1 **Long Wavelength Sinuosity of Linear Dunes on Earth and Titan and the Effect of**
2 **Underlying Topography**

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22 **Key Points:**

23 • Local variations in dune trend are identified in some linear dunefields on Earth and Titan.

24 • The cause is identified as underlying topographic relief resulting in down-slope
25 deflection of dunes.

26 • Dunefield patterning offers the potential to infer topographic relief, with implications for
27 identifying planetary lander sites.
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Abstract

On both Earth and Titan, some linear dunefields are characterized by curvilinear patterning atypical of the regularity and straightness of typical longitudinal dunefields. We use remotely sensed imagery and an automated dune crestline detection algorithm to analyze the controls on spatial patterning. Here it is shown that topography can influence the patterning, as dune alignments bend to deflect downslope under the influence of gravity. The effect is pronounced in a terrestrial dunefield (the Great Sandy Desert, Australia) where substantial topography underlies, but absent where the dunefield is underlain by subdued relief (southwestern Kalahari). This knowledge allows the inference of subtle topographic changes underlying dunefields from dunefield patterning, where other sources of elevation data may be absent. This methodology is explored using the Belet Sand Sea of Titan, and likely areas of topographic change at resolutions finer than those currently available from radar altimetry are inferred.

Plain Language Summary

Linear dunes form large dunefields both on Earth and Saturn's moon Titan, and look remarkably similar on both worlds. They are characterized by repeated ridges of sand which extend approximately parallel to the wind, and may continue unbroken for tens or even hundreds of kilometers. Perhaps their most remarkable feature is their regularity, and consistent orientation of the dunes. In a few locations, however, the dunes form distinctive curved patterns. This study investigates the causes of this phenomenon, by comparing two dunefields on Earth; Australia's Great Sandy Desert, where the curved dunes are abundant, and the Kalahari of southern Africa, where they are absent.

The cause of the curved dunes is shown to be underlying topography. The Kalahari is very flat, and thus the dunes form straight lines. But the Great Sandy Desert lies over a long-dry river valley system, and where the dunes encounter slopes, the deflect downslope. On Titan, knowledge of surface elevations and topography is patchy, and with lander missions planned better understanding is important. The method of analysis proposed here is demonstrated on radar data from the Belet dunefield of Titan, and we show that topography can be inferred from dune patterning alone.

1 Introduction

Accurate determination of surface topography is crucial for the success of planetary landers (e.g. Braun & Manning, 2007; Golombek et al., 1997; Striepe et al., 2006; Witte et al., 2016). Although final guidance is typically done autonomously (e.g. using LiDAR; Johnson et al., 2002), initial site selection remains crucial if hazard avoidance is to be maximized. This is often hampered by a lack of high-resolution imaging and/or topographic data of a world's surface, perhaps best illustrated by the design of the Huygens lander for Saturn's moon Titan as part of the Cassini-Huygens mission, given that at the time of launch it was unclear whether the landing would be on a solid or liquid surface (Zarnecki et al., 2005). The fact that the surface was revealed during the descent of the lander not only to be solid, but topographically complex (Soderblom et al., 2007), makes the successful landing even more remarkable. The continued Cassini Prime, Equinox, Solstice and Grand Finale missions (2005-2017) included a total of 127 Titan close flybys, and yet the most robust published elevation model for Titan (Corlies et al., 2017), based on radar altimetry, radar SAR and photogrammetry, is still based on just 9.2% coverage, with the rest interpolated. Both for reasons of understanding geological processes (Corlies et al., 2017), but also in the light of future exploration of Titan (Lorenz et al., 2017; Turtle et al., 2018), better understanding of Titan's topography is needed.

