Immature beach/dune sands along a passive continental margin: Composition, grain size and hydraulic properties of coastal sands, Parque del Plata and Las Vegas, Uruguay

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Abstract
The modal composition of sandstones has long been used as a tool for palaeotectonic and palaeoenvironmental analyses. Herein it is demonstrated that caution must be used when beach sand composition is utilized to assess tectonic provenances at both the local and continental scales. The occurrence of quartz arenites and compositionally mature sands along the coast of Brazil corresponds well to their passive margin location. However, modern sands from some beach locations in coastal Uruguay are less compositionally mature compared to the quartz arenites found in coastal Brazil. Along the beaches of Las Vegas and Parque del Plata, the composition of the beach and dune sands is impacted by the transport of continental outwash sediments derived from the Palaeozoic and Precambrian rocks in the interior to the beach by a low-gradient stream, Arroyo Solis Chico, and the erosion of Pleistocene-age formations that crop out on the beach and along an erosional scrap. The mean beach composition ratio of monocrystalline quartz to feldspar to rock fragments plus composite quartz grains is 67.5/8.0/24.5 compared to the ratio along the coast of Brazil at 86/4/10. The beach and coastal dunes environment studied is representative of about 35% of coastal Uruguay. At the smaller scale, changes in the textural properties of the beach and dune sands (grain-size distribution and roundness) are caused by the addition of the sediment derived from erosion and stream transport. Porosity values show little influence and range between 0.35 and 0.36, but hydraulic conductivity is influenced to a greater degree, ranging from 18.5 to 31 m/day. Within one kilometre down-drift of the river, the mean grain diameter and the mean hydraulic conductivity increase to the same values found in the up-gradient area before influence of the sediment flux, due to the offshore transport of the finer sediment fraction during down-gradient movement along the beach. The Arroyo Solis Chico area demonstrates that abrupt changes in composition and hydraulic properties can occur over short distances in sands deposited in passive margin environments. The potential for this local variability in sand composition and hydraulic properties should be considered in the analyses of ancient marine sandstones deposited in beach and coastal dunes environments.
1 INTRODUCTION

It has been suggested that, at a continent-scale, the composition of beach sand can be used to determine tectonic provenance (Potter, 1986). In this classic paper the quartz–feldspar–rock fragment ratios (Q:F:Rf) of 218 modern beach sands collected in South America were measured with the result that tectonics were determined to be the predominant factor controlling mineralogy of the sands. The Q:F:Rf ratios of the beach sands coincided with the expected compositional maturities at the active margin on the Pacific Coast (24:16:60) and the passive margin along coastal Brazil (90:4:5). While the sediment-tectonic model was accurate for these regions, which constitute 75% of coastal South America, the area of coastal Uruguay and Argentina did not correspond to the expected passive margin mineralogy with Argentina showing a composition ratio of 28:14:58. Potter (1986) suggested that the reason the Argentinian beach sands are compositionally similar to those of the leading-edge of a continent may be explained by the narrowness of the continent in Patagonia and the climate. The boundary between the Brazilian and the Argentinian compositions was the outfall of the Rio de la Plata into the Atlantic Ocean, which on the south side of the estuary is the border between Brazil and Uruguay.

Potter (1986) also concluded that other factors must be considered when using beach sand composition to predict the tectonic provenance of ancient sandstones, including climate, relief and continental geography. A key part of this research is to further assess why the mineralogy of the beach sands of part of coastal Uruguay does not accurately predict tectonic provenance as found in coastal Brazil based on the Potter (1986) model. This investigation will contribute towards more accurate interpretations of the rock record based on sediment composition. In addition, the impacts of the sediment balance of the beaches and dunes on grain-size distribution, porosity and hydraulic conductivity were used to assess the impact of local sediment contributions to the overall composition and sediment characteristics.

Variation in the local composition of beach and coastal dune sands is controlled by the composition of new sediment added to the system by stream or river input, erosion of bounding or outcropping geological units (cliffs and shoreline outcrop of rocks), onshore movement of sediment from subtidal areas (high tide bars), longshore transport and mechanical abrasion of the metastable minerals, storm transport of beach sediment to deeper water, selective wind transport of sediment to the foredunes, cycling of coastal dune sands back onto beaches, geochemical removal of metastable minerals within the dunes and offshore migration of the very fine sand and silt fraction (Abuodha, 2003; Davis & Fitzgerald, 2004; Pye, 1991, 1993; Suttener, Basu, & Mack, 1981; Valloni, 1985). Beach sediments found along the passive margin of continents are commonly predominantly composed of quartz sands containing 10%–15% or less of feldspar and rock fragments in the areas not under the influence of major rivers transporting large concentrations of feldspars and rock fragments sediment to the coast (Bhatia, 1983; Dickinson et al., 1983; Garzanti et al., 2014; Kasper-Zubillaga, Armstrong-Altrin, Carranza-Edwards, Morton-Berma, & Santa Cruz, 2013; Lucchi, 1985; Potter, 1986; Table 1). Long distance and duration transport in the littoral zone in passive margin settings can produce predominantly quartz sands (quartz arenites) such as those found in the eastern Gulf of Mexico, the shorelines of Florida and most of Brazil (Hsu, 1960; Martens, 1935; Potter, 1986). While the average composition of beach sands along passive margins contains a high percentage of quartz (Bhatia, 1983), specific circumstances can cause areas of beach sediments rich in feldspars and rock fragments to occur along a passive margin, such as erosion of glacial sediments along the New England coast of the United States (McMaster & Garrison, 1966). Also, there are regions along the passive margins of continents where river influx of sands containing large concentrations of feldspars and rock fragments is maintained for great distances, such as the West Africa coast where the Orange River sediment influx influences an extensive coastal region (Garzanti et al., 2014, 2017).

