, led us to interpret them as yardangs.

When the statistical model was applied to T83 BLFs, 5 yardangs out of 17 features were classified (Table 16). The discrepancy between the model classification and the classification made based upon the geomorphological interpretations is likely due to similar scales between the features in T83 and the dunes in T3 used in the training data (Figs. 33 & 34). The inability of the model to examine the similarities in

Fig. 37. (Above) SAR image of interpreted yardangs in T83. (Below) Radar image of yardangs in the Lut Desert, Iran. Note the similarities in appearance between the interpreted yardangs in T83 with the yardangs in the Lut Desert. Both fields display a high feature density consistent with yardang fields as observed in the Dunhuang and Puna fields as well.
appearance shown in Fig. 37 is what likely led to the difference between our morphology-based classifications and the model classification. Fluvial erosion in T83 may have also altered the feature shapes enough to differentiate them and perhaps cause the sinuosity to increase, such that the models were unable to classify them as yardangs.

BLF’s in T83 are located near BLF’s in T64 (Fig. 14). In accordance with the this and the BLFs in T83 being located on what appears to be a dome or topographically higher region (Figs. 30), we suggest that they formed in materials similar to the yardangs in T64-1. It is possible that a series of dome-like ash deposits or flows related to cryovocanism near T64 may have covered a geographically large area, which extends over into the current T83 swath. This area could have been uplifted, causing it to be subject to aeolian and fluvial incision, providing a proper setting where yardangs could develop. This potential cryovolcanic event appears to be unique to the region where these yardangs formed.

BLFs in T23 and T30 were classified as stabilized dunes based upon similarities with dunes in the Namib Sand Sea and T3 as well as observed branching, characteristic of dunes and not yardangs. BLFs in T23 are similar in spacing and width to dunes in both the Namib Sand Sea and T3 (Figs. 33-35). Branching is observed and BLF sinuosity values are significantly higher (Fig. 36). The sinuosity IQR for BLFs in T23 lies within the yardang-dune to dune bands similar to dunes in the Namib Sand Sea and T3 with only a slightly higher median (Table 15).

BLF widths in T30 are nearly identical to the dune width in the Namib Sand Sea (Fig. 34) and the IQR for sinuosity is nearly identical to the BLFs in T23. Spacing is similar to T3 while lengths are similar to T23 (Fig. 36; Table 15).

The statistical model generated using random forests classified the all the BLFs
in T23 to be dunes except for one, corroborating our interpretations. For the BLFs in T30, model 1 classified 5 of 15 as yardangs (Table 16).

BLFs in T64-2 are unique in that they are found proximal to a field of more clearly defined yardangs in the same swath and general location. We interpret BLFs in T64-2 to be dunes due to possible branching (Fig. 28). The BLFs are also more sinuous than all observed yardang fields and shorter in length amongst all BLFs, dunes in the Namib Sand Sea and T3, and yardangs in the Lut Desert (Figs. 33 & 36; Table 15). They are similar in width to dunes in T3 and have the overall greatest spacing (Figs. 34 & 35; Table 15). The model classified 5 yardangs and 9 dunes in T64-2 (Table 16), corroborating our interpretation.

BLFs in T56 are unique in that we interpret them to be likely be interdunes, based upon the presence of dune-like, SAR-dark lineations between the bright features. Thus, it seems irrelevant to discuss our measurements and the statistical model since the parameters for classification do not pertain to these features.

While useful in examining and classifying the BLFs found in Titan, the random forest analysis is insufficient alone to classify the features found on Titan. This is evident when examining the discrepancies between model classifications and geomorphologic observations found in fields on swaths T23, T56, and T83. This could be caused by feature maturity since yardangs tend to become narrower, more streamlined, with wider corridors, and may have greater discontinuity (de Silva et al., 2010, Dong et al., 2012); as well as the models’ inability to take into account branching, alterations from fluvial activity, and a lack of training data for yardangs on Titan. It is also important to note the models did not predict entire fields of yardangs, but rather the presence of some yardangs across the fields. While this is not entirely unrealistic, since yardangs and dunes can be found in yardang fields such as those in China (Fig.
3) and Iran, the measured features are morphologically similar enough across the fields that there is no reason to expect dunes and yardangs will be interspersed within the same field. Due to this and the errors naturally associated with the model (Table 16), it is unwise to attempt to classify individual features, independent of their presence in a group or field. It is far more realistic to use the models coupled with detailed morphology, observations and measurements to broadly distinguish between yardangs and dune fields.

It is thought that yardangs orient in the direction of the predominant winds as abrasion and deflation, amongst other processes, streamline the features (McCauley et al., 1977, Whitney, 1983, Goudie, 2008). Studies have not yet been successful at linking yardang orientation to regional-scale model winds on Mars (Mandt et al., 2009). Primary wind directions are evidenced by dunes near yardang fields, the presence and orientations of large gravel ripples near yardang fields, and wind streaks; enabling the use of these features as both current indicators for primary wind direction in this. Some of the yardangs found at the southwest margins of the T64-1 field seem more ragged, and appear to underlie the other, more northerly yardangs, indicating that they may be older features.