Linear dunes (that is, dunes forming approximately longitudinal to the net sand-moving winds; Fryberger & Dean, 1979; Lancaster, 1982; Tsoar, 1983) are the most abundant desert dune type on Earth (Lancaster 1989; Lancaster, 1995). They also form the most extensive dune system in the solar system as an equator-encircling belt on Titan covering as much as 15% of the body (Lorenz & Radebaugh, 2009; Lorenz et al., 2006; Radebaugh et al., 2008; Radebaugh et al., 2010). Whether linear dunes align with the net annual sand transporting wind (McKee, 1979), to maximize the net annual sand transport across the crest of the dune (Rubin & Hunter, 1987), or if there is a supply-limited control on their orientation (du Pont et al., 2014; Ping et al., 2014) is debated. Their remarkable regularity and consistency in terms of orientation, relief and spacing across distances of 1-10^3 km distinguish them; "Earth has no landform more regular and extensive" (Cooke et al., 1993; p.374). Typically, this regularity is expressed in landforms which, on Earth, are 5 – 120 m high, extend for 10 – 100 km, are regularly spaced on the order of 500 – 5000 m, and which typically occur in groupings of up to 1000 with orientations deviating by only a few degrees over the course of 100s of km (Fig. 1a, 1b; Lancaster, 1995). On Titan, an estimated 2×10^5 km^3 of organic material is distributed in the equatorial belt of linear dunes, typically approaching ~100 m high where measurements are possible, and similarly arranged in regular, repeated patterns of hundreds of adjacent dunes (Lorenz et al., 2008; Lorenz & Radebaugh, 2009; Lorenz et al., 2006; Radebaugh et al., 2008; Rodriguez et al., 2014).

Although linear dunes are characterized by their regularity and organization relative to the regional wind regime, their orientation and planform patterning can also be influenced by obstacles within the dunefield. On both Earth (Fig 1c) and Titan (Fig 1d) dunes are seen to reorient themselves upwind of topographic obstacles. This topographic steering is well-reported for terrestrial coastal dunes (e.g. Bauer et al., 2012; Walker et al., 2009), and the mechanism relates to feedbacks with the deformable bed and boundary layer which propagate upwind (Wilson, 1972), by which bedforms may be deflected even kilometres upwind of the obstruction to sediment transport.

102   In some dunefields, however, a singular, preferential orientation of the dunes is less pronounced;
103   the dunes' orientation over a given region, whilst spacing remains regular, is more complex. This
104   effect is seen in areas of the Great Sandy Desert of northwestern Australia (Fig. 1e), as well as
105   the Australian Great Victoria Desert (Hesse, 2010; 2011) and is also observed on some of Titan's
106   dunefields (Fig. 1f). In both of these cases, the dunes have a pronounced, large-scale curvilinear
107   patterning in planform, resulting in long-wavelength (~10-100 km) sinuosity of the dunes
108   without obvious topographical obstructions causing the deflections in patterning (Lucas et al.,
109   2015), as well as the continental-scale (100-1000 km) curvature shown by some dunefields
110   relating to synoptic-scale changes in typical wind regime (e.g. Hesse, 2010; Lancaster, 1981).
111   There is, however, pronounced variability in the topography underlying the Great Sandy Desert,
112   and it is this topographical influence that we seek to investigate. This paper thus aims to 1)
113   investigate the causes of broad-scale linear dune curvilinearity in the terrestrial setting, and 2)
114   explore the analogue inferences that can thus be derived for Titan's dunefields. We do this by
115   investigating 1) the Great Sandy Desert of western Australia, where locally curvilinear
116   duneforms are found, 2) the southwestern Kalahari, where a regional shift in linear dune
117   orientation exists but localized variability is absent and 3) the Belet Sand Sea on Titan, where
118   localized shifts in dune orientation are apparent. This enables us to deduce the topographic
119   influences on different terrestrial dunefields and to explore the likely inferences for planetary
120   topography that can be interpreted from dunefield patterning.