Beach–dune complexes commonly occur near inflowing streams along the passive margin of continents, particularly where the rivers and streams are contributing sediment to the shoreline and where tidal currents modify wave-induced beach sediment transport (Psuty, 2004). Few investigations have been conducted in areas where low-gradient streams contribute sediment to the coast and erosion of existing siliciclastic sedimentary formations is occurring simultaneously. Based on a literature survey, no investigations have been conducted in coastal Uruguay that relate grain size and hydraulic properties to sediment influx along the coast. This is quite important because the dynamics of sediment transport are controlled to a degree by the porosity and permeability of the sediment, particularly in the swash zone (Packwood, 1983; Reis & Gama, 2010).

The longshore sediment transport direction along beaches fronting stream and dune systems is commonly constant within a modern framework when averaged over many years,
based on the configuration of the shoreline in relation to the predominant wind direction(s) and generated wave pattern (Davis & Fitzgerald, 2004). Unidirectional transport likely at the beach–dune complex associated with the intersection of Arroyo Solis Chico with the Rio de la Plata micro-tidal estuary in coastal Uruguay (Goso et al., 2014). While the Rio de la Plata is a somewhat restricted estuarine water body, it is subject to storms passing through the area from the Southern Ocean that cause periodic intense wave activity impacting the shoreline (Panario & Piñeiro, 1997). The direction of long-shore sediment transport is from east to west at this location based on the geometry of spits that have propagated across several stream mouths (Goso, Mesa, & Alvez, 2011). Climate change may in the future alter the rate of sediment transport with a possible increase in the number and intensity of storms (Ortega, Celentano, Finkl, & Defeo, 2013; Verocai, Gómez-Erache, Nagy, & Bidegain, 2015).

Grain-size characteristics, particularly mean grain diameter, sorting and shape, affect the porosity and hydraulic conductivity (permeability) of the beach and dune sands. A large percentage of the global hydrocarbon reserves found in siliciclastic sediments occur in shallow-marine, nearshore, beach and associated dune facies (Siddiqui, Sum, & Yusoff, 2017). It is important to link the composition, grain-size characteristics and hydraulic properties of the sediments in modern coastal environments to allow more accurate modelling of ancient rocks (Siddiqui, Rahman, Sum, Mathew, & Menier, 2015; Siddiqui, Rahman, Sum, Mahew, Menier, et al., 2015; Siddiqui, et al., 2017; Thomas, 1998)

### Table 1

| Beach sand locations | Tectonic provenance | Reference |
|----------------------|---------------------|-----------|
| Gulf Coast, USA      | Passive margin      | Hsu (1960) |
| New England, USA     | Passive margin      | McMaster and Garrison (1966) |
| Adriatic beaches, Italy | Active margin     | Gazzi, Zaffa, Gandolf, & Pagnelli, 1973 |
| Mariana forarc and backarc, Japan | Active margin | Packer and Ingersoll (1986) |
| W. South America     | Active margin       | Potter (1986) |
| Brazil               | Passive margin      | Potter (1986) |
| N. South America     | Mixed tectonic provenances | Potter (1986) |
| Argentina/Uruguay    | Passive margin      | Potter (1986) |
| Antarctica           | Active margin       | Pirrie (1991) |
| Calabria, Italy      | Active margin       | La Pera and Critella (1997) |
| SW Mexico Pacific    | Active margin       | Carranza-Edwards, Kasper-Zubillaga, Rosales-Hoz, Morales de la Garza, and Lozana-Santa Cruz (2009) |
| NW Gulf of Mexico    | Passive margin      | Kasper-Zubillaga et al. (2013) |
| Namibia, Africa      | Passive margin      | Garzanti et al. (2014) |
| Orange littoral cell, Angola | Passive margin | Garzanti et al. (2017) |

### 2 | Geographic and Geological Background

Uruguay lies between Argentina and Brazil on the eastern, passive margin of South America (Figure 1). It is bounded to the south by the Rio de la Plata, a broad micro-tidal estuary into which flows the converged Paraná and Uruguay rivers. Investigations conducted on the sands within the Paraná and Uruguay rivers have shown that they are composed mostly of quartz with average Q:F:Rf ratios of 97:2:1 and 92:3:5, respectively (Missimer, Maliva, Perea, & Badin, 2017; Potter, 1986). Many small streams or arroyos enter the Rio de la Plata along the Uruguayan coastline (Figure 1). From direct observation and a review of Google Earth photography, the coast is characterized by long reaches of cliffs eroded into outcropping sedimentary strata (about 25%), sandy beaches with coastal dunes segmented by inflowing streams (about 35%), sandy beaches formed by the erosion of late Pleistocene-age coastal dunes with some bounding interior coastal lagoons (about 25%), rocky headlands composed of igneous and metamorphic rocks (about 10%) and rocky beaches containing outcropping rock or gravel, pebbles and cobbles (about 5%; Goso et al., 2011; Panario & Gutiérrez, 2006; Urien, 1970, 1972). The slope of the beaches and overall beach and dune profiles varies greatly.

Many of the small streams entering the Rio de la Plata along the western half of Uruguay drain an area underlain by Precambrian craton (Figure 2) and coastal deposits of Oligocene to Pleistocene-age sediments, which range in
lithology from sandy carbonate rocks to muddy, reddish-coloured continental outwash siliciclastic sediments, to greenish-coloured slightly sandy marine muds (Figure 3). Some of the Neogene sediments form cliffs along the shoreline (Figure 3; Goso et al., 2014; Missimer et al., 2017).

