The relationship between barchan size and barchan morphology: a case study from Northern Namibia

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Abstract

Landform allometry has been a topic of inquiry since at least the 1970s. In this study, the presence of allometry is investigated for a barchan dunefield in northern Namibia. Using a combination of traditional morphometric parameters and techniques borrowed from geometric morphometrics it is shown that barchan allometry is present. This allometry is a combination of positive and negative allometry. Barchans show a definite change in mean shape as the size of the dune increases becoming more asymmetric. Differences in horn length, along with dune width, show positive allometry indicating that it changes faster than the shape changes. Barchan bilateral asymmetry and stoss length show negative allometry indicating that changes in these variables lag behind changes in size. Together, these results hint at the possible presence of threshold size differences beyond which distinct shape changes can be observed.

Keywords: Barchan; allometry; shape; size; geometric Morphometrics

Introduction

Barchans are free dunes that form in regions where both sand supply and wind direction variability are low (Al-Dousari et al., 2015; Wiggs, 2013). It is the most common dune form on Earth (Zhang et al., 2018) and is also considered to be the simplest and best understood type of dune (Herrmann et al., 2005). Their ubiquitous distribution is, however, debated with some authors (e.g., Schwämmle and Herrmann (2005)) considering barchans to be relatively uncommon while Peel et al. (1974) even considering barchans to be rare. The root cause of this discrepancy may involve viewing barchan abundance from either their distribution around the globe, where they can be considered widespread and 'common', or the amount of sediment they contain relative to other aeolian features.

The evolution of the characteristic shape of barchans has been studied from a simulation perspective (Durán et al., 2010; Wippermann & Gross, 1986) and direct observation (Elbelrhiti, 2012)]. Starting from an initial accumulation of sand with no typical barchan features (i.e. no horn or slip face), two processes act concurrently. These are horizontal displacement and shape modification. The rate of sediment displacement is inversely proportional to the amount of sediment that is being moved (Wiggs, 2013). Since the height of the accumulated sediment above the surface is lower at the edges, these get displaced faster. Ultimately, they will lead to the development of the characteristic horns of the barchan. The slip face develops due to an accumulation of sediment at the brink of the dune. This occurs as divergent airflow at the brink results in a sudden drop of the wind's sediment transport capacity (Wiggs, 2013). Sediment is deposited and when the accumulation reaches a critical level, gravitational collapse occurs leading to the establishment of a slip face (Andreotti et al., 2002; Parteli et al., 2007). The shape of a barchan is not constant and can change signifcantly over time (Hersen and Douady, 2005; Pike, 2000).

Mathematically, barchans are considered symmetrical objects that are deformed through the action of local environmental variables (Herrmann et al., 2005). These include: passing weather systems (Bourke, 2010); the angle between bimodal winds (Lv et al., 2016); topography and asymmetric sediment supply (Parteli et al., 2014). These environmental influences also lead to barchan asymmetry (Parteli et al., 2014) which manifests as either a preferential elongation (Bourke, 2010) or widening of one of the horns (Elbelrhiti et al., 2008). These are also typical metrics used when describing barchan asymmetry (Tsoar & Parteli, 2016; Zhang et al., 2018). Asymmetry is such a common part of barchan morphology that asymmetric dunes are considered to be the dominant manifestation (Andreotti et al., 2002; Parteli et al., 2014). Because of this preferential elongation occurring in one half of the barchan, barchan asymmetry can also be considered as a deviation from bilateral symmetry. Bilateral symmetry is described relative to a line of reflection where one half of an object is identical to the other half of an object (Claes et al., 2012).

Barchans also occur in a range of sizes that do not necessarily remain constant over time (Pike, 2000). The minimum height of a barchan is disputed with estimates ranging from 50 cm (Parteli et al., 2007) to a height of 2 m (Schwämmle & Herrmann, 2005). Using the equations provided by Hesp and Hastings (1998) this converts to a minimum width ranging from 15.48 m to 23.88 m and a stoss slope length (using the equation provided by Sauermann et al. (2000) and assuming an angle of repose of 31°) from between 0.08 m and 3.3 m. Jimenez et al. (1999) recorded an average width of 259 m (SD = 138) for barchans in Brazil while Dong et al. (2000) recorded an average width of 19.9 m (SD = 4.48) for barchans in China. Submarine barchans can be considerably larger having a width of 1451 m (SD = 694) in the Torres strait (Daniell & Hughes, 2007). This difference is due to the higher density of ocean water compared to the atmosphere (Parteli et al., 2007). Recorded stoss lengths can range from 22.6 m (SD = 6.48) for barchans in Peru (Finkel, 1959) to 185 m (SD = 104) for dunes in Egypt (Hamdan et al., 2016).

When the shape of a landform changes as the size changes, it is referred to as allometry (Minár et al., 2013). When a constant shape is maintained, isometry prevails (Evans, 2006). Allometry has been applied to landforms since at least the 1970s (Bull, 1977; Mosley & Parker, 1972). More contemporary studies on allometry have been applied to glacial cirques (Delmas et al., 2015; Evans, 2009), coastal foredunes (de Almeida et al., 2019). deltas (Wolinsky et al., 2010) and barchans (Boulghobra, 2016; Bourke et al., 2006; Hesp & Hastings, 1998; Sauermann et al., 2000; Todd, 2005). Boulghobra (2016) observed that the level of asymmetry increases as the size of barchans increases. Hesp and Hastings (1998) found that barchans follow scaling laws and tend towards isometry. The results of Sauermann et al. (2000) contradict the findings of Hesp and Hastings (1998) and found that barchans are allometric. Although the work of Sauermann et al. (2000) shows that barchans do not have shape invariance, as it relates to size, their work is limited since it only considers the ratio between certain barchan morphometric attributes: width, length and height. Considering these contrasting views and that the size and shape of barchans change over time, there is scope for further research on barchan allometry due to the contrasting views in the literature and the potential of considering more shape variables.