121   **2 Materials and Methods**

122 We use the Aster GDEM (NASA/METI, 2001), and Landsat8 RGB (Red:Green:Blue – Bands 4-
123 2) and panchromatic data (Band 8), to analyse a) a region of the Great Sandy Desert in
124 northwestern Australia, between 19 - 21°S and 122 - 125°E, b) the southwestern Kalahari of
125 southern Africa, between 24 - 27°S and 19-21 °E. All analysis was performed within ArcGIS
126 10.3. The Linear Dune Oriented (LIDO) algorithm presented by Telfer et al. (2015) was used on
127 the 15 m resolution panchromatic Band 8 data to define dune crestlines based on changes in
128 image brightness apparent at the crests of the dunes. A pan-sharpened RGB composite was used
129 for validation of the automated classification of crestlines. Full methodological details of the
130 algorithm, its accuracy and precision, and details of the images used are provided in Telfer et al.
131 (2015) and in the Supplementary Material, but in summary, the routine uses a pair of 5x5 Sobel
132 operators on the panchromatic image to derive gradient magnitude and direction. These are used
133 to identify reflectance gradients within ± 45° of the modal direction (which correspond to dune
134 crest orientation), and the reflectance gradient magnitude is then used to define candidate
135 crestline pixels. In this instance, the recursivity of defining strong and weak candidate dune
136 crest-line zones proposed in Telfer et al. (2015) was not found necessary, and pixels were
137 included where the gradient magnitude exceeded $\mu + (1.25 \times \sigma)$ (where μ is the mean reflectance,
138 and σ the standard deviation). Resultant zones of less than 4500 m^2 were excluded to reduce
139 noise, and candidate pixels were then vectorized using ArcGIS's ArcScan tool (see
140 Supplementary Material for details of the settings employed). Only vectorized crestline sections
141 in excess of 1 km length were considered for further analysis to further reduce noise. ArcGIS's
142 Linear Directional Mean tool was used to derive a regional average orientation for the dunes, and
143 the variation of individual dunes from this mean was subsequently classified using the Natural
144 Breaks method with Jenks optimization within ArcGIS.

145 For the Belet dunefield of Titan, we use a mosaic of the equatorial, trailing hemisphere T8 and
146 T61 Cassini Synthetic Aperture RADAR (SAR) swaths. These offered a pixel size of
147 approximately 180 × 180 m. The study area extends from latitudes -5.6° to -10.2°– -12.3° and
148 longitudes 108.7° to 124.3°; a total area of approximately 180,000 km^2. The dunes on Titan are
149 characterized by a change in their 2.17 cm SAR reflectance relative to the surrounding terrain,
150 with dunes being SAR-dark and underlying materials, and sometimes crestline reflections, being
151 SAR-bright, similar to 3-cm SAR observations of fine dune sand on Earth. This, together with
152 presence in some areas of apparently sandy interdunes and relatively poor image resolutions,
153 means that rather than observing the change in visible light at the crestline (i.e. the contrast
154 between illuminated and shadowed flanks of the dunes), we note that we are likely to be
155 mapping the dune/interdune margin (e.g. Savage et al. 2014). Nonetheless, examples of the
156 resultant digitization (see Supplementary Material) suggest that the routine accurately captures
157 overall trends at the scales investigated here. The LIDO algorithm was again used to define dune
158 trendlines, although the different characteristics of the SAR observations necessitated some
159 modification of the protocol. Due to the noisier nature of the Cassini SAR data compared to the
160 Landsat images, a 3 × 3 low-pass filter was applied initially to reduce the influence of unduly
161 SAR-bright pixels. This was then passed with the same pair of Sobel operators, from which
162 gradient magnitude and direction were calculated. Despite clear visual differentiation of many of
163 the dunes, the strength of the gradient was highly variable on a pixel-by-pixel basis, and a
164 relaxed criterion of $\mu - (0.25 \times \sigma)$ sigma was required. Combined with a slightly widened
165 criterion for inclusion in terms of gradient direction (± 60° of the mode), suitable delineation of
166 dune sections was achieved. Once again, relatively small candidate zones were removed (< 1.6

167   km^2) and trendlines vectorized with ArcScan. Reflecting the lower resolution of the SAR data,
168   only sections longer than 3 km were included for further analysis.

3 Results

3.1 Great Sandy Desert

171   The LIDO algorithm identified a total of 44 823 crestline sections in excess of 1 km in length
172   (mean = 2.14 km, standard deviation = 1.36 km, maximum = 39.70 km) for the studied sector of
173   the Great Sandy Desert. This region epitomizes the long-wavelength, sinuous linear dunes, and is
174   topographically characterized by a broad E-W drainage in its northern half (the Mandora
175   palaeodrainage (Tapley, 1988; Wyrwoll et al., 1986); the catchment is currently dry), with ~230
176   m relief, and highlands (~250 m elevation) in the south (Fig. 2a). The dunes propagate
177   essentially westwards under the influence of easterly net sand-transporting winds associated with
178   the continental anticyclone (Hesse, 2010; Kalma et al., 1988). Linear dunes (Fig. 2b) are widely
179   distributed across the region, and do not show clear regional trends in abundance, though there
180   are, as is common in linear dunefields, some localized groupings of dunes, especially in the
181   southern part of the study area. However, when the deviation of individual dune orientation is
182   calculated against the regional mean (roughly E – W: 281.4°; Fig. 2c), a relationship with the
183   topography (Fig. 2a) becomes apparent. When the deflection from Fig. 2c is averaged to a 5km
184   grid (Fig. 3a), the zonal nature of the local reorientation of the dunes can be clearly seen, and is,
185   in, part, related to landscape roughness, in this case the standard deviation of elevations from
186   Fig. 2a over a 5 km grid (Fig. 3b). However, it is when the slope orientation, derived from the
187   regional elevation data from Fig. 2a and gridded to 5 km squares, shown as arrows in Fig. 3c, is
188   shown against the 5 km gridded dune deflection (3a) that the true nature of the relationship
189   becomes apparent (Fig. 3c). Dunes deflect northwards (red colors) when the slope descends
190   towards the north, and southwards (blue) in the case of south-dipping slopes. Given the westward
191   propagation of the dunefield, dunes deflect downslope when obliquely encountering both rising
192   and falling topography.