The study area is located at the entrance of Arroyo Solis Chico into the Rio de la Plata, between Parque del Plata on the west and Las Vegas on the east (Figure 4). Arroyo Solis Chico is a low-gradient stream that has a drainage basin of between 600 and 700 km² (Uruguay Navy, 1999) and is subject to periodic flooding. The shoreline in the vicinity of the intersection of the stream with the coast currently contains a westward prograding spit which causes the stream discharge to bend to the west (Figure 4). On the stream side of the spit (east), gravel-sized sediment is mixed with fine-grained sand, while on the beach side of the spit the sediment is mostly sand with sparse marine shells. The back beach on the east side of Arroyo Solis Chico at southern Las Vegas is an erosional scarp containing some exposed Pleistocene sediments, including reddish-coloured continental outwash sediments and green-coloured lagoonal muds (Libertad Formation), and gravel and sand beach deposits (Chuy Formation; Goso et al., 2014). The Pleistocene-age Libertad Formation crops out on the beach and probably also crops out in the subtidal, nearshore area.

Inland from the back beach, large foredunes occur on both sides of Arroyo Solis Chico (Figure 5a–c). The maximum elevation of the dune crests is 5–7 m above mean sea-level. Some of the dunes contain mature vegetation while others contain actively moving, unstable sand. The road bordering the landward side of the dune complex on the north side of the stream is commonly blocked by onshore aeolian-transported sand.

Arroyo Solis Chico cuts across outcrops of several Oligocene and Pleistocene-age siliciclastic sediment units (Figure 3). These units typically are muddy sands and gravels that contain immature grains eroded from the Precambrian rocks present locally and in higher elevation
areas located to the north. The upper basin of Arroyo Solis Chico drains a variety of Precambrian metamorphic and igneous rock types as shown on the Geological Map of Uruguay (Bossi et al., 1975; Figure 2).

3 | METHODS

3.1 | Changes in the shoreline position and dune configuration in time

A time series of aerial photographs were used to document the historic changes in shoreline position and dune configuration at the intersection between Arroyo Solis Chico and the Rio de la Plata. The examined photographs begin with an oblique view taken in 1943 and then a series of rectified satellite photographs collected from September 2006 to October 2017. These changes were documented by Goso (2006).

3.2 | Sampling for grain-size distribution of the beach and dune sands

Four perpendicular transects were sampled from the beach swash zone to the distal side of the dunes (Figure 4). Two transects were west of Arroyo Solis Chico adjacent to the town of Parque del Plata and two transects were located east of the arroyo in front of the town of Las Vegas. A minimum of three samples were collected on the beach, at the upper swash zone, the mid-beach and the back beach about 5 m from the windward toe of the dune. Five or more samples were collected from each dune transect including at the windward toe, the mid-windward slope, the crest, the middle leeward slope and the leeward base. Most of the transects contained eight samples while some contained up to 11 samples. In addition, four samples were collected from the beach swash zone both west and east of the discharge channel of Arroyo Solis Chico. These swash zone
samples were collected from the edge of the channel, and at 50, 100 and 200 m from the channel mouth. The location of the arroyo mouth has changed slightly between the time the samples were collected and the sample locations shown in Figure 4. One sample was collected from the landward edge of the Arroyo Solis Chico channel behind the central part of the beach spit structure. A handheld global positioning system unit was used to obtain the latitude and longitude of each sample site and the distances between the samples were determined using a measuring tape.

Each collected sediment sample weighed about 500 g and was carefully washed with freshwater to remove salt. The samples were dried in an oven at 200°C and placed in containers for transport to the laboratory. The grain-size distribution, porosity and hydraulic conductivity of all samples were measured (50 samples). During beach and dune sampling, care was taken not to cross sediment unit boundaries with only the upper 2–5 cm of sediment collected.

Three samples from the Libertad Formation were collected from outcrops occurring near the east Las Vegas transect (Figure 4 for location). The volume of the samples was about 600 cm³. Each sample was dried and weighed. The samples were wet sieved through a 230 mesh screen to
separate the mud fraction from the gravel and sand. The mud and sand/gravel fractions were weighed to determine the percentage of the primary size components.

3.3 | Grain-size distribution measurements and moment calculations

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. A computer program developed by Rosas et al. (2014) was used to calculate the mean grain diameter, dispersion, skewness and kurtosis of the size distribution based on the Folk and Ward (1957) equations.

3.4 | Composition of the beach, dune and possibly stream-transported sands

Each sample was subdivided into four size fractions, granule (greater than sand), coarse (−1 to 1 Ø), medium (1 to −2 Ø) and fine (−2 to −4 Ø) sand fractions, as suggested by Grantham and Velbel (1988). In some cases, only two or three of the fractions occurred within a sample (Table 2). Standard grain thin sections were made for each size increment and stained with Na-cobaltinitrate to facilitate identification of potassium feldspar grains (stains to yellow colour) and with K-rhodizonate to aid in identification of plagioclase grains that are not twined (stains to a pink colour; Houghton, 1980). Each thin section was point-counted for composition using 500 grains, when possible, based on the number of grains in the section (some of the granule and coarse size fraction thin sections contained a smaller number of grains). A full range of grain types, including individual light minerals, binary minerals (e.g. quartz + potassium feldspar), rock fragments of various types and transparent heavy minerals, were recorded. The results of the point counts were plotted on ternary diagrams.