There are several different methods available for extracting shape information from barchans. However, the most common method is distance measurements between pre-defined points on the barchan's surface. These can range from a single measurement (Norris & Norris, 1961) to the more common two measurements (Bourke & Goudie, 2009; Hamdan et al., 2016; Lorenz et al., 2013) or even nine measurements (Maghsoudi et al., 2017). To compensate for size differences, it is common practice to use ratios between the different measurements. However, it is still analytically challenging to use pairwise measurements to get a complete overview of the shape of barchans. For example, an ideal shape analysis should maintain the spatial relationship between features on an object's surface. Stated differently, it must be possible to reconstruct the original shape from the shape information extracted. This can be done using the traditional distance measurement approach, but it would take $2n-3$ measurements (Strauss & Bookstein, 1982). With a small number of points on the object, this is not a problem. But, a small number of points cannot sufficiently describe the boundary (and therefore shape) of an object. Also, there is a challenge to create suitable ratios so that the size information can be removed from the shape information. Using the equation provided by Strauss and Bookstein (1982), the number of distance measurements scales rapidly as the number of points increase making such an approach challenging. A more simplified approach involves using the coordinates of the points on the object to perform the analysis.

Methods that rely on coordinates to describe shape are collectively grouped under geometric morphometrics (GM). Geometric morphometrics is based on the statistical theory of shape developed by Kendall (1977). Shape is described as a collection of points (referred to as landmarks in the literature) located on an object's boundary. Even though this does not represent the complete boundary proposed by Falomir et al. (2013), it does provide an approximation of such a boundary. For example, it is common practice in GIS to represent vector files as a collection of individual vertices connected by straight lines. In GM, these vertices correspond to identified landmarks. Each of these points contains information relating to the position of an object in space, its orientation and its size. Kendall (1977) argued that shape information is that information that remains once the influence of size, position and orientation has been removed. As such, data that is prepared for geometric morphometric analysis need to go through the process of translation, orientation and scaling respectively (Brombin & Salmaso, 2013; Klingenberg, 2010; Slice, 2007; Zelditch et al., 2004). The long history of GM in the biological sciences has lead to the development of extensive theories and tools, including statistical analyses, for the description of shape differences. This makes it suitable for investigating allometry.

Important for this technique is the correct placement of landmarks in such a way that they correspond between individual objects (Dryden & Mardia, 1993; Zelditch et al., 2004). In the case of barchans, this means that the landmarks must be easily and accurately located between different specimens. Given the particular shape of barchans, this is a challenging task. When the landmark coordinates have been obtained, it can be analysed using either Ordinary Procrustes Analysis (OPA) or Generalized Procrustes Analysis (GPA). When only two specimens are being compared, OPA is commonly used (Baltanás & Danielopol, 2011). When more than two objects are being compared, GPA is the preferred technique (Mitteroecker & Gunz, 2009). Both of these approaches make use of a metric, the Procrustes distance, to measure the similarity between two shapes (Mitteroecker & Gunz, 2009; Zelditch et al., 2004). The smaller the Procrustes distance, the more similar the two objects are in terms of their shape. Geometric morphometrics also includes a metric for estimating size using landmark coordinates. This is referred to as the centroid size (CS) and is the square root of the sum of squared distances from each landmark to the centroid of the configuration (Mitteroecker & Gunz, 2009; Zelditch et al., 2004). This ability to extract size and shape information from the same input data makes GM a useful tool for investigating allometry.

This study focusses on the barchan allometry, or more specifically static allometry (Mosley & Parker, 1972), from two perspectives: asymmetry allometry and shape allometry. Stated differently, the goal is to determine whether there are significant differences in the level of asymmetry and shape as the size of barchans increases. This is achieved by determining if barchans of different sizes have significantly different levels of asymmetry. It is also tested whether barchans of different sizes occur as distinctly different shapes. By combining these analyses a more complete picture of barchan allometry can be obtained. Following the reasoning of Delmas et al. (2015), allometry is investigated using different representatives of barchans from the same dunefield. These two aspects are evaluated for barchans in the Kunene region of northern Namibia. Although the findings cannot be directly extended to all environments and localities where barchans occur, it can add to the debate. However, it is not the goal here to develop a model that adequately explains the allometry.

Methodology

Study site

Ninety dunes were sampled using Google Earth™ historical imagery (12 November 2012) from the Kunene region in northern Namibia located between the latitudes of 18.8°S and 19°S and between the longitudes 12°E and 12.5°E. The site has an average elevation of 58 m.a.s.l with a topography that is gently sloping from the north-east to the south-west (Figure 1). Vectors of wind data, derived from the NCEP/NCAR reanalysis platform (Ashkenazy et al., 2012; Bao & Zhang, 2013) are plotted in Figure 2. The mean wind direction is approximately southerly (179°). This is similar to the results found by Barnes (2001) working further south at Walvis Bay who reported wind directions that oscillate between south-southeasterly and south-southwesterly. Bourke and Goudie (2009) also reported southerly to southwesterly winds along the coast at Walvis Bay. Similarly, Scheidt and Lancaster (2013) working along the Namib Sand Sea reported winds dominating between south-southwest and southwest. The wind regime, in terms of direction, is therefore similar to the that observed further south along the Namibian coast.