Fig. 38. SAR image of yardangs in T64-1. The red lines denote measured yardangs. The green lines denote possible yardangs that were not included in the data set due to uncertainty regarding their location. Note the various orientations of the green features which may suggest older yardangs that formed under different wind regimes that are now being destroyed under the current wind regime.
Because they are oriented differently to the northerly yardangs, we may also assume that they formed under a different wind regime (Fig. 37).

Fig. 39. (Above) Global map of Titan with dune long axis orientation vectors denoted by the white arrows. (Below) Global map of maximum gross bedform-normal transport with a wind threshold speed of $u_t=0.4$ m/s predicted by Tokano (2010) with BLF and stabilized dune orientations from this study overlain in red. Notice how the orientations in the northern midlatitudes strongly resemble orientations predicted by Tokano (2010).

All of the features in the northern midlatitudes examined, excluding the dunes in T3, trend northwest to southeast (Fig. 38). If the BLFs are yardangs, and if we can assume winds blow down the yardang long axis, which appears generally true (but is still under discussion), then
they can be used to determine the prevailing wind direction and sediment transport. These features indicate that the winds at the northern midlatitudes blow in a south-southeast direction, toward the equator, with sediment transport in the same direction. The BLFs nearer to the equator have significantly stronger west-east trends indicating prevailing winds blew from west to east, matching known wind directions deduced from linear dune long axes (Lorenz and Radebaugh 2009) and seasonal model winds (Tokano 2010) in the large sand seas. BLF orientations can be used to refine atmospheric circulation models, if we assume winds blow directly down the yardang long axis (Fig. 38).

5 CONCLUSION

In this study, we have compared bright linear features (BLF) on Titan with yardangs in China, Argentina, and Iran as well as with large linear dunes in the Namib Sand Sea and on Titan. A detailed geomorphologic and morphometric comparison between the various fields was conducted and coupled with the application of a random forest statistical analysis for landform classification.

By coupling these models with detailed morphological observations and measurements it is possible to broadly distinguish between yardangs and dune fields. Features in T18 and T64 appear similar to yardangs in radar images of Iran’s Lut Desert (Figs. 1 & 18). They are also classified as yardangs in the statistical analysis. BLFs in T64-1 show a strong morphologic similarity with those in T18 and to the yardangs of the Lut Desert, Iran; moreover, the statistical model classifies all of them as yardangs (Table 16). We therefore interpret it to be a yardang field. While the BLFs in T83 morphologically closely resemble the BLFs in T64 and the
yardangs in Iran, most were not classified as yardangs in any of the statistical models. However, we classify them as yardangs due to the morphological similarities with Iran and T64-1 (Fig. 1 & 30). On the other hand, BLFs in T23 show branching similar to dunes, yet some of the models identify yardangs in the data. Due to the branching, sinuosity values, and the random forest model classification, this field is best identified as a dune field. BLFs in T30 have the same morphology as those in T23 including branching (Figs. 20 & 22), a higher degree of sinuosity, and a greater number of dune predictions. They have similar widths and spacings and have very similar ranges of sinuosity (Figs. 34-36). We therefore suggest the BLFs in T23 to be the bright floors between dark dunes in a dune field. BLFs in T56 are lighter than most titanian dunes, but they still have dune-like aspects, such as a clear SAR difference between dune and interdune, indicating they are likely dunes.

Yardangs in T64-1 and T83 are found atop highly erodible domes, and could have formed in cryovolcanic deposits similar in nature (e.g. particle size, hardness, and origin) to the materials in which the yardangs in the Puna formed in, based upon morphological similarities. Yardangs in T18 likely formed in erodible basin fill type deposits similar to terrestrial yardangs in the Lut Desert, due to the similarities in morphology and appearance between the two fields.

Due to limitations and error within the statistical models as well as contradictions with geomorphological interpretations, we advise that random forest classification analysis be used to broadly classify fields and not individual features in a field. The random forest model’s greatest weakness is a lack of data for landforms of confirmed origin on Titan for the training set. By incorporating the dunes in T3 and the proposed yardangs in T64-1 and T18 as training data it is believed that the accuracy of classifications within these models will greatly increase and provide a more robust means for classification.
Addition of all known mega-yardang fields on Earth, Mars, and possibly Venus to the data set in the future would enable a stronger and more robust model for classification. Other statistical methods and models such as Principal Component Analysis, Cluster Analysis, and Multivariate Statistical Analysis may also be applied to these features for not only classification purposes but to also indicate key defining differences between dunes and yardangs.

In conclusion, it appears that sinuosity is a defining characteristic of yardangs and leads to the best classification of potential yardang features, morphologically and when aided by random forest statistical analysis. We maintain that BLFs in T18, T64-1, and T83 are yardangs, erodible sediment carved on Titan by wind. BLF orientations can be used to validate global climate models and surface wind projections, now and in the past, and host rock properties can be extrapolated when drawing upon morphologic similarities with terrestrial yardang fields.


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