Statistical comparisons of grain size characteristics, hydraulic conductivity, and porosity of barchan desert dunes to coastal dunes

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ABSTRACT

Ancient dune sand environments in deserts and coasts are aquifers and hydrocarbon reservoirs that commonly have preserved high permeability (hydraulic conductivity). A paucity of research has been performed on variations in the distribution of permeability associated with the positions within the dunes and the differences between these patterns in desert and coastal dunes. A comparison of dune sand grain size and hydraulic properties of a desert barchan dune field in Saudi Arabia to a coastal dune field in Uruguay has revealed some important differences and similarities. The grain size characteristics show that the mean grain diameter was significantly lower in the coastal dune field compared to the coastal dune field (1.95–2.79 phi) and the sorting was better in the coastal dune field (0.40–0.66 phi). The skewness and kurtosis of the dune sands were not significantly different with the skewness < 0.1 and the kurtosis near 1.0. No statistical differences based on dune position were found in the coastal dunes, but there were significant differences in position in the desert dunes. The porosity differed between the desert dunes and the coastal dunes with the mean values being 0.39 and 0.35 respectively. No significant porosity variation with dune position was found in either dune type. The coastal dunes had a significantly higher mean hydraulic conductivity of 25.3 m/d compared to the desert dunes of 9.32 m/d. The dune crests in the desert dunes had significantly higher hydraulic conductivity values compared to other locations in the dune profile.

1. Introduction

Interior dune occurrence is divided into sand seas and dune fields (informal) based on very large areas verses small areas respectively. Sand seas of large area tend to occur in the eastern hemisphere arid zones of the Sahara, the Middle East, central Asia, Australia and southern Africa, while numerous small interior dune fields are ubiquitous in arid regions in a variety of geomorphic settings (Lancaster, 1995). Sand seas cover large areas of the Sahara, Arabia, and Australia at 28\%, 26\%, and 38\% respectively (Thomas, 1997). Coastal dunes (CD) form above the high tide line of sandy beaches occurring along many coastlines of oceans, estuaries and lakes, particularly on windward coasts where sand occurs within the size range of 2.0–0.2 mm in diameter (Carter et al., 1990).

A myriad of statistical analyses of grain size properties of desert dunes have been made to assess aerial changes in different parts of the dune profile and to make comparisons between different dune fields and geometries (Folk, 1971; Lancaster, 1981, 1982, 1986; Sneh and Weissbrod, 1983; Vincent, 1984; Watson, 1986; Thomas and Martin, 1987; Abolkhair, 1986; Buckley, 1989; Livingston et al., 1999; Khalaf, 1989; Wang et al., 2003; Kaspar-Zubillaga and Carranza-Edwards, 2005; Zhu et al., 2014; Wasson, 1983). In contrast, fewer investigations have been conducted on CD grain size distribution, especially dealing with statistical comparisons (Vincent, 1996; Ahlbrandt, 1979; Kaspar-Zubillaga and Carranza-Edwards, 2005).

There are known differences in the grain size distribution between interior desert barchan dunes (IDBD) and CDs (Ahlbrandt, 1979; Kaspar-Zubillaga and Carranza-Edwards, 2005). CDs commonly are composed of coarser sand, contain less mud, have generally better sorting, and have a more restricted range in skewness and kurtosis values compared to desert dunes (Kaspar-Zubillaga and Carranza-Edwards, 2005). Because of these variations, it is likely that differences in the distribution of the hydraulic properties of the dune sands should also vary with the grain size characteristics (Rosas et al., 2014). However, few investigations of the comparative grain size properties of dune sands and the porosity and hydraulic conductivity associated with those variations have been made (Rosas et al., 2014; Lopez et al., 2015).

The changes in hydraulic properties of desert dune sands were assessed along with grain size properties in IDBDs in Saudi Arabia by Lopez et al. (2015). They found that the total porosity was relatively consistent across the dune profile, but the hydraulic conductivity varied significantly with the dune crest having the highest value in most cases. The interdune area had the lowest hydraulic conductivity and the correspondingly lowest mean grain diameter. No such investigation has been conducted on the hydraulic properties of CDs to allow comparisons to be made.
It is the purpose of this research to assess the statistical differences in grain size properties across dune profiles in IDBDs compared to those in CDs at similarly sampled sites; one in Saudi Arabia and the other in Uruguay. In addition, the pattern of variation in total porosity and hydraulic conductivity was also investigated to determine if there are significant differences between these dune types and locations. This type of assessment is required to help model variations in hydraulic properties of dune aquifers and the initial properties of ancient sands and sandstones prior to significant compression, compaction and diagenesis. In addition, the type of information developed herein will be quite useful to improve numerical models of field morphodynamics of dunes by helping researchers to more accurately set boundary conditions and initial assumptions related to grain size and the hydraulic characteristics of dune sediments which influence both sediment transport and dune geometry (de Luna et al., 2012; Gabarrou et al., 2018).