3.2 Southwestern Kalahari

194   The studied sector of the southwestern Kalahari dunefield occupies a broad swathe of dunes
195   trending approximately NNW-SSE, and the LIDO algorithm identified 30 782 crestline sections
196   in excess of 1 km in length. The topography of the region is very subdued (Fig. 4a) and has
197   indeed led to the coining of the term 'geomonotony' (Eckhardt, 2010); dunes are on the order of
198   8 – 10 m in elevation, and the few dry valleys that dissect the dunes are typically broad (~10 km)
199   and shallow (~30 m). Deviations to the mean regional trend of the dune crestlines are limited to a
200   shift from north-south trending at the northern end of the study area to northwest-southeast
201   trending at the southern edge of the dunefield (Fig. 4b and 4c). This overall pattern is well-
202   reported, and typically associated with the southern African continental anticyclone (Lancaster,
203   1980; Lancaster, 1981; Lancaster, 1988). Although some very localized reorganisation of pattern
204   and orientation in the vicinity of dry valleys is apparent along the Auob and Nossop river valleys
205   (Fig. 4a; Bullard & Nash, 1998, 2000), in general, the zonal variability evident in the Great
206   Sandy is absent here. Similarly, no clear relationship exists between the deflection of the dunes
207   (Fig. 5a) and the minimal landscape roughness (Fig 5.b), or the low-relief slopes evident
208   throughout the dunefield (Fig. 5c). Only in a small region adjoining the Nossob catchment in the

209   far north of the study region does enhanced topography coincide with local deflection of the
210   dunes at the scale investigated here.

211   **4 Discussion**

212   The findings presented in the preceding section can be summarized; where substantial
213   topographic variation exists beneath a linear dunefield, it can result in downslope deflection of
214   the dunes and disruption of the regional pattern. This effect is quantified in Figure 6. For the
215   Great Sandy Desert, with its substantial (~200 m) local variation in topography, there is a strong
216   correlation between the incidence angle between the dunes and the underlying slope, and the
217   resultant deviation from the regional mean trend of the dunes (Fig. 6a). This correlation is further
218   increased (Fig. 6b) when the incident angle of the dune trend/slope angle is weighted by the
219   magnitude of the slope; that is, steeper local slopes seem to deflect dunes more than shallow
220   gradients. The magnitude of the deflection of the dune is maximized when the dune/slope
221   intercept reaches 90° (that is, when the dune trend is orthogonal to the local slope). By contrast,
222   for the Kalahari, with its low relief underlying the dunefield, no such correlation is apparent,
223   either unweighted (Fig. 6c) or weighted (Fig. 6d). Although the effect is seen here manifested
224   around a large valley system, the presence of deflection even on dunes extending up slopes
225   implies that similar effects are likely on positive relief.

226   A number of possibilities exist for the mechanism controlling this effect. Because, by definition
227   of their topographic expression, aeolian entrainment and deposition on dune surfaces is rarely on
228   horizontal, flat surfaces, the influence of slope on aeolian processes has been studied using
229   numerical modelling (e.g. Tsoar et al., 1996; White & Tsoar, 1998), computational fluid
230   dynamics (Fariaet al., 2011; Huang et al., 2008) and wind tunnel experimentation (Bullard &
231   Nash, 1998; Bullard et al., 2000; Iversen & Rasmussen, 1994, 1999; White & Tsoar, 1998). Few
232   studies have focussed at the landform scale, and fewer still consider the role of oblique slopes.
233   However, wind tunnel experimentation has suggested that the net result of oblique winds
234   incident to a valley is the deflection of the wind along the valley (i.e. in the opposite direction to
235   that observed here for downward slopes) (Bullard and Nash, 2000; Garvey et al., 2005). This
236   suggests that a mechanism other than simple topographic steering of winds along valleys is
237   necessary to explain the observations.