Two sets of compositional plots by grain size are presented; one is a normal quartz-feldspar-rock fragments (QFR) plot and the other adds composite quartz grains to the rock fragments category. The QFR system was selected because quantification of rock fragments has depositional significance and the analyses can be compared to those previously completed by Potter (1984, 1986, 1994). All quartz grains were examined to record extinction type and inclusions using the classification of Folk (1968). The number of grains was counted in each polycrystalline quartz grain and recorded.

3.5 | Determination of quartz grain roundness

The shape of all quartz grains was determined using the Powers (1953) images and classified using the Folk (1968) system. In addition, the samples were compared using a simple shape index calculated from the point count data. The very angular classification was given a value of 1 and the well-rounded classification was given a value of 6. The equation used to calculate the index was: (1 times number of very small angular grains + 2 times number of slightly angular grains + 3 times number of moderately angular grains + 4 times number of well-rounded grains + 5 times number of very well-rounded grains) / total number of grains.
| Location                        | Environment | Sample no. | Size range (mm) | No. grains counted |
|--------------------------------|-------------|------------|-----------------|--------------------|
| Parque del Plata west          | Beach       | M-418      | 2–0.5           | 147                |
|                                |             |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |
| Dune                           | M-423       |            | 2–0.5           | 500                |
|                                |             |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |
| Parque del Plata east          | Beach       | M-255      | 2–0.5           | 500                |
|                                |             |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |
| Dune                           | M-265       |            | 2–0.5           | 500                |
|                                |             |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |
| Dune                           | M-259       |            | 2–0.5           | 500                |
|                                |             |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |
| Las Vegas west                 | Beach       | M-268      | 2–0.5           | 500                |
|                                |             |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |
| Dune                           | M-274       |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |
| Las Vegas east                 | Beach       | M-363      | 2–0.5           | 500                |
|                                |             |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |
| Dune                           | M-371       |            | 2–0.5           | 500                |
|                                |             |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |
| Arroyo Solis Chico spit west   | Beach       | M-414      | 2–0.5           | 500                |
|                                |             |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |
| Arroyo Solis Chico spit east   | Beach       | M-411      | 2–0.5           | 500                |
|                                |             |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |
| Arroyo Solis Chico spit inner beach | Beach | M-426 | 2–0.5 | 500 |
|                                |             |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |
| Upper Libertad Formation       | Terrestrial Outwash | M-435 | 2–0.5 | 500 |
|                                |             |            | 0.5–0.25        | 500                |
|                                |             |            | 0.25–0.0635     | 500                |

(Continues)
angular grains) + (2 times number of angular grains) + (3 times number of subangular grains) + (4 times number of subrounded grains) + (5 times rounded grains) + (6 times number of well-rounded grains) and the sum was divided by the total number of counted grains. This index was previously used by Missimer and Maliva (2017). The roundness index was used to compare samples.

### 3.6 Porosity of the beach and dune sands

The porosity of the sediment was measured using the volumetric displacement and bulk density methods simultaneously as described by Missimer and Lopez (2018). Samples that showed a divergence in measured porosity of greater than 3% were run a second time and if the composition adversely affected the bulk density value, only the porosity obtained using the volumetric displacement method was reported.

### 3.7 Hydraulic conductivity of the beach and dune sands

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. (2017) and following the American Society for Testing and Materials (2006) standard D2434-68. Sediment was added to the permeameter chamber in a dry state to facilitate removal of air in the pores. The sediment column height ranged from 5.8 to 6.2 cm and the area of the cylinder was 31.65 cm². Flow through the permeameter was from the bottom to the top during all measurements. The head through the permeameter was maintained at 65.3 cm to minimize any disruption of the sediments. 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 a steady-state was achieved as evidenced by minimal variation in the recorded time between successive time measurements. 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 the computer program created by Rosas et al. (2014).

### Results

#### 4.1 Historical variation in the pattern of beach sedimentation

A comparison of aerial views of the shoreline at the mouth of Arroyo Solis Chico shows that the general geometry of the shoreline has not changed greatly since at least 1943. The sediment transport was generally from east to west as evidenced by the presence of a spit that diverts flow from Arroyo Solis Chico to the west (Figure 6a–j). The barrier spit length from the east to west across the mouth of Arroyo Solis Chico has varied from 861 to 1,414 m over the 11-year interval shown in Figure 6 (Table 3). Storms and flood events did not cause a breach of the spit during the time-period encompassed by the aerial photographs. Flood discharge can be seen in Figure 6f, where the entrance of the arroyo was deflected seaward. The geometry of the spit has changed historically in length as measured from the dune located on the eastern side of the arroyo, and the entrance angle of the arroyo into the Rio de la Plata has also changed.

The cliff retreat at Las Vegas and to the south has been estimated to range from 66 to 100 cm/year based on measurements made between 2006 and 2015. Goso et al. (2007) published a recession rate of 110 cm from 1972 to 2006. The estimated rates made by other investigators range from 67 to 156 cm/year (IMFIA, 2008). Based on the estimated cliff recession rate, about 33,000 m³/year of sediment is added to the beach from this source.