2. Background geology of areas investigated

2.1. Saudi Arabia dune field

The Wadi Khulays dune field is located about 50 km northeast of Jeddah in western Saudi Arabia (Fig. 1). It is a relatively small barchan dune field lying south of the outwash plain of the Wadi Khulays catchment which is the sand source (Sagga, 1998). The dunes formed from sand transported by the predominantly northwest wind across the plain to the southeast with the center of the dune field located at about N22°6’, E39°14’. The dune heights vary from 3.5 to 8 m above the interdune plain. The sediment composition is primarily quartz sand but contains a variety of other siliciclastic mineral and rock fragment types (Lopez et al., 2015). The specific locations of the sampled dunes are shown in Fig. 2.

2.2. Uruguay coastal Holocene dunes

A large part of Uruguay contains beaches with Holocene CDs occurring along the landward part of the beach system (Missimer et al., 2019). In the eastern part of the country, the shoreline is commonly bordered by Pleistocene-age dunes occurring within the Chuy Formation with a set of Holocene dunes lying seaward of the Pleistocene dunes (Goso et al., 2014). The heights of the Holocene CDs generally range from 5 to 8 m above mean sea level. The composition of the dune sand is predominantly quartz sand (40–65%) but contains significant percentages of feldspars and both igneous and metamorphic rock fragments (Missimer et al., 2019). Sand-size marine mollusk fragments are a minor component of the sand. A series of samples were collected across the dunes in profiles from east of Atlantida to La Paloma along the central Uruguay coastal (Fig. 3a, b, c, d).

3. Methods

3.1. Field sampling of the dune sands

A series of five samples were collected from each dune beginning at the windward interdune (IDBD) or base (CD) with additional samples collected at the mid-windward or stoss slope, the crest, the mid-leeward slope or slipface, and the leeward base or toe (Fig. 2 upper panel). Each sample had a volume of about 500 cm³ and was collected from the surface to a depth of no > 5 cm. The total number of dunes sampled was 10 in Saudi Arabia and 11 in Uruguay which equates to 50 and 55 individual samples respectively.

3.2. Grain size analysis and determination of statistical properties for size distribution

Grain size distributions were measured using standard sieving techniques as described by Folk and Ward (1957) and Tanner and Balsillie (1995) with 34 sieve increments (0.25-phi intervals) to provide the maximum amount of detail. The grain size statistical parameters of Folk and Ward (1957) include the mean grain diameter, sorting (dispersion), skewness, and kurtosis. These parameters provide a clear description of the size distribution of the sands. They were calculated using a spreadsheet program developed by Rosas et al. (2014). These parameters were compared in terms of position on the dune with calculated means and standard deviations.

3.3. Measurement of total porosity

Total porosity can be accurately measured using either the volumetric saturation or the bulk density method (Missimer and Lopez, 2018). The volumetric saturation method consists of measuring the ratio of volume of water contained on a sediment (Vw) to the volume of the sediment (Vs). Technical recommendations to minimize the entrapment of air (which can increase the uncertainty of the measurements), as well as the step-by-step procedure to ensure accurate measurements can be found in Lopez et al. (2015) and Missimer and Lopez (2018). For the bulk density method, the density of non-porous quartz (2.65 g/cm³) is used to obtain the weight (Wq) that the measured

Fig. 1. Locations of the Wadi Khulays dune field in Saudi Arabia. The sand source area is located directly below the wind direction label which is to the northwest of the sampled dunes wg = hich are shown in orange x’s. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
volume of sand would have if it consisted entirely of pure quartz. The porosity is calculated as the ratio \((W_p - W_s)/W_q\) where \(W_s\) is the actual weight of the volume of sand.

The total porosity of samples collected from Saudi Arabia were measured using solely the volumetric saturation method because of the variation in mineralogy of the samples, while the total porosity of the CDs in Uruguay was obtained with the combined measurement procedure described in Missimer and Lopez (2018). The latter involves using both measurements (volumetric saturation and bulk density) to reduce uncertainty.