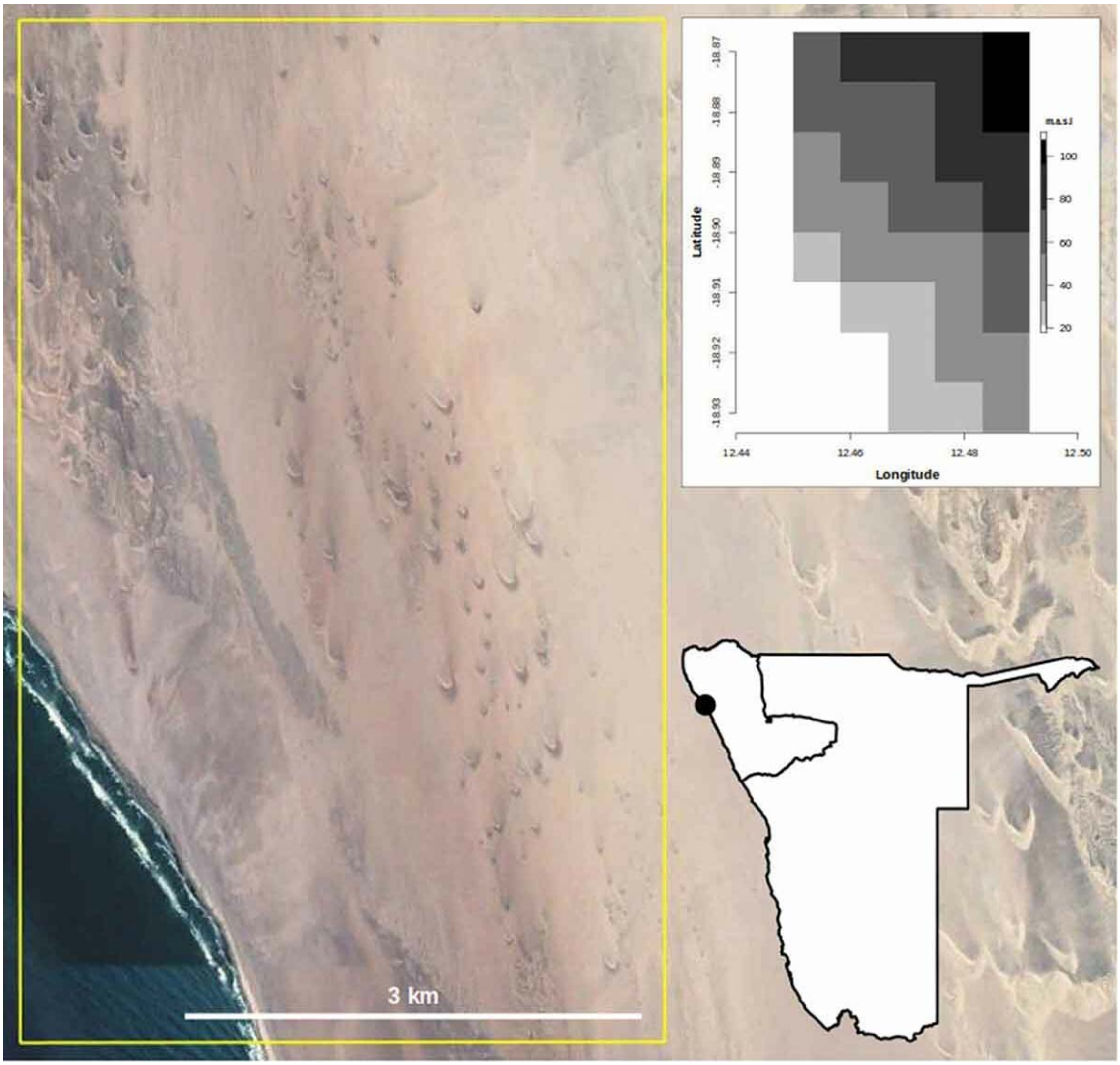

Figure 1. The barchan dune field used in this study. The inset at the top right is raster image of the topography (approx. 30 m resolution) while the inset at the bottom left is the location of the dune field in Namibia. Image from Google Earth™

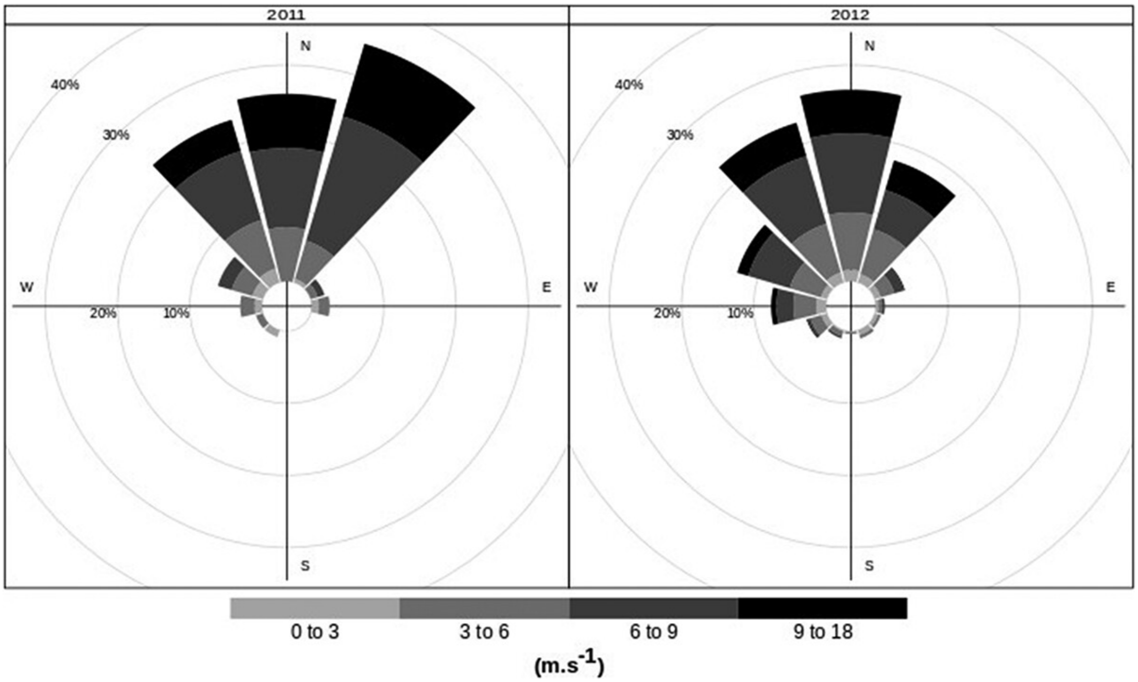

Figure 2. Wind vectors for all wind speeds (n = 1465) in the study site separated into years. Note that the wind vectors indicate the direction in which the wind is blowing

From the wind data, and using the method described by Fryberger (1979), a drift potential (DP) 747.7 was calculated. The region also has a resulting drift potential (RDP) of 629.2 and a resultant drift direction (RDD) of 352°. The RDP value of the study site is higher than reported at Walvis Bay by Bourke and Goudie (2009) suggesting a more intense sand transport environment. The RDP/DP value is approximately 0.84 suggesting a high-energy wind environment with narrow unimodal directional variability (Pearce & Walker, 2005). This value is similar to that calculated for Luderitz (RDP.DP = 0.85) in southern Namibia (Tsoar, 2001) and for southern Iran (RDP/DP = 0.84)(Moosavi et al., 2014), but less than that calculated for a barchan dune field in Morocco (RDP/DP = 0.9) (Elbelrhiti et al., 2008). Approximately 62.2% of the wind readings were of a speed sufficient to result in particle movement (i.e. they were above 11 knots). This indicates that this area is a very active region in terms of aeolian processes. Therefore, there is a high probability that barchan shapes within this region are the result of active present-day processes.

Data collection

The source of imagery and position information for this project was Google Earth™. The imagery was downloaded at the highest resolution possible while coordinate information was obtained from the available .kml files. Although the positional accuracy of Google Earth™ images has been questioned (Mohammed et al., 2013; Paredes-Hernández et al., 2013) it is still considered as a source of data in barchan research (Bourke & Goudie, 2009; Dakir et al., 2016; Hugenholtz et al., 2012; Lorenz et al., 2013). Only isolated barchans from the dune field were sampled for analysis. Additional sampling criteria include features with relatively unaltered brinklines and a size large enough to be properly digitized at the resolution of the imagery. The choice of using isolated barchans was to avoid the subjective element associated with digitizing the boundaries in merged barchans (Hugenholtz et al., 2012).