#### 4.2 Comparative composition of the sediments

The beach sediment is predominantly composed of monocrystalline and composite (polycrystalline) quartz grains with

| Location Formation | Environment     | Sample no. | Size range (mm) | No. grains counted |
|--------------------|-----------------|------------|-----------------|-------------------|
| Lower Libertad     | Terrestrial Outwash | M-453      | '2              | 28                |
|                    |                 |            | 2–0.5           | 500               |
|                    |                 |            | 0.5–0.25        | 500               |
|                    |                 |            | 0.25–0.0635     | 500               |
| Lower Libertad     | Marine          | M-455      | 2–0.5           | 154               |
|                    |                 |            | 0.5–0.25        | 500               |
|                    |                 |            | 0.25–0.0635     | 500               |
some metamorphic and igneous rock fragments, feldspars and a few mollusc fragments (Table 4; Figures 7 and 8). The beach and dune sediments from the four transects show no distinctive pattern with respect to quartz content in the sand size fractions. The Las Vegas transects have a generally higher percentage of feldspar compared to the Parque del Plata transects. In all of the transects, potassium feldspar is more abundant than plagioclase. However, the beach samples collected from the spit swash and the inner beach on the spit are enriched in plagioclase compared to potassium feldspar. Detailed composition data for each sample are provided in Table S1a–d in the Supplemental Materials.

The Libertad Formation contains a variety of rock fragments including igneous, metamorphic and sedimentary types (Figure 8a). The upper sample from the Libertad Formation has a similar feldspar content as the average for the transect beach samples, but potassium feldspar is slightly more abundant than plagioclase. The lower sample from the Libertad Formation also contains less quartz than the beach and dune samples but has a higher percentage of feldspar. The terrestrial (red) facies sample has a potassium feldspar to

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**FIGURE 6** Changes in the shoreline configuration at the mouth of Arroyo Solis Chico from September 2006 to October 2017

**TABLE 3** Aerial photograph date and length of barrier spit

| Date image | Spit barrier extent (m) |
|------------|-------------------------|
| Sept 2006  | 948                     |
| Nov 2009   | 1,394                   |
| Apr 2011   | 1,414                   |
| Aug 2012   | 861                     |
| Aug 2012   | 872                     |
| Jun 2013   | 896                     |
| Jan 2015   | 1,063                   |
| Nov 2016   | 1,302                   |
| Oct 2017   | 1,196                   |
plagioclase ratio of about 1.0, whereas the lagoonal (green) facies has more plagioclase, especially in the fine fraction, which has 22% feldspar with a very low potassium feldspar/plagioclase ratio. The mud percentages of the upper and lower red-coloured facies, and the green-coloured lagoonal facies of the Libertad Formation are 63%, 64% and 97%, respectively.

### Table 4: Statistical comparison of composition data

| Sand grain-size fraction | Category | Beach (swash) | Dune | Inner Arroyo Solis Chico shore | Pleistocene formations |
|-------------------------|----------|---------------|------|-------------------------------|-----------------------|
| Granule                 | No. samples | 1 | 0 | 1 | 2 |
| Q                       | 65.4 | 0 | 30.1 | 28.6 ± 40.4 |
| F                       | 7.7  | 0 | 5.5  | 0  |
| R<sub>t</sub>           | 26.9 | 0 | 64.4 | 71.5 ± 40.4 |
| Q<sub>m</sub>/Q         | 0.59 | 0 | 0.9  | 0.06 |
| Q<sub>c</sub>/Q         | 0.41 | 0 | 0.91 | 0.94 |
| F<sub>c</sub>/F         | 1.0  | 0 | 0.26 | 0  |
| Q<sub>m</sub>           | 38.5 | 0 | 2.7  | 17.9 ± 25.2 |
| F                       | 7.7  | 0 | 5.5  | 0  |
| R<sub>t</sub> + Q<sub>c</sub> | 53.8 | 0 | 91.8 | 82.2 ± 25.2 |
| Coarse                  | No. samples | 6 | 4 | 1 | 3 |
| 110–500 grains          | Q         | 77.1 ± 9.2 | 76.2 ± 5.7 | 65.0 | 64.9 ± 23.2 |
|                         | F         | 7.2 ± 3.8  | 5.8 ± 1.5  | 6.8  | 6.7 ± 2.1  |
|                         | R<sub>t</sub> | 15.7 ± 6.5 | 18.0 ± 6.0 | 28.2 | 28.4 ± 22.2 |
|                         | Q<sub>m</sub>/Q | 0.65 ± 0.07 | 0.65 ± 0.14 | 0.49 | 0.59 ± 0.21 |
|                         | Q<sub>c</sub>/Q | 0.36 ± 0.07 | 0.35 ± 0.14 | 0.51 | 0.41 ± 0.22 |
|                         | F<sub>c</sub>/F | 0.86 ± 0.09 | 0.87 ± 0.13 | 0.79 | 0.76 ± 0.23 |
|                         | Q<sub>m</sub> | 56.9 ± 1±59 | 49.1 ± 12.1 | 32  | 44.4 ± 31.4 |
|                         | F         | 6.7 ± 3.3  | 5.7 ± 1.6  | 6.8  | 6.7 ± 2.1  |
|                         | R<sub>t</sub> + Q<sub>c</sub> | 36.3 ± 14.8 | 44.8 ± 11.7 | 61.2 | 48.9 ± 30.0 |
| Medium                  | No. samples | 6 | 5 | 1 | 3 |
| 500 grains              | Q         | 84.5 ± 3.9  | 88.6 ± 3.2  | 65  | 77.8 ± 14.1 |
|                         | F         | 5.6 ± 2.7  | 4.4 ± 1.5  | 6.8  | 4.5 ± 0.8  |
|                         | R<sub>t</sub> | 9.9 ± 4.6  | 7.0 ± 2.4  | 28.2 | 17.7 ± 14.7 |
|                         | Q<sub>m</sub>/Q | 0.83 ± 0.02 | 0.87 ± 0.02 | 0.49 | 0.82 ± 0.04 |
|                         | Q<sub>c</sub>/Q | 0.17 ± 0.03 | 0.13 ± 0.02 | 0.51 | 0.18 ± 0.04 |
|                         | F<sub>c</sub>/F | 0.74 ± 0.25 | 0.87 ± 0.10 | 0.79 | 0.52 ± 0.01 |
|                         | Q<sub>m</sub> | 69.8 ± 4.3  | 77.1 ± 2.1  | 55.3 | 67 ± 15.6  |
|                         | F         | 5.6 ± 2.7  | 4.4 ± 1.5  | 10.2 | 4.5 ± 0.8  |
|                         | R<sub>t</sub> + Q<sub>c</sub> | 24.6 ± 4.6  | 18.4 ± 2.1  | 35.5 | 28.8 ± 16.1 |
| Fine                    | No. samples | 6 | 5 | 1 | 3 |
| 500 grains              | Q         | 82.6 ± 4.1  | 87.0 ± 3.5  | 78.8 | 71.8 ± 10.8 |
|                         | F         | 10.6 ± 2.9 | 6.3 ± 2.1  | 13.4 | 13.4 ± 7.7 |
|                         | R<sub>t</sub> | 6.9 ± 2.3  | 6.7 ± 3.0  | 7.8  | 14.8 ± 11.4 |
|                         | Q<sub>m</sub>/Q | 0.92 ± 0.03 | 0.93 ± 0.01 | 0.93 | 0.93 ± 0.03 |
|                         | Q<sub>c</sub>/Q | 0.09 ± 0.02 | 0.07 ± 0.01 | 0.07 | 0.07 ± 0.03 |
|                         | F<sub>c</sub>/F | 0.79 ± 0.26 | 0.85 ± 0.16 | 0.29 | 0.52 ± 0.25 |
|                         | Q<sub>m</sub> | 76.4 ± 2.4  | 81.2 ± 3.1  | 73.3 | 66.7 ± 11.3 |
|                         | F         | 8.7 ± 2.3  | 6.3 ± 2.1  | 13.4 | 13.4 ± 7.7 |
|                         | R<sub>t</sub> + Q<sub>c</sub> | 14.9 ± 3.5  | 12.6 ± 3.4  | 13.2 | 19.9 ± 12.9 |