### 3.4. Measurement of hydraulic conductivity

The hydraulic conductivity of the sediment samples was determined using a standard constant-head permeameter based on the methodology described by Wenzel (1942) and Franco et al. (2016) and following the American Society for Testing and Materials (2006) standard D2434-68. After being thoroughly mixed in a container, the sand was added to the permeameter chamber in a dry form. To facilitate removal of air in the pores, water was introduced to the chamber from the bottom upwards. The sediment column height ranged from 5.8 to 6.2 cm and area of the cylinder was 31.65 cm². Flow through the permeameter during pre-conditioning and measurement was from the bottom upwards during all measurements. The head through the permeameter was maintained at 65.3 cm to minimize any disruption of the sand. Between 20 and 25 L of water was run through the permeameter apparatus before measurements were made to allow for an equilibrium state to be reached wherein any air bubbles were removed from the sand column and the flow rate had stabilized. Three to five measurements were made of the time to fill a 1,000 mL cylinder. Measurements were repeated until steady-state was achieved as evidenced by minimal variation between successive time measurements and no downward trend in the time. An average of the measurements was used to calculate the hydraulic conductivity. The temperature of the water was also measured during each analysis to allow for normalization of hydraulic conductivity values to a temperature of 25 °C using a computer program created by Rosas et al. (2014).

#### 3.5. Statistical comparison analysis

A number of tools were used to determine whether there are statistical differences between the hydrogeological properties (hydraulic conductivity, porosity, and grain size Folk moments) of IDBD and CD samples. First, the distribution of the properties was examined using a kernel density plot (Simonoff, 1996; Duong, 2007). The density plot is a data visualization technique that uses a kernel smoother to visualize the distribution of samples, and unlike histograms, it is not sensitive to the number of bins used (Sheather, 2004). The y-axis of a density plot represents the probability density (the area under the curve will sum to 1, although individual values can be higher than 1 if the \(x\) values are small). Furthermore, it is easier to directly compare multiple distributions in a single plot. Next, to test for normality of the distribution, the Shapiro and Wilk test was used, which states a null hypothesis that the samples are normally distributed (that is, if the obtained p-value is small, the null hypothesis is rejected and the distribution is considered not normal). The use of non-parametric tests is recommended for samples that are not normally distributed (MacFarland and Yates, 2016). The Wilcoxon signed-rank test is the non-parametric alternative to the Student’s t-test (Wilcoxon, 1945). The null hypothesis is that the two groups being compared are not significantly different. This test was used to compare the values between IDBD and CD samples. The properties of the dune samples within each environment were also analyzed after grouping the samples by location on the dune. That is, is there any variation in the properties of IDBDs explained by the location on the dune (crest, windward, leeward)? To do this, the Analysis of Variance (ANOVA) test was used. ANOVA relies on comparing the variance of the whole data set against the variance within groups. The null hypothesis in ANOVA is that there are no significant differences among the groups that are being tested, and therefore, both of these variances would be similar. If the ANOVA test resulted in small p-values, that is, to reject the null hypothesis, then the Tukey Honest Significant Differences (Tukey HSD) test was performed. The Tukey HSD test was used to make pairwise comparisons between the groups being tested. This was done to reveal if there are any significant differences between, for example, the values found in the crest of the dune against the windward base.

### 4. Results

#### 4.1. Grain size characteristics

A compilation of all measurements made during the investigation are given in the Supplemental Materials. All of the grain size data...
4.2. Statistical analysis of grain size characteristics on CD and IDBD sands

The analysis described in the methods section (3.5) was applied to the four Folk grain size moments, including the first (mean), second (sorting or dispersion), third (skewness) and fourth (kurtosis) in phi (ф = -Log2d) units. Fig. 4 shows the distribution of measured moments as density plots for both groups of samples. It can be observed that for the mean and sorting there is an evident difference in the average values, with higher mean grain diameter represented as lower phi values in the CD samples, and the CDs show a higher degree of sorting. Skewness and kurtosis values were closer in both groups (there is significant overlap between both distributions). A non-parametric Wilcoxon signed-rank test was performed and confirmed a statistically significant difference (confidence interval of 0.95) between both groups (CD versus IDBD) for only the mean and sorting. The average values for both groups are shown in Table 1.

Then, an analysis to reveal the significance of differences (Folk moments) between CDs and IDBDs by location was performed (i.e. comparing samples taken from the same location within the dune). The results are shown in Table 2. The mean grain diameter and sorting values were shown to be significantly different (between CDs and IDBDs) for all locations within the dunes. The skewness values were different on samples taken from all but the crest and windward base, while the kurtosis values were different only on the leeward base.