Size data was obtained from the .kml files using the R packages ‘sf’ (Pebesma, 2018) and ‘maptools’ (Bivand & Lewin-Koh, 2020). The .kml file contains position information for the tips of the horns, the toe, the brinkline and the bottom of the slip face. These correspond to the points most frequently used in barchan shape studies (Bourke & Goudie, 2009; Cacchione et al., 1987; Courrech Du Pont, 2015; Hamdan et al., 2016; Lorenz et al., 2013; Norris, 1966). The collected data was then transformed from the WGS84 coordinate reference system to Hartebeeshoek94. This was done to transform the data from non-Euclidean to Euclidean space so that further analysis can be undertaken.

The centroid size was determined using the coordinates in the .kml file before projection and was used as the shape classification variable when testing for shape diversity. It is because the centroid size gives an impression of the entire size of the dune, as opposed to a single metric such as stoss length, that it was used as the criteria for assigning each dune to an appropriate cluster. The ‘classInt’ package for R (Bivand, 2020) was used with quantile breaks to generate four clusters. For each cluster, an upper and lower bound was determined and individual barchans were then assigned to each cluster based on their size. Such a partition of samples was also used by Evans (2006) to test for allometry in cirques.

Using the projected coordinates of the .kml file the length of the stoss slope, the width of the barchan and the lengths of the individual horns were calculated. The length of the stoss slope was calculated as the Euclidean distance between the toe of the dune and the crest. It is important to note that this distance is not the inclined distance on the surface of the dune. It represents the planimetric distance between the toe and the crest. The width of the dune was calculated as the Euclidean distance between the horns. The literature is divided on how this distance should be measured with Norris (1966) measuring the Euclidean distance between each horn tip (regardless of the level of asymmetry), and Sauermann et al. (2000) measuring the distance as perpendicular to the longitudinal axis. The latter approach was used in this study. To determine the perpendicular distance between the horns from the available points required the use of geometry. Triangles were constructed between each horn tip, the dune crest and the toe of the dune. The stoss slope, therefore, served as a common base for the two triangles. Under these conditions, the height of a triangle will correspond to the distance between the horn tip and an extension of the line representing the stoss slope. For each triangle, the area was calculated using Heron’s formula. The height of the separate triangles can then be easily calculated using the area and base length. Adding these heights together gives the perpendicular width of the dune measured between the horns. The length of the horns was calculated as the distance from the toe of the dune to the tip of the horns. Although this is different from the conventional means of calculating horn length (e.g., as used by Sauermann et al. (2000)), it still serves the same purpose. Since both horns are measured from a common point, their lengths can be directly compared allowing conventional descriptions of asymmetry based on horn length to be applied.

Both shape and asymmetry were described using geometric morphometrics. Although other

indicators of shape are occasionally used, such as the ac ratio which can be converted to shape classes, these techniques do not allow bilateral symmetry to be tested since the calculation does not contain information on which side of the barchan experienced elongation. Therefore, they are unsuited for this study. The coordinate information contained within the .kml file was not sufficient to get a complete description of shape and asymmetry. It was therefore necessary to extract landmark coordinates from the imagery data. To ensure that the landmarks were placed at geometrically corresponding positions along the barchan the following procedure was followed. Some points along the barchan are easily identifiable such as the tips of the horns, the toe and the meeting point between the stoss slope and the horns. Other points located along the curved portion are harder to identify consistently between specimens. For these regions, the landmark points were placed by breaking the barchan's outline into a series of curves. On each of these curves, a landmark was placed at the point of maximum curvature.

Using curves to describe a barchan's boundary is not new since barchan dune boundaries have been broken into separate parabolic curves by earlier authors (Moosavi et al., 2014; Sauermann et al., 2000). A key difference in the approach followed here was that the curves were not considered to be knowable *a priori*. For example, if it is known beforehand that the barchan curve can be described by a known parabolic equation, the points of maximum curvature can be calculated using calculus and the landmarks accurately located. However, this is not possible if the function is unknown. Instead, a heuristic solution was applied with the assumption that the curve which describes the barchan's boundary was continuous and differentiable. Since Hesp and Hastings (1998) found barchans to be aerodynamically maintained structures this assumption is likely to be valid since an abrupt break in the curve, which would exclude the differentiable condition, would have been smoothed by aeolian action.

This method is heuristic in the sense that it uses geometry to solve a differential problem. From a calculus perspective points of maximum curvature are calculated using the first derivative of the function. However, since the curve of the barchan cannot be known before analysis, this solution is not possible. Another property of turning points is that their tangent lines are parallel to the x-axis. This property makes it possible to place landmarks following geometric principles. If a line is constructed that is parallel to a given x-axis, then the point on the curve that is tangential to that line will represent the point of maximum curvature. To aid in this process, the free software Geogebra (https://www.geogebra.org/) was used. A line was constructed parallel to a segment. This line was then dragged towards the boundary of the barchan until it just touched the barchan. A point placed at this location is therefore approximately located at the turning point of the curve between the two endpoints of the segment.

The following approach was used to define the landmarks (Figure 3):

1. Place landmarks one and 11 at the points where the slip face merges with the left and right horns respectively.
2. Identify landmarks two and 10 as being the tips of the left and right horn respectively.
3. Position landmark six at the toe of the barchan.
4. Bisect the angle made by landmarks two, six and ten. This line will be referred to as the longitudinal axis of the dune and is similar in position to that used by Finkel (1959).
5. Place landmarks four and eight on the most lateral side of the barchan in such a way that a line that is drawn tangent to the barchan at its most lateral point is parallel to the longitudinal axis. These points correspond roughly to those used by Elbelrhiti et al. (2008) to describe barchan width.
6. Landmark 13 and 16 are located at the base of the slip face (a region that Taniguchi and Endo (2007) refers to as the bay-head) and the brink line respectively. They are placed in such a way that a tangent line drawn on the barchan at this point is parallel to the line connecting landmarks one and 11.