(Continues)
The beach and dune sediments have about equal average quartz contents with the coarse-sand-sized fractions having less quartz compared to the middle and fine-grained fractions (Table 4). Feldspar content decreases by more than 1% in all of the fractions from the beach to the dune samples. Rock fragments are more abundant in the dunes compared to the beach samples in the coarse fraction only (beach 15.7 ± 6.5 beach compared to 18.0 ± 6.0 dune).
A comparison of the composition of the formation sediments to the beach and dune sediments shows that the eroding sediments have less quartz, an equal or greater feldspar fraction and more abundant rock fragments (see Table 3). Also, the ratio of potassium feldspar to plagioclase is significantly lower. The inner beach sample from the spit shows a similar composition to the formation samples (see Table 3).

### 4.3 Comparative quartz grain characteristics (extinction and inclusions)

Within the granule fraction, quartz grains in the beach sand samples have predominantly a single, straight extinction and inclusions with few vacuoles and no microlites (Table 5). The samples from the inner bank of Arroyo Solis Chico and the Pleistocene formations are predominantly composite grains with strongly undulose extinctions and abundant vacuoles.

Quartz grains with a single-grain straight extinction were most abundant in the coarse grain fraction in the dune samples (67.2%), followed by the beach samples (59.8%) and then the inner shore of Arroyo Solis Chico and the Pleistocene formations at 47.7% and 49.4%, respectively. Considering inclusion properties, the most common grains with few vacuoles and no microlites occurred in the dune samples (73.7%), followed by the beach samples (69.9%) and then at slightly lesser abundances in the samples from the inner shore of Arroyo Solis Chico and the Pleistocene formations. The patterns of mean extinction variation in the medium-grained and fine-grained fractions were similar to that of the coarse-grained fraction.

### 4.4 Comparison of roundness of quartz grains

Within the granule sediment fraction, the roundest quartz grains occurred in the inner bank of Arroyo Solis Chico followed by the Pleistocene formations and the beach samples (Table 6). A similar pattern occurred in the coarse-sand fraction with the mean roundest quartz grains occurring in the inner bank of Arroyo Solis Chico followed by the Pleistocene formation, the dune and then the beach samples. The mean roundness pattern was slightly different in the medium grain
TABLE 5  Quartz properties, extinction and inclusion percentages