Possible differences in the measured Folk moments within the locations (windward base, windward mid-slope, crest, leeward mid-slope and leeward base) of the dunes within each of the two groups (CD and IDBD) of dunes were also analyzed. Figs. 5 and 6 show boxplot comparisons for the IDBDs and CDs. No statistically significant differences were found for the CD samples. However, from Fig. 5, evident differences in some of the moments for the IDBDs can be observed, which was confirmed by the ANOVA test (all four groups showed p-values < 0.05 for the IDBD). A Tukey Honest Significant Differences test was applied to the IDBD samples. Table 3 shows the results, with most significant differences found between the leeward base and other locations for the Folk sorting, skewness, and kurtosis moments.

4.3. Statistical analysis on hydraulic conductivity and porosity values

The distribution of porosity and hydraulic conductivity over both groups is shown as density plots in Fig. 7. The 50 values of porosity for the IDBDs are close to a normal distribution, with the Shapiro-Wilk test revealing a p-value of 0.28 (the null-hypothesis, that the distribution is similar to a normal distribution, is accepted), while the 55CD samples can be considered significantly different to a normal distribution (p-value < 0.05, i.e. the null-hypothesis is rejected). Similarly, the hydraulic conductivity values within the IDBDs were found to be normally distributed (p-value of 0.89) while the ones in the CDs were not (p-value < 0.05). A non-parametric Wilcoxon signed-rank test was performed and revealed a significant difference between the means of porosity values among both groups (0.35 for the CDs, and 0.39 for the IDBDs). The hydraulic conductivity values were also found to be different (25.3 m/day for CDs, and 9.32 m/day for the IDBDs). This analysis was repeated (comparison between CDs and IDBDs) with the values grouped by locations within the dunes (crest, windward and leeward mid-slopes), and also revealed significant differences in both porosity and hydraulic conductivity values. It should be noted however, that these analyses each consisted of only 10–11 samples. Table 4 shows the mean and standard deviation of porosity and hydraulic conductivity

statistical values are shown in appendix Table A1 which is located in the Supplemental Data.
It was also tested whether there were differences within the locations of the dunes for each of the two groups of dunes (CDs and IDDBs) separately. Fig. 8 shows boxplot comparisons for the IDDBs and CDs. No statistically significant differences among the porosity values were found. However, there were significant differences between the grouped hydraulic conductivity values (grouped by location within the dunes) for the IDDBs (ANOVA p-value ~ 1E-4) only. To further identify which pairs of locations had significant differences in hydraulic conductivity values within the IDDBs, the Tukey Honest Significant Differences test was applied. The test revealed significant differences for the crest/windward base, windward base/leeward mid-slope, and windward base/windward mid-slope pairs.

### 4.4. Analysis of hydraulic conductivity/porosity relationships between IDDBs and CDs

Fig. 9 shows a scatterplot of the relationship between the measured hydraulic conductivity and porosity values for all samples. It is clear that the relationship is largely different between samples taken from the IDDBs and CDs. The latter have higher conductivity values and lower porosity, but there is no clear relation between these two values for the CDs (p-value > 0.05). On the IDDBs, however, there seems to be a positive slope in the relationship, but only when analyzing the complete set (samples taken from all locations within the IDDBs). The relation has a slope of 0.42 m/day and an intercept of −0.12 m/day, however, the correlation is poor and not significant (p-value = 0.265). Similarly, by analyzing the relationships among individual locations (e.g. hydraulic conductivity and porosity relationships for samples taken at the crest), the correlation was found to be not significant (p-values > 0.05).

### 4.5. Analysis of mean grain diameter/porosity relationships between IDDBs and CDs

The relation between mean grain diameter and porosity was also found to be markedly different between CDs and IDDBs (Fig. 10).

## Table 1
Average Folk moments for CDs and IDDBs. The mean and sorting were revealed to be significantly different (bold font).

<table>
<thead>
<tr>
<th>Dune type</th>
<th>Folk Mean (phi)</th>
<th>Folk Sorting (phi)</th>
<th>Folk Skewness (phi)</th>
<th>Folk Kurtosis (phi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>1.951</td>
<td>0.397</td>
<td>0.009</td>
<td>1.002</td>
</tr>
<tr>
<td>IDDB</td>
<td>2.790</td>
<td>0.664</td>
<td>0.088</td>
<td>1.051</td>
</tr>
</tbody>
</table>

## Table 2
Average Folk moments for CDs and IDDBs by position on the dune. Values with significant differences (p-values < 0.05) between CDs and IDDBs are shown in bold.