7. For landmarks 14 and 12 the tangent line needs to be parallel to the line between one and 13 and 11 and 13 respectively.
8. A similar approach is followed for landmarks 15 and 17 with the tangent line being parallel the line segment connecting points one and 16 and the line segment connecting points 11 and 16.
9. Landmarks three and nine are placed so that the tangent line is parallel to the line segment connecting points two and four and the line segment connecting points ten and eight respectively.
10. And lastly landmarks five and seven are placed in such a way so their tangents are parallel to the line segment connecting points four and six and the segment connecting points eight and six.

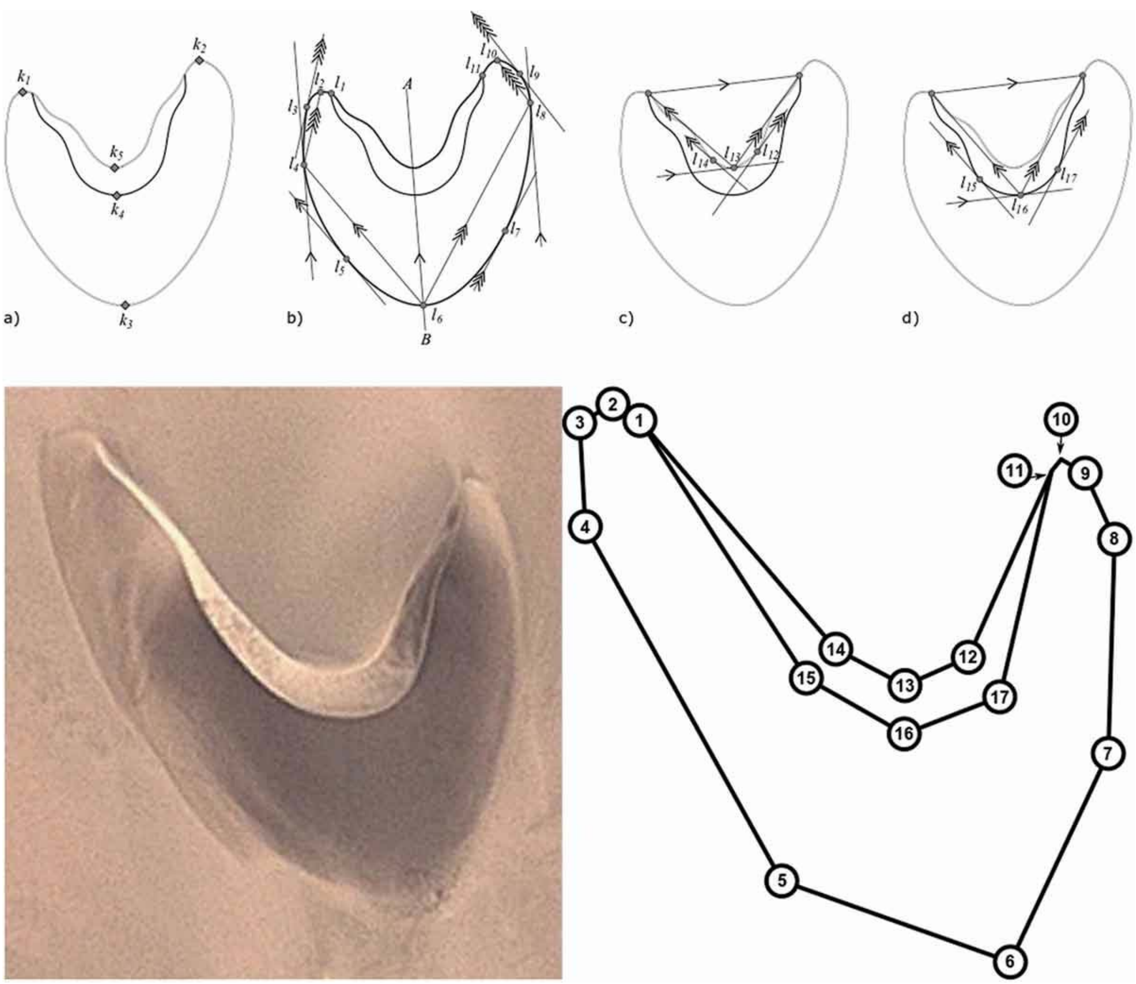

Figure 3. Top: The process followed to assign landmarks on a barchan's boundary. Bottom: An example barchan with numbered landmarks

Data analysis

Most of the data analysis was carried using the R package 'geomorph' (Adams et al., 2013). Generalized Procrustes analysis was carried out, using the landmarks identified on the images, to test for shape differences between clusters. A key aspect of GPA is that it makes use of a mean shape with which the other shapes within a group can be compared. Canonical variates analysis (CVA) was extracted from the barchan landmark data using the 'shapes' package (Dryden, 2019). This data can be used to describe shape differences between different groups (Dryden & Mardia, 2016; Zelditch et al., 2004). However, it is only a visualization technique and does not allow for hypothesis testing (Zelditch et al., 2004).

To test for asymmetry a combination of conventional metrics and geometric morphometrics were used. For the latter, the asymmetry of the barchans was determined by calculating the Procrustes distance between a barchan and its mirror image. Since this is computationally equal to calculating the Procrustes distance between two different objects, OPA was used. The comparison of an object with its relabelled mirror image is an effective way to describe asymmetry (Klingenberg & McIntyre, 1998; Mitteroecker & Gunz, 2009). Using this approach, a perfectly symmetrical object will be identical to its mirror image and, as a result, will have a Procrustes distance of zero. The bigger the difference between an object and its mirror image, the more asymmetrical that object is and the larger the Procrustes distance will be. In effect, this can serve as an indicator for the presence of bilateral asymmetry. It is important to emphasize that the landmarks of the mirrored image need to be relabelled. In landmark-based GM the sequence of labelling of landmarks is important since the analysis process compares landmarks of the same number. In the current method, the left horn tip is landmark two. When a mirror image is created, the left horn tip becomes the right horn tip. As such, the uncorrected mirror image will have the number two landmark on the right horn. This will result in significant miscalculations. Once the Procrustes distance for each dune has been calculated, it is plotted along with the centroid size to test if there is a pattern that relates the size of the barchans to the level of asymmetry. Differences in horn length were used as the conventional metric for asymmetry using coordinates in the .kml file.