| Grain-size fraction | Category          | Beach (swash) | Dune | Inner Arroyo Solis Chico shore | Pleistocene formations |
|---------------------|------------------|---------------|------|--------------------------------|------------------------|
|                     |                  |               |      |                                |                        |
| Granule             | No. samples      | 1             | 0    | 1                              | 2                      |
| No. of grains       |                  | 17            | 0    | 22                             | 16                     |
| Extinction          |                  |               |      |                                |                        |
| Single grain, straight |                | 58.8          | 0    | 9.1                            | 6.3                    |
| Single grain, slightly undulose |         | 0             | 0    | 0                              | 0                      |
| Single grain, strongly undulose |            | 0             | 0    | 0                              | 0                      |
| Semi-composite grain, straight to slightly undulose | | 0             | 0    | 0                              | 0                      |
| Composite grain, straight to slightly undulose |            | 11.8          | 0    | 0                              | 0                      |
| Composite grain, strongly undulose |         | 29.4          | 0    | 90.9                           | 93.8                   |
| Inclusions          |                  |               |      |                                |                        |
| Abundant vacuoles   |                  | 11.8          | 0    | 45.5                           | 56.3                   |
| Rutile needles      |                  | 0             | 0    | 0                              | 0                      |
| Microlites          |                  | 17.6          | 0    | 18.2                           | 12.5                   |
| Few vacuoles, no microlites |    | 70.6          | 0    | 36.4                           | 31.3                   |
| Coarse sand         | No. samples      | 6             | 4    | 1                              | 3                      |
| Total grains        |                  | 1476          | 816  | 323                            | 629                    |
| Extinction          |                  |               |      |                                |                        |
| Single grain, straight |                | 59.8          | 67.2 | 47.7                           | 49.4                   |
| Single grain, slightly undulose |         | 2.5           | 1.1  | 0.3                            | 1.1                    |
| Single grain, strongly undulose |            | 1.3           | 0.4  | 0.3                            | 0.7                    |
| Semi-composite grain, straight to slightly undulose | | 1.0           | 0.1  | 0.9                            | 0.3                    |
| Composite grain, straight to slightly undulose |            | 15.4          | 14.7 | 16.1                           | 12.6                   |
| Composite grain, strongly undulose |         | 20.4          | 16.5 | 34.7                           | 35.9                   |
| Inclusions          |                  |               |      |                                |                        |
| Abundant vacuoles   |                  | 22.9          | 19.0 | 25.7                           | 21.0                   |
| Rutile needles      |                  | 0.8           | 0.7  | 0.3                            | 0                      |
| Microlites          |                  | 6.5           | 6.6  | 7.7                            | 14.3                   |
| Few vacuoles, no microlites |    | 69.9          | 73.7 | 66.3                           | 64.7                   |
| Medium sand         | No. Samples      | 6             | 5    | 1                              | 3                      |
| Total grains        |                  | 2,542         | 2,209| 353                            | 1,165                  |
| Extinction          |                  |               |      |                                |                        |
| Single grain, straight |                | 79.7          | 85.2 | 72.5                           | 80.5                   |
| Single grain, slightly undulose |         | 1.4           | 1.3  | 2.8                            | 0.9                    |
| Single grain, strongly undulose |            | 0.7           | 0.3  | 1.7                            | 0.3                    |
| Semi-composite grain, straight to slightly undulose | | 0.5           | 0.2  | 1.1                            | 0.3                    |
| Composite grain, straight to slightly undulose |            | 8.9           | 6.8  | 8.8                            | 4.3                    |
| Composite grain, strongly undulose |         | 8.5           | 6.1  | 13.0                           | 13.8                   |
| Inclusions          |                  |               |      |                                |                        |
| Abundant vacuoles   |                  | 11.6          | 12.3 | 11.6                           | 9.2                    |
| Rutile needles      |                  | 0.7           | 0.5  | 0.3                            | 0                      |
| Microlites          |                  | 7.5           | 6.2  | 11.3                           | 14.0                   |

(Continues)
sand fraction wherein the roundest grains occurred in the Pleistocene formation followed by the dune samples, the beach samples and the inner bank of Arroyo Solis Chico. In the fine sand fraction, the mean roundest quartz grains were found in the dune samples, followed by the beach samples with the other samples being nearly the same.

| Grain-size fraction | Category | Beach (swash) | Dune | Inner Arroyo Solis Chico shore | Pleistocene formations |
|---------------------|----------|---------------|------|-------------------------------|-----------------------|
| Few vacuoles, no microlites |          | 80.1          | 80.9 | 76.8                          | 76.8                  |
| Fine sand           | No. Samples | 6             | 5    | 1                             | 3                     |
| Total Grains        |          | 2463          | 2146 | 393                           | 1068                  |

| Extinction          |          |               |      |                               |                       |
|---------------------|----------|---------------|------|-------------------------------|-----------------------|
| Single grain, straight |        | 87.9          | 91.6 | 92.4                          | 90.1                  |
| Single grain, slightly undulose |       | 1.5           | 1.1  | 0.3                           | 2.1                   |
| Single grain, strongly undulose |       | 0.7           | 0.4  | 0.3                           | 0.7                   |
| Semi-composite grain, straight to slightly undulose | | 0.4           | 0.1  | 0.3                           | 0.2                   |
| Composite grain, straight to slightly undulose |       | 3.9           | 2.6  | 2.3                           | 1.6                   |
| Composite grain, strongly undulose |      | 5.4           | 4.1  | 4.6                           | 5.5                   |

| Inclusions           |          |               |      |                               |                       |
|----------------------|----------|---------------|------|-------------------------------|-----------------------|
| Abundant vacuoles    |          | 10.7          | 10.8 | 7.4                           | 8.0                   |
| Rutile needles       |          | 0.5           | 0.8  | 0.3                           | 0                     |
| Microlites           |          | 6.3           | 5.7  | 0.4                           | 8.0                   |
| Few vacuoles, no microlites |     | 82.4          | 82.8 | 84.6                          | 83.9                  |