<table>
<thead>
<tr>
<th>Dune type</th>
<th>Position</th>
<th>Folk Mean (phi)</th>
<th>Folk Sorting (phi)</th>
<th>Folk Skewness (phi)</th>
<th>Folk Kurtosis (phi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>Leeward base</td>
<td>1.997</td>
<td>0.396</td>
<td>0.051</td>
<td>1.003</td>
</tr>
<tr>
<td>IDDB</td>
<td>Leeward base</td>
<td>2.718</td>
<td>1.003</td>
<td>0.296</td>
<td>1.256</td>
</tr>
<tr>
<td>CD</td>
<td>Leeward mid-slope</td>
<td>1.981</td>
<td>0.398</td>
<td>0.020</td>
<td>1.007</td>
</tr>
<tr>
<td>IDDB</td>
<td>Leeward mid-slope</td>
<td>2.859</td>
<td>0.692</td>
<td>0.165</td>
<td>1.110</td>
</tr>
<tr>
<td>CD</td>
<td>Crest</td>
<td>1.947</td>
<td>0.394</td>
<td>−0.037</td>
<td>0.994</td>
</tr>
<tr>
<td>IDDB</td>
<td>Crest</td>
<td>2.804</td>
<td>0.552</td>
<td>−0.000</td>
<td>0.944</td>
</tr>
<tr>
<td>IDDB</td>
<td>Windward mid-slope</td>
<td>2.695</td>
<td>0.535</td>
<td>−0.078</td>
<td>0.965</td>
</tr>
<tr>
<td>CD</td>
<td>Windward mid-slope</td>
<td>1.988</td>
<td>0.403</td>
<td>0.014</td>
<td>0.986</td>
</tr>
<tr>
<td>CD</td>
<td>Windward base</td>
<td>1.842</td>
<td>0.390</td>
<td>−0.005</td>
<td>1.021</td>
</tr>
<tr>
<td>IDDB</td>
<td>Windward base</td>
<td>2.874</td>
<td>0.538</td>
<td>0.059</td>
<td>0.982</td>
</tr>
</tbody>
</table>
Among IDBD samples, the porosity values are scattered (from 0.32 up to 0.44) while the mean grain diameter values are constrained to a small range (2.5 – 3.0 phi). On the CDs, however, the range of mean grain diameter values is larger (0.5 – 2.4 phi) while porosity values range from 0.33 up to 0.36. The porosity in CDs appears to increase with the mean grain diameter values (in phi units), with the exception of samples with mean values < 1 (however it was found that these samples were from the same dune). The correlation for CDs was not significant (p-value = 0.1133) unless the samples with mean grain diameter of 1 were excluded (from one particular dune), with a p-value of 0.0011 but a poor correlation coefficient ($R^2 = 0.198$). The slope for this relation is 0.64 and it has an intercept of 0.19.

4.6. Analysis of mean grain diameter/hydraulic conductivity relationships between CDs and IDBDs

As with previous comparisons (Sections 4.5 and 4.6), the relationship between main grain diameter and hydraulic conductivity for CDs and IDBDs was clearly different (Fig. 11). In CDs it was observed that a

<table>
<thead>
<tr>
<th>Dune location comparison</th>
<th>Folk Mean (phi)</th>
<th>Folk Sorting (phi)</th>
<th>Folk Skewness (phi)</th>
<th>Folk Kurtosis (phi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMS - LB</td>
<td>0.108</td>
<td>0.002</td>
<td>0.025</td>
<td>0.406</td>
</tr>
<tr>
<td>C - LB</td>
<td>0.544</td>
<td>0.000</td>
<td>1E-07</td>
<td>0.004</td>
</tr>
<tr>
<td>WMS - LB</td>
<td>0.994</td>
<td>3.4E-06</td>
<td>2E-10</td>
<td>0.008</td>
</tr>
<tr>
<td>WB - LB</td>
<td>0.058</td>
<td>3.9E-06</td>
<td>1.05E-05</td>
<td>0.014</td>
</tr>
<tr>
<td>C - LMS</td>
<td>0.869</td>
<td>0.396</td>
<td>0.003</td>
<td>0.272</td>
</tr>
<tr>
<td>WMS - LMS</td>
<td>0.042</td>
<td>0.284</td>
<td>6.8E-06</td>
<td>0.407</td>
</tr>
<tr>
<td>WB - LMS</td>
<td>1.000</td>
<td>0.303</td>
<td>0.107</td>
<td>0.529</td>
</tr>
<tr>
<td>WMS - C</td>
<td>0.310</td>
<td>1.000</td>
<td>0.360</td>
<td>1.000</td>
</tr>
<tr>
<td>WB - C</td>
<td>0.726</td>
<td>1.000</td>
<td>0.628</td>
<td>0.990</td>
</tr>
<tr>
<td>WB - WMS</td>
<td>0.021</td>
<td>1.000</td>
<td>0.018</td>
<td>1.000</td>
</tr>
</tbody>
</table>
There is a clear negative trend in hydraulic conductivity with increasing phi units of mean grain diameter occurs. The relation in this case was significant (p-value < 2.2 E-16) with a correlation coefficient of $R^2 = 0.92$, a slope of $-10.2$ m/day and intercept of $45.19$ m/day. For IDBDs, the relation was not as clear, and indeed was not significant (p-value of 0.619), unless the windward base samples were excluded (p-value of 0.0089, $R^2 = 0.166$, slope and intercept of $0.64$ m/day and $0.11$ m/day). Note that the slope of the relation for IDBDs was positive, while for the CDs it was negative.