Both differences in shape and asymmetry between size clusters were used to test if allometry is present. The Dunn-test with the Bonferroni correction was applied to the centroid sizes of each cluster to test for significant differences. For barchan shape, Goodall's F-test was used to test for significant differences between the mean shape in each cluster (Monteiro & Cannatella, 1999). It is considered to be the best test for evaluating group differences in shape (Rohlf, 2000). The results of the CVA were plotted to see, visually, if any distinct groupings occur and how strongly those groupings are associated with the size clusters. Allometry exponents were extracted using regression on log-log plots (Delmas et al., 2015) for the dune width and the length of the stoss slope as the centroid size of the dune increases. Allometric tests for asymmetry involved using the Dunn-test with Bonferroni correction on the OPA Procrustes distances to determine if they are significantly different between each cluster. The exponents were also extracted using the log-log plot for the differences in horn length. However, since the Procrustes distance is a shape variable, it cannot be log-transformed and is usually plotted only with the independent as a logarithm (Mitteroecker et al., 2013).

Results

As a whole, the bachans in the Kunene region have a mean dune width of 46.6 m (SD = 28.1) and a mean stoss length of 38.8 m (SD = 20.04). Their widths and stoss lengths are significantly ($p < 0.01$) smaller than those reported by Barnes (2001) working further towards the south. When compared to barchan dimensions published in other sources (Al-Harthi, 2002; Bailey, 1906; Barnes, 2001; Dong et al., 2000; Douglass, 1909; Embabi, 1982; Finkel, 1959; Hamdan et al., 2016; Jimenez et al., 1999; Long & Sharp, 1964; Norris, 1966; Rempel, 1936; Sagga, 1998; Wang et al., 2007), the barchans of the northern Kunene are relatively small (Figure 4). The mean sizes of the clusters were all significantly different from each other (Figure 4) and their morphometric properties are summarized in Table 1. Most of the barchans (n = 76) have an elongated left horn while the remainder (n = 14) have an elongated right horn. All of the dunes in this dunefield can, therefore, be considered to be asymmetric based on conventional metrics. In terms of the $\frac{a}{c}$ ratio, 31 dunes had a ratio exceeding one indicating that 34% of the dunes have a stoss slope length that is longer than the width between the horns. A histogram of the $\frac{a}{c}$ ratios is provided in Figure 5. The average $\frac{a}{c}$ ratios of the barchans (0.92) is slightly smaller than the findings of Barnes (2001) (1.03) working further towards the south.

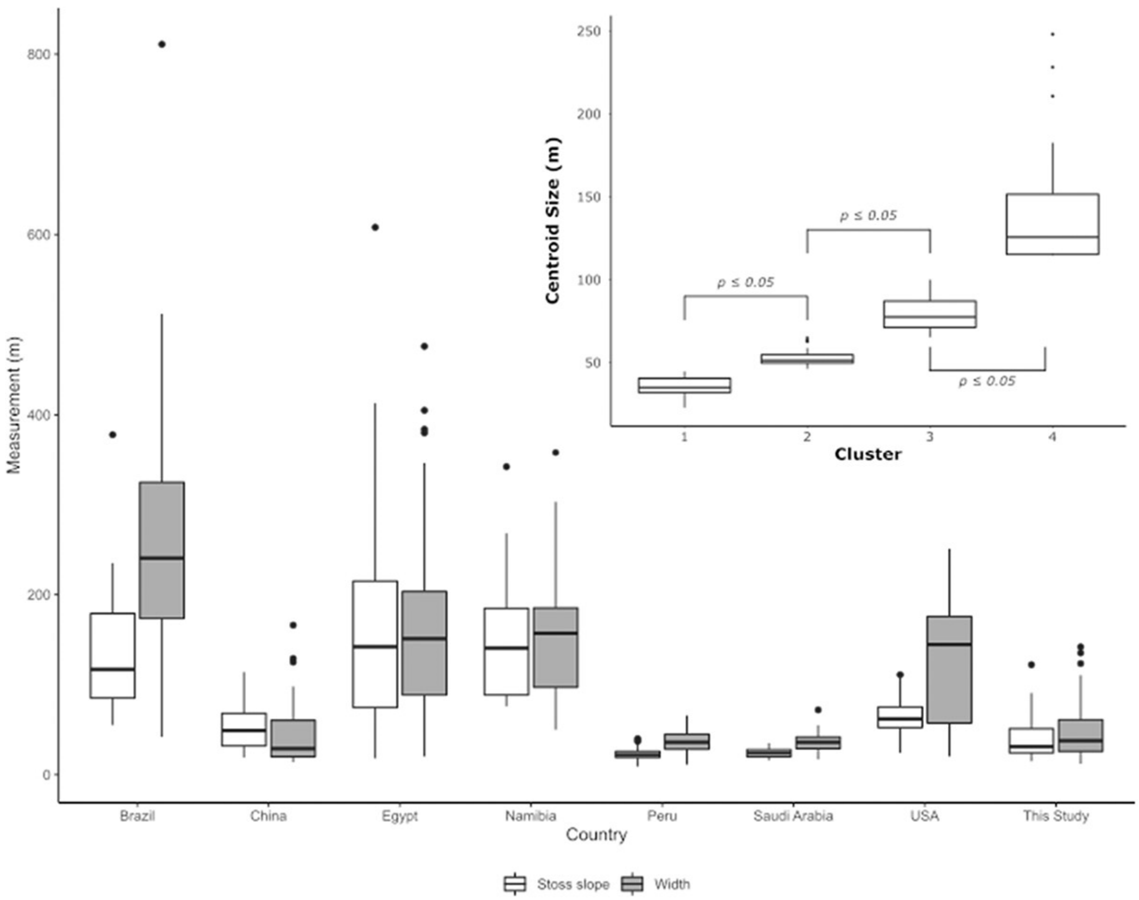

Figure 4. A size comparison of the dunes from this study with published barchan dimensions from other countries. Inset boxplot shows the size distribution of barchans within each cluster