**Table 5** (Continued)

**Table 6** Quartz grain shape statistical analysis

| Grain-size fraction | Category | Beach swash | Dune | Inner Arroyo Solis Chico shore | Pleistocene formations |
|---------------------|----------|-------------|------|-------------------------------|-----------------------|
| Granule             | No. samples | 1           | 0    | 1                             | 2                     |
|                     | Total grains | 17          | 0    | 22                            | 16                    |
|                     | $Q_m/Q$     | 0.59        | 0    | 0.9                           | 0.6                   |
|                     | $Q_c/Q$     | 0.41        | 0    | 0.91                          | 0.94                  |
|                     | Shape index | 3.47        | 0    | 4.32                          | 3.81                  |
| Coarse              | No. samples | 6           | 4    | 1                             | 3                     |
|                     | Total grains | 1476        | 816  | 323                           | 629                   |
|                     | $Q_m/Q$     | 0.65 ± 0.07 | 0.65 ± 0.14 | 0.49                          | 0.59 ± 0.21           |
|                     | $Q_c/Q$     | 0.36 ± 0.07 | 0.35 ± 0.14 | 0.51                          | 0.41 ± 0.22           |
|                     | Shape index | 3.98        | 4.05 | 4.32                          | 4.13                  |
| Medium              | No. samples | 6           | 5    | 1                             | 3                     |
|                     | Total grains | 2542        | 2209 | 353                           | 1165                  |
|                     | $Q_m/Q$     | 0.83 ± 0.02 | 0.87 ± 0.02 | 0.49                          | 0.82 ± 0.04           |
|                     | $Q_c/Q$     | 0.17 ± 0.03 | 0.13 ± 0.02 | 0.51                          | 0.18 ± 0.04           |
|                     | Shape index | 3.82        | 3.89 | 3.80                          | 3.97                  |
| Fine                | No. samples | 6           | 5    | 1                             | 3                     |
|                     | Total grains | 2463        | 2146 | 393                           | 1068                  |
|                     | $Q_m/Q$     | 0.82 ± 0.03 | 0.87 ± 0.03 | 0.71                          | 0.76 ± 0.08           |
|                     | $Q_c/Q$     | 0.18 ± 0.03 | 0.13 ± 0.03 | 0.29                          | 0.23 ± 0.07           |
|                     | Shape index | 3.68        | 3.76 | 3.61                          | 3.60                  |

*Grain shape index based on Powers (1953) images where 1 = very angular and 6 = well-rounded.
### 4.5 Comparative quartz grain statistical properties of the beach, dune sediments and Pleistocene sediments

The values that describe the statistical characteristics of the sediments are given for all samples in Table 7. The Folk and Ward (1957) parameters are compared to assess variations along the sample transects (Figure 9) and for mean comparisons of the transects and the various depositional environments (Table 8). All values are reported in phi units which are defined as $\phi = \log_2 \text{mm}$.

### 4.6 Mean grain diameter

The four beach–dune transects show quite different mean grain diameter (size) patterns (Figure 9). In the Parque del Plata transects, the mean grain diameter tends to decrease from the swash to the back beach and then vary within the dune. In the Parque del Plata west transect, the mean grain diameter increases in the dune, whereas in the Parque del Plata east samples, it fluctuates but is overall similar to the beach samples.

The mean beach and dune grain size at Parque del Plata west is $2.10 \phi$ for the beach samples and $2.05 \phi$ for the dune samples, which are very similar (Table 7). The mean grain size of the beach and dune sands at the Parque del Plata east is $1.84 \phi$ and $1.90 \phi$, respectively. The variation in mean grain size in the Las Vegas west transect is the most regular of all transects, with grain size increasing from the swash zone to the dune and then declining to the dune crest and back to the back-beach value at the landward dune base. The beach sand is slightly coarser compared to the dune sand with mean sizes of $2.27 \phi$ and $2.33 \phi$, respectively. The mean grain size is quite variable across the entire Las Vegas east transect. However, the mean values for the beach and dune sands of $2.11 \phi$ and $2.13 \phi$, respectively, are nearly equal.

#### TABLE 7 Statistical analysis of the grain-size coefficients

| Location | No. samples | Mean (phi) | Dispersion (phi) | Skewness (phi) | Kurtosis (phi) |
|----------|-------------|------------|------------------|----------------|----------------|
| Parque del Plata west | | | | | |
| Beach | 3 | $2.10 \pm 0.01$ | $0.31 \pm 0.01$ | $0.01 \pm 0.01$ | $0.95 \pm 0.03$ |
| Dune | 5 | $2.05 \pm 0.09$ | $0.33 \pm 0.02$ | $0.03 \pm 0.01$ | $1.01 \pm 0.04$ |
| Total | 8 | $2.07 \pm 0.07$ | $0.32 \pm 0.03$ | $0.02 \pm 0.03$ | $0.99 \pm 0.04$ |
| Parque del Plata east | | | | | |
| Beach | 4 | $1.84 \pm 0.12$ | $0.69 \pm 0.03$ | $0.30 \pm 0.02$ | $2.81 \pm 0.32$ |
| Dune | 8 | $1.90 \pm 0.11$ | $0.64 \pm 0.14$ | $0.27 \pm 0.13$ | $2.72 \pm 0.88$ |
| Total | 12 | $1.88 \pm 0.11$ | $0.66 \pm 0.12$ | $0.28 \pm 0.10$ | $2.75 \pm 0.73$ |
| Spit swash west–Beach swash | | | | | |
| | 4 | $2.14 \pm 0.11$ | $0.35 \pm 0.03$ | $0.01 \pm 0.03$ | $0.95 \pm 0.08$ |
| Inner Bank of Arroyo Solis Chico spit | 1 | 1.60 | 1.23 | 0.54 | 1.40 |
| Spit swash east–Beach(swash | 4 | $2.06 \pm 0.18$ | $0.40 \pm 0.08$ | $-0.01 \pm 0.08$ | $1.02 \pm 0.09$ |
| Las Vegas west | | | | | |
| Beach | 3 | $2.27 \pm 0.11$ | $0.77 \pm 0.07$ | $0.42 \pm 0.01$ | $3.