4.7. Analysis of sorting/hydraulic conductivity relationships between IDBDs and CDs

Fig. 12 shows the relation between sorting (phi units) and hydraulic conductivity. Similar as in other relations analyzed in this study, the CDs seem to have a better correlation between these two properties. The correlation for CDs is significant (p-value < 1 E-8 and $R^2 = 0.50$), with a positive slope of $0.82$ m/day and intercept of $0.55$ m/day. There is a decline in hydraulic conductivity as sorting becomes poorer (increase in values). The IDBD samples also seem to have a positive slope, however the correlation is not significant (p-value of 0.38). Most of the measured sorting values on IDBD samples taken from the leeward base seem to be larger than the rest of the IDBD samples. When the IDDB samples are analyzed without the leeward base samples, the relation was still poor (p-value = 0.9297).

4.8. Analysis of skewness/kurtosis relationships between IDBDs and CDs

The relation between skewness and kurtosis was analyzed (Fig. 13). This relation was the only one (among the ones we analyzed) where the correlation is not significant (p-value = 0.619), unless the windward base samples were excluded (p-value of 0.0089, $R^2 = 0.166$, slope and intercept of $0.64$ m/day and $0.11$ m/day). Note that the slope of the relation for IDBDs was positive, while for the CDs it was negative.

5. Discussion

5.1. Grain size characteristics comparison of dune types

The statistical analysis showed that two of the four statistical parameters showed differences between the dune types. The CDs contained a higher mean grain diameter, similar to the findings of Kaspar-Zubillaga and Carranza-Edwards (2005). The sorting was also statistically different. There were no significant differences in the skewness or kurtosis.

Direct observation of the dunes showed that the source area for the IDDBs contained a large mix of sediment types from boulders to mud with the wind winnowing the sediment. The beach source areas in Uruguay contained sand with a larger mean grain diameter and no mud. In the case of the IDDBs, there is a higher percentage of the fine sand fraction which on the source beaches was lower. Therefore, the CDs should have a larger grain diameter. The difference in sorting is likely also caused by the sediment characteristics of the source areas with the source beaches having virtually zero mud. In addition, in the CDs there is periodical a reversal of transport direction between the beaches and the dunes based on the wind rose data which may influence the grain size properties. This direction change likely influences the windward side of the dune to a greater degree by eroding part of the crest onto the mid-windward slope and to the windward base. In addition, in the complex dunes at some locations the second and third dune line to the landward direction may be the source of sand for the leeward part of the first dune.

A comparison of mean grain size values on the dunes by type yielded differing results by position. At the windward base only the mean grain diameter and the sorting were statistically different with the IDDBs having a higher mean grain diameter and the sorting being better in the CDs. No statistical difference was found in the skewness or kurtosis. At the mid-windward slope, the mean, sorting, and skewness were statistically different. The mean grain diameter was higher in the CDs, the sorting was better in the CDs and the skewness was slightly positive in the CDs and slightly negative in the IDDBs. At the crest, the mean grain diameter, sorting, and skewness were different and the kurtosis was not statistically different. At the leeward slope the same general pattern of statistical difference as the crest was observed. At the leeward base, all four grain size characteristics showed significant statistical differences. While the mean grain diameter and the sorting were