238   Two possibilities are suggested here for a mechanism by which the dunes are deflected
239   downslope. Firstly, it may simply be a gravitational effect, as whether dunes are descending or
240   ascending incident oblique slopes, the deflection is downhill. Whilst gravity-driven (that is,
241   katabatic) winds are known to be influenced by topography (e.g. Nylen et al., 2004), it is also
242   possible that gravitational effects would also presumably affect individual transported grains by
243   preferential settling on deposition from aeolian transport downslope; on deposition, grains might
244   roll downhill, but will not roll uphill. Extrapolated to the landform scale, the result would be the
245   deflection of the dune crestline down the slope. Alternatively, it may be that the effect of the
246   valley on the localized wind regime acts in a manner analogous to that known to occur over
247   positive topographic features, such as coastal foredunes. Here, the effect of topography in
248   steering incident winds towards the normal direction of the crestline is well described (reviewed
249   in Hesp et al., 2015), and results from the pressure gradient force resulting from differential flow
250   acceleration associated with oblique incident winds. Whilst the impacts of such topographic
251   steering have predominantly been studied on dunes transverse to the net air flow, it is possible

252   that pressure-driven force associated with flow separation could deflect the linear dunes. Such
253   effects have been modelled using wind tunnels and differing geometries of valley (Bullard et al.,
254   2000), and whilst it was generally observed that the effect of negative topography was the
255   steering of streamlines along the valley line (i.e. the opposite direction to that observed here), it
256   is also noted that the effects are a function of a complex set of variables including valley
257   geometry, thermal stability of the airmass and wind regime. Further study is needed to
258   disentangle the relative roles of gravity-driven mechanisms and possible localized effects of
259   topography on the wind regime in realigning the dunes.

260   These results suggest a method for identifying topography from dunefield patterning where no
261   such elevation data might otherwise be sparse, or missing, at the relevant scale. Here we apply
262   the dune trendline detection method to the Belet dunefield on Titan, where similar curvilinear
263   dune patterning to that observed in the Great Sandy Desert is present. The studied region consists
264   of a broad belt of west-east trending dunes (sand transport direction inferred to be eastward from
265   dune interactions with obstacles; Radebaugh et al. 2010) with several radar-bright obstacles
266   interrupting the patterning, and a dark, largely dune-free corridor to the southeast of the images.
267   The LIDO algorithm identifies 5322 dune sections of at least 3 km length within the studied
268   region, with a radial mean orientation of 79°.

269   When the deviation in the dune orientations from the regional mean is considered (Figure 7a),
270   the superficial similarity with the Great Sandy Desert is further supported. Unlike in the
271   Kalahari, variation in dune orientation occurs at a relatively local scale. In some instances
272   (Figure 7b), such as in the far northwest of the studied area, these deviations are clearly adjacent
273   to radar-bright gaps in the dune sands, and this effect is both well-reported (Ewing et al., 2015;
274   Lorenz et al., 2006; Radebaugh et al., 2008; Radebaugh et al., 2010; Savage et al., 2014), and
275   likely to be due to deflection of dunes around obstacles (i.e. mountains or hills) standing proud of
276   the dunefield. But in other areas, localized variance in dune trendline is not obviously associated
277   with obstacles, and thus we propose that this is likely the result of underlying topography at a
278   scale not observed by Cassini SAR and radar altimetry data. The resultant likely topographic
279   trends are illustrated in Figure 7b, and are likely to be at a scale more subtle than that observable
280   from the Titan Digital Elevation Model (DEM) (Corlies et al., 2017). While some lineations in
281   the southern and eastern part of the image can still be observed but not selected by the LIDO
282   algorithm, it is tempting to suggest that at least a portion of that corridor is, in the light of its
283   morphology and the inferred slopes down into this region, a fluvial or relic fluvial valley (Birch
284   et al., 2016; Burr et al., 2013; Jaumann et al., 2008; Langhans et al., 2012; Lorenz et al., 2008).
285   It is also possible that small-scale (i.e. individual dune) deflections evident in some parts of the
286   studied area are indicative of localized dune trends, but further work is needed to confirm this.
287   Such information may prove valuable in planning lander sites for future missions to Titan, as it
288   offers additional information regarding the surface of potential landing sites and their surface
289   topography. In addition to the likely increase in surface roughness associated with fluvial erosion
290   creating local topographic relief, it is also likely that Titan's fluvial channels, especially those
291   that are radar-bright, may have increased frequency of fluvially-derived clasts (Burr et al., 2013),
292   an additional hazard for planetary landers.