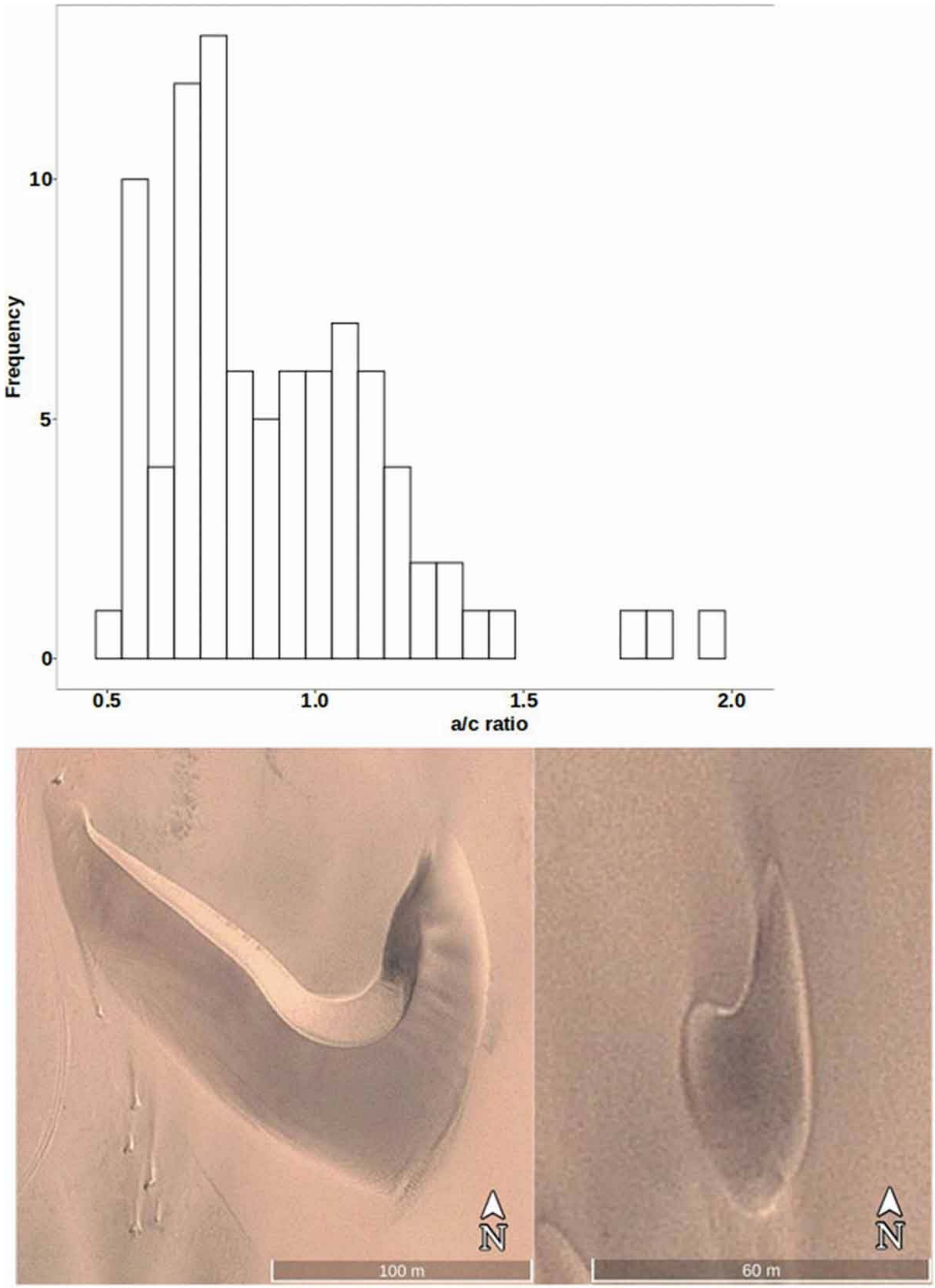

Figure 5. A histogram of the $\frac{a}{c}$ ratios for the barchans in the dune field. The barchans below the histogram represent the extreme ends of the $\frac{a}{c}$ ratio. Images from Google Earth™

Table 1. Morphometric change for barchans in the sample. Horn asymmetry refers to the difference in length between the right and left horn

Morphometric attribute	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Centroid size	35.5 (SD = 6.0)	52.9 (SD = 5.4)	79.6 (SD = 10.9)	143.1 (SD = 40.4)
Width	20.9 (SD = 5.3)	31.4 (SD = 6.7)	48.1 (SD = 9.5)	85.3 (SD = 23.6)
Stoss length	21.9 (SD = 4.1)	26.8 (SD = 4.2)	41.3 (SD = 10.2)	64.9 (SD = 18.2)
Horn asymmetry	4.2 (SD = 5.1)	13.1 (SD = 9.3)	22.2 (SD = 10.9)	62.6 (SD = 43.5)
Bilateral asymmetry	0.36 (SD = 0.1)	0.46 (SD = 0.15)	0.49 (SD = 0.1)	0.63 (SD = 0.14)

The results of the significance tests are summarized in Table 2. A complex pattern emerges where variables that show a significant difference between clusters are not consistent. A general observation can be made that dunes that are in adjacent clusters (e.g., between clusters one and two) have variables that do not differ significantly between them. Barchans that are separated by at least one cluster size (e.g., between clusters one and three) show a significant difference between all the variables tested. The extracted allometric exponents (Table 3) show a combination of positive and negative allometry. A positive allometric relationship indicates that the variable in question changes at a more rapid rate than the dune size, while a negative allometric relationship indicates the opposite. No isometric relationships were found within the data although dune width, with an exponent of 1.02, can be considered as a borderline isometric variable. The results of CVA are given in Figure 6. This echoes the findings of the significance tests between mean shapes. No significant difference was found between the mean shape of clusters two and three as well as clusters three and four. In both cases there was also a considerable amount of overlap in the convex hulls of the CVA plot for these clusters.

Figure 6. The results of the canonical variates analysis along with convex hulls to demarcate the different clusters. There is a considerable amount of overlap between clusters that are closer in average size (such as clusters two and three) while clusters that have a bigger difference (such as clusters one and four) have no overlap. Each plotted shape represents a dune in the dataset

Table 2. Changes in morphometric parameters along with changes in centroid size (CS). Horn asymmetry refers to the difference in length between the right and left horn

Group 1	Group 2	Change in CS	Significant	p-value	Not significant
Cluster 1	Cluster 2	17.4 m	Horn asymmetry	≤ 0.05	Bilateral asymmetry
		$p \leq 0.05$	Mean shape	≤ 0.05	Stoss length
					Dune width
Cluster 1	Cluster 3	44.1 m	Dune width	≤ 0.0001	
		$p \leq 0.0001$	Stoss length	≤ 0.0001	
			Horn asymmetry	≤ 0.0001	
			Bilateral asymmetry	≤ 0.01	
			Mean shape	≤ 0.05	
Cluster 1	Cluster 4	107.6 m	Dune width	≤ 0.0001	
		$p \leq 0.0001$	Stoss length	≤ 0.0001	
			Horn asymmetry	≤ 0.0001	
			Bilateral asymmetry	≤ 0.0001	
			Mean shape	≤ 0.05	
Cluster 2	Cluster 3	26.7 m	Dune width	≤ 0.05	Horn asymmetry
		$p \leq 0.05$	Stoss length	≤ 0.05	Bilateral asymmetry
					Mean shape
Cluster 2	Cluster 4	90.2	Dune width	≤ 0.0001	
		$p \leq 0.0001$	Stoss length	≤ 0.0001	
			Horn asymmetry	≤ 0.0001	
			Bilateral asymmetry	≤ 0.01	
			Mean shape	≤ 0.05	
Cluster 3	Cluster 4	63.5	Dune width	≤ 0.05	Stoss length
		$p \leq 0.05$	Horn asymmetry	≤ 0.05	Bilateral asymmetry
					Mean shape