<table>
<thead>
<tr>
<th>Location on dune</th>
<th>Porosity (CD)</th>
<th>Porosity (IDDB)</th>
<th>K (CD)</th>
<th>K (IDDB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windward base</td>
<td>0.352 (0.008)</td>
<td>0.384 (0.020)</td>
<td>24.78 (5.74)</td>
<td>5.10 (2.74)</td>
</tr>
<tr>
<td>Windward mid-slope</td>
<td>0.355 (0.006)</td>
<td>0.401 (0.032)</td>
<td>24.90 (4.57)</td>
<td>10.04 (2.58)</td>
</tr>
<tr>
<td>Crest</td>
<td>0.356 (0.008)</td>
<td>0.397 (0.018)</td>
<td>24.52 (4.96)</td>
<td>11.70 (3.05)</td>
</tr>
<tr>
<td>Leeward mid-slope</td>
<td>0.354 (0.005)</td>
<td>0.405 (0.025)</td>
<td>24.99 (4.55)</td>
<td>10.89 (3.57)</td>
</tr>
<tr>
<td>Leeward base</td>
<td>0.354 (0.007)</td>
<td>0.395 (0.020)</td>
<td>24.57 (5.03)</td>
<td>8.78 (2.59)</td>
</tr>
</tbody>
</table>
rather consistently different, in the case of the leeward base position the CDs contained a more positive skewness and higher kurtosis compared to the IDBDs. In the IDBDs the inter-dune area was commonly desert pavement (sometime muddy and hard), while in the coastal zone there was always some sand landward of the dune base.

The differences in the grain size statistics are likely based primarily on source area sediment size characteristics, but may also be a function of the relationship to the wind direction over the year. A comparison of wind rose diagrams shows that the maximum wind velocities are larger in Uruguay compared to the Saudi Arabia site and the wind direction is predominantly from an angle in Saudi Arabia (Fig. 14). In addition, the wind rose in coastal Uruguay shows significant wind from the landward direction that can reverse sediment transport. These differences in wind direction may explain some of the differences in the grain size parameters.
5.2. Hydraulic properties characteristics comparison of dune types

A comparison of the porosity and hydraulic conductivity data between the IDBDs and CDs showed significant differences in their average properties. The IDBDs had a higher average porosity of 0.39 compared to the CDs at 0.35. Based on the larger mean grain diameter and better sorting of the CDs, this is the expected result. Also, the average hydraulic conductivity of the CDs was higher at 24.3 m/d compared to the IDBDs at 9.32 m/d. This is again expected in that the mean grain diameter was larger, the sorting was better, and there was a lower percentage (none) of mud in the CDs. While the porosity values did not change significantly within the position on the dunes, the hydraulic conductivity did have a significant variation on the IDBDs but not on the CDs.

Since dunes migrate and the sand is stacked, the variation in vertical hydraulic properties with the dune subsurface was well represented by the variations in hydraulic properties of the dune surface as measured at five locations. The lack of variation in porosity across the dunes shows a model of dune porosity can use an average value for the full thickness of a dune facies with confidence. The variation in hydraulic

Fig. 10. Scatterplot of mean grain diameter versus porosity values in all samples. The color shows the positions within the dunes (LB: leeward base, LMS: leeward mid-slope, C: crest, WMS: windward mid-slope, WB: windward base). The IDBD samples are shown as triangles, while the coastal samples are shown as dots.

Fig. 11. Scatterplot of mean grain diameter versus hydraulic conductivity in all samples. The color shows the positions within the dunes (LB: leeward base, LMS: leeward mid-slope, C: crest, WMS: windward mid-slope, WB: windward base). The IDBD samples are shown as triangles, while the coastal samples are shown as dots.
conductivity (permeability) is indeed of greater significance in the surface of the dune and will also follow a similar pattern in the sub-surface. In large-scale dune facies modeling, consideration needs to be given to using different layers to represent the range of hydraulic conductivity values, whereas use of an overall average may create large errors in modeling.

5.3. Statistical relationships between mixed grain size and hydraulic properties

A series of scatterplots have been used to assess relationships between hydraulic properties of sediments and grain size statistical parameters along with hydraulic parameters. Five different relationships were evaluated, including hydraulic conductivity versus porosity, mean grain diameter versus porosity, mean grain diameter versus hydraulic conductivity, sorting (dispersion) versus hydraulic conductivity, and skewness versus kurtosis.

![Scatterplot of dispersion versus hydraulic conductivity in all samples.](image1)

**Fig. 12.** Scatterplot of dispersion versus hydraulic conductivity in all samples. The color shows the positions within the dunes (LB: leeward base, LMS: leeward mid-slope, C: crest, WMS: windward mid-slope, WB: windward base). The IDBD samples are shown as triangles, while the coastal samples are shown as dots.