293   It has been noted that despite the differences of Titan's different atmospheric density (146 KPa,
294   or 145% that of Earth), gravity (1.35 m s^{-2}, or 14% that of Earth) and likely particle density (0.4-
295   1.5 g cm^{-3}, or 15-55% that of Earth's silicate sands), the similarity of the resultant aeolian

296   landforms to terrestrial dunes is striking (Lorenz et al., 2006). The presence of curvilinear
297   longitudinal dune forms is further evidence of this similarity. It is possible that their presence on
298   Titan, given the low gravity and very low particle/fluid density ratio (Burr et al., 2015), might
299   favour pressure-gradient mechanisms.

5 Conclusions

301   We investigate the properties of linear (longitudinal) dunefields where the typically highly-
302   consistent orientation of dunes is less pronounced, and curvilinear, long-wavelength sinuosity is
303   apparent. Such patterning is scarce on Earth, but relatively common on Titan. We show that on
304   Earth, such patterning results from underlying topography causing the dunes to deflect
305   downslope as they form and propagate. The effect is maximized as the incidence angle between
306   the dunes and the slope approaches 90°, and is further shown to be dependent on the gradient of
307   the slope, with steeper slopes resulting in more pronounced deflection. Dune morphometry thus
308   offers an additional source of information regarding local and regional topography where such
309   information is scarce, as is the case for some planetary dunefields. The mechanism by which the
310   dunes are deflected likely relates to either gravity-driven processes affecting either the airflow or
311   settling grains, or by local pressure gradients related to airflow separation; the presence of the
312   curving dunes even in Titan's low gravity may favour the latter. We demonstrate the potential of
313   this method to infer topography in a region of the Belet Sand Sea in Titan's equatorial belt, and
314   suggest it offers the potential to increase topographic understanding of the surface of Titan both
315   for geological purposes and in terms of identifying optimal lander sites for future missions. To
316   find the lowest relief areas amongst the dunes, future landers would be best guided away from
317   areas where dunes demonstrate long-wavelength sinuosity.

318   **Acknowledgments, Samples, and Data**

328

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494   **Figure 1**. Linear dunes are typified by remarkably regular planform patterning, with dunes
495   aligned approximately parallel to the net sand-transporting regional winds. Examples from a) the
496   Simpson Desert, Australia and b) the southwestern Kalahari of central southern Africa highlight
497   this regularity. In the case of the Kalahari, the orientation patterns demonstrate the occasional
498   tendency of these dunefields to reflect changes in the orientation of regional-scale atmospheric
499   circulation patterns. Such dunes may reorient around topographic obstacles to sand-transporting
500   wind flow, illustrated here from c) the Libyan Sahara (23.75°N, 21.38°E) and d) the Belet
501   dunefield of Titan (from the T61 swath, Aug. 2009). Figure 1a, 1b, 1c and 1e are courtesy of
502   Google Earth/SPOT/CNRS. In some regions, however, the dunes take a curvilinear form without
503   obvious topographic obstructions causing the change to patterning, seen here in e) the Great
504   Sandy Desert of northwestern Australia and f) the Belet dunefield (from T8, October 2005).

505   **Figure 2.** Topographic data and dune alignment for the Great Sandy Desert. a) The relief of the
506   Great Sandy Desert, b) Dune crestlines as determined by the LIDO automated detection routine,
507   and c) the deflection of the dune orientations relative to the regional mean (red = northwards;
508   blue = southwards), which highlights the localized nature of the pattern deviation. Net sand
509   transport is east-west.