Table 3. Allometry variables obtained from log regression. The type of allometry is obtained from the guidelines provided in Bull (1977)

Variable	Exponent	R^2	Type of allometry
Bilateral asymmetry	0.19	0.4	Negative
Horn asymmetry	2.24	0.65	Positive
Width	1.02	0.92	Positive
Stoss length	0.79	0.84	Negative

Discussion

This study aimed to determine whether allometry is present within barchan dunes. For this to be the case, there needs to be a significant change in the shape of individual barchans as their size increases. In this stiudy, individual barchans were not tracked over the course of their migration, although this does provide an interesting option for further studies. Instead, a similar approach to Evans (2006) was followed where the morphometric properties of barchans of different sizes were tested for allometry. This is a form of static allometry (Mosley & Parker, 1972) and limits the conclusions that can be drawn. Specifically, it is not possible to infer any direct role that a process has on an individual dune. The nature of an individual case study also prevents the extrapolation of the findings to all barchans. This is an important point to consider since the published dimensions show that barchans in Peru, for example, have a very low level of size variability (Figure 4) and the findings here might not be reflected in those barchans. That being said, several interesting observations can be made.

The significant difference in CS between all of the size clusters indicates that the approach followed is suitable for investigating barchan allometry. Although the barchans in the Kunene are smaller than those found elsewhere, they still do occur in a variety of different sizes. As such, the dunes in this region do fulfill the one criterion for studying allometry, namely size variation.

A surprising finding was that barchans in adjacent clusters had non-significant differences in morphometric parameters while those with at least one cluster separating them had significant differences. Such a negative result is very interesting since it does hint at the existence of 'threshold size difference' beyond which all morphometric parameters can be considered significantly different. This has not yet been considered in the case of barchans and it opens up interesting research opportunities. For example, the barchan sediment budget is governed by sediment influx and outflux which occur on the stoss slope and horns respectively (Elbelrhiti et al., 2008). Barchans are also aerodynamically maintained structures (Hesp & Hastings, 1998) and their size is a direct representation of the sediment distribution. If this is the case then a threshold size of significant shape change would represent a situation where the amount of sediment that has accumulated to an extent where a new aerodynamic equilibrium arises. This adds support to the view of Phillips (2011) that barchans are not in steady-state equilibrium. If this were the case, then the irregular distribution of significant differences would not be present. With regards to allometry, these findings suggest that allometry is still present among all size clusters, but that the aspect of shape that changes is different depending on the dune's size. What makes this even more complex is that the size interval between clusters was not constant (Table 2). This suggests that whatever relationship may be present, it might not be a linear one.

The mean shape is a parameter that refers to differences in the entire shape of the dune. This showed a significant difference ($p \leq 0.05$) between the majority of clusters. At its most basic this in itself is an indicator for allometry based on the provided definitions(Almeida et al., 2019; Evans, 2006; Wolinsky et al., 2010). There is, however, no significant difference between the mean shapes of clusters two and three or clusters three and four. Yet there is a significant difference between clusters one and two. This agrees mostly with the earlier observation that there is a threshold size difference that needs to be attained before drastic differences in shape manifest. What that difference is, however, remains to be explored. What can be seen, however, is that the level of asymmetry increases as the dunes become larger. On average, with increasing dune size the left (i.e. west) horn becomes elongated. This supports the observation of Boulghobra (2016) that larger dunes are more asymmetric than smaller dunes. It also differs from the findings of Barnes (2001) who found no side preference for horn elongation. Why the left horn is more elongated than the other is open for debate. Research has suggested a potential relationship between the inclination of the surface and horn lengthening where the downslope horn becomes elongated relative to the upslope horn (Finkel, 1959; Parteli et al., 2014). Given that the topography in this region dips slightly towards the southwest (Figure 1) this could be a potential explanation.

Significant differences between horn lengths occur between relatively small changes in size. Given that the allometric exponent of differences in horn length was 2.24 (Table 3) this in itself is not surprising. Such a high exponent suggests that the rate of change in this variable is much higher than the rate of change in dune size. In other words, the difference in horn lengths increases faster than the dune size. What was surprising, however, was the lack of a significant difference between clusters two and three. This indicates that, even with such a high allometric exponent, there can be size classes where a pronounced difference does not manifest. Why this is the case is unknown, but it may indicate a more complex relationship between process and size. The data does not allow speculation on what this relationship may be. However, it does indicate that some processes were operating on the horns because the width of the dune (measured at the horn tips) increased significantly while the differences in horn length did not. Additionally, lengthening of the stoss slope, which did not change significantly between clusters one and two, changed significantly between clusters two and three. To fully explore this relationship, a dynamic allometric study that tracks individual barchans needs to be carried out.

Where bilateral asymmetry is concerned, the size lag is very prominent with significant differences occurring exclusively in cases where there is at least one cluster separating two clusters. The lack of a significant difference in bilateral asymmetry can be explained by the low exponent value (Table 3). Here, the low value indicates that bilateral asymmetry changes at a slower rate than barchan size. Therefore, significant changes in bilateral asymmetry will not necessarily accompany significant changes in barchan size. The fact that the size intervals between clusters are not constant also suggests that this ‘lag’ in insignificant differences might not be linear.

Conclusion

This study found that there is sufficient evidence to conclude that allometry is present in barchans. As the size of the dunes increase there are significant differences in shape, asymmetry (both conventional and bilateral), width and stoss slope length. However, the variability in attributes with the size is not constant. Analysis suggests that certain morphometric differences only manifest when certain size thresholds are exceeded. This adds an interesting new dimension to the study of landform allometry that has not yet been addressed in the literature. However, given the sizes of dunes present within the sample area further study is needed to determine whether these patterns hold over larger barchan sizes.

Emphasis should be placed on studying dynamic allometry to better relate the relationship between form and process.

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