![Scatterplot of skewness versus kurtosis in all samples.](image2)

**Fig. 13.** Scatterplot of skewness versus kurtosis in all samples. The color shows the positions within the dunes (LB: leeward base, LMS: leeward mid-slope, C: crest, WMS: windward mid-slope, WB: windward base). The IDBD samples are shown as triangles, while the coastal samples are shown as dots.
There were no statistically significant relationships between hydraulic conductivity and porosity on the two dune types, but there was a positive trend of increasing hydraulic conductivity with increasing porosity in the IDBDs, but it was not statistically significant. In beach sands there is also a positive slope with hydraulic conductivity increasing as porosity increases which is significant as found by Franco et al. (2016).

In the sorting versus hydraulic conductivity plot, the hydraulic conductivity decreases with poorer sorting. This relationship is well known and has been found and discussed by many researchers (Beard and Weyl, 1973). In the IDBDs there is a similar trend, but it is not statistically significant.

In both dune types as skewness increases as the kurtosis increases. The relationship is statistically significant in both cases. However, the correlation coefficient is greater for the IDBDs.

5.4. Corresponding processes producing sand for the IDBDs and CDs

The source area for the sand produced at the IDBD site in western Saudi Arabia is predominantly the lower reach of Wadi Khulays which is shown on the right of Fig. 1 directly below the wind direction label. The surrounding coastal plain surface contains minimal sand that can be mobilized by wind because of the generally stiff surface caused by dust fallout and wetting over the centuries. The sand within the wadi is periodically replaced by flood-driven sediment, commonly flash floods, moving from the upper basin seaward (a distance of 80 to 100 km). The IDBDs tend to move away from the wadi during periods of minimal sand supply and form closer to the wadi after a flood event (authors observation).

The sand supply allowing CDs to form in Uruguay is produced from the beach which is constantly being renewed to a large degree. However, the sand supply to the beach is supplemented at the Parque del Plata site (Fig. 3b) by influx from small streams as well as erosion of some Pleistocene outwash deposits in the up-gradient direction (littoral drift direction) (Missimer et al., 2019). In this area the composition of the beach and dune sands has a very similar mineralogy with a slight reduction in the percentage of metastable grains (e.g., feldspars and rock fragments) as reported by Missimer et al. (2019). The CDs near La Paloma (Fig. 3c) form from beach sand, but the beach is retreating as a pre-existing Pleistocene dune field is being eroded. Recent compositional analyses have revealed that that in many locations in this area, the dune sand is less compositionally mature than the beach sand. In this case the fingerprinting of the source of the dune sand is assessed by geochemical analysis. A similar analysis was accomplished by Gholami et al. (2019) using chemical analyses at a complex site where numerous sand sources contributed to the dune sands.

As the geologic framework and sand origins of the IDBD and CD sites are common to other sites around the globe, we expect similar statistical findings relating hydro-sedimentological properties of dune sands to their positions in similar settings. Furthermore, our findings are relevant to improve numerical models of field dune morphodynamics by helping researchers to more accurately set boundary conditions and initial assumptions related to grain size and the hydraulic characteristics of dune sediments which influence both sediment transport and dune geometry (de Luna et al., 2012; Gabarrou et al., 2018). Collection of additional data would tend to further improve the statistical correlations.

6. Conclusions

Statistically significant differences between grain size characteristics and hydraulic properties of IDBDs compared to CDs were found. The IDBDs in western Saudi Arabia contained sands with a lower mean grain diameter and lower hydraulic conductivity compared to the CDs of Uruguay. The difference is caused by the sand size of the source sediment and the strength and variation of the wind at the coast (reversing sediment transport) compared to that in the IDBDs where they migrate consistently in one direction. In addition, the sorting of the CD sands was greater than the IDBD sand which may be another reason why the hydraulic conductivity was higher in the CDs. There are also significant differences in the grain size characteristics based on the position on dunes in both the IDBD and CD environments. The interior leeward base of both dune types shows significant differences in all four grain size moments, whereas at other positions only the first two or three moments show significant differences. The porosity of the IDBDs was higher compared to the CDs based on the lower mean grain diameter and the other grain size moments that affect it. In both dune
environments, there were no statistically significant differences in porosity based on the position on the dunes. Based on the analysis of the grain size data, it appears that the differences in the parameters could be used to estimate the wind direction of ancient dunes in locations where the general geometry of the dune field has been altered by erosion. The leeward base of the dunes has significantly different grain size properties in all four grain size moments whereas the windward base has significant differences in only the first two moments (mean grain diameter and sorting).

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Appendix A. Supplementary data

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References