510   **Figure 3.** The influence of relief on the orientation of sand dunes in the Great Sandy Desert. a)
511   shows the deviation in the regional directional trend from 2c shown here as 5 km-gridded means;
512   b) landscape roughness (here calculated as the standard deviation of elevations within a 5 km
513   grid) can be seen to closely resemble the pattern of dune deflection; c) the relative orientation of
514   the slope (arrows point downslope and are scaled by gradient) correlates most closely with the
515   deflection of the dunes (see Fig. 6).

516   **Figure 4.** Topographic data and dune alignment for the Kalahari. a) The relief of the
517   southwestern Kalahari, whilst showing greater regional changes than the Great Sandy, has much
518   more subdued local expression of relief. b) The dunes occur in a broad swathe with net sand-
519   transporting wind from the north-northwest and c) deviations in the dune crestline orientations,
520   unlike the Great Sandy, do not show pronounced local variation (cf Figure 2c), but instead reflect
521   large-scale regional changes.

522   **Figure 5.** The influence of relief on the orientation of sand dunes in the Kalahari. a) The
523   southwestern Kalahari's regional trend in dune orientation is largely independent of the relief,
524   and b) the topographic roughness (again, shown as standard deviations of elevation around a 5
525   km downsampled grid of the Aster GDEM v2.0 data) is much lower throughout the dunefield.
526   The higher relief mountains in the southwestern corner of the image are beyond the dunefield
527   limits. c) The magnitude and orientation of local slopes again highlights the lower relief apparent
528   here.

529   **Figure 6.** The relationship between the deflection of the dunes and the incident slope angle is
530   dependent upon the degree of underlying topography. a) The deflection of the Great Sandy's
531   dunes from the regional mean (approximately east-west; 280.4°) plotted as a function of the
532   relative orientation of the 5 km gridded local slope, and b) the same data, but weighted according
533   to the magnitude of the gradient. Here a cubic fit is used to reflect the likely maximum deflection
534   as slope incidence approaches +/- 90°. By contrast, no trend is apparent for the low-relief
535   southwestern Kalahari, with the data either c) unweighted or d) weighted.

536   **Figure 7.** The orientations of dune section at the eastern end of the Belet dunefield, as
537   determined reveals some dune deviations attributable to deflection around obstacles, but also
538   some which are not apparently associated with this mechanism. a) The dune trends mapped as
539   deviations from the regional mean with major radar-bright obstacles highlighted in white, and b)
540   annotated inferences reveal deviations likely due to not just topographic obstacles to airflow
541   (white arrows), but also those likely due to underlying topography. Here, the inferred
542   topographic trend is illustrated with a black arrow pointed downslope. These reveal details of
543   topography not apparent from either c) the Imaging Science Subsystem (ISS) imagery or d) the
544   derived elevation model data product (here from Lorenz et al., 2013).

Figure 1.

Figure 2.

a)

122°E   123°E   124°E   125°E

19°S

Study area location

Mandora palaeodrainage

20°S

Elevation (m)
High : 255

Low : 21

21°S

b)

50 km

N

c)

Deflection
(positive
northwards)

-101.4°

-101.4° - -16.9°

-16.9° - -12.4°

-12.4° - -8.9°

-8.9° - -5.9°

-5.9° - -2.9°

-2.9° - 0.6°

0.6° - 4.9°

4.9° - 15.5°

15.5° - 67.5°

Figure 3.

a)

b)

c)

Figure 4.

a)

19°E 20°E 21°E

24°S

1269
766
Elevation (m)

Study area
location

Nossop River

25°S

Auob River

26°S

N

50 km

27°S

b)

c)

Deflection
(positive
southwards)

─ -84.2 - -57.2
─ -57.2 - -19.2
─ -19.2 - -12.2
─ -12.2 - -5.2
─ -5.2 - -0.2
─ -0.2 - 3.8
─ 3.8 - 7.8
─ 7.8 - 11.8
─ 11.8 - 19.8
─ 19.8 - 37.8

Figure 5.

a) b) c)

N

50 km

Figure 6.

Figure 7.

Deviation from regional mean (°)
- -98.8 – -15.5
- -15.5 – -9.8
- -9.8 – -5.9
- -5.9 – -2.3
- -2.3 – 1.3
- 1.3 – 5.7
- 5.7 – 10.6
- 10.6 – 16.6
- 16.6 – 77.2
- obstacles

Fig. 1f extent

100 km

Fig. 7a and 7b extent

200 km

Fig. 7a and 7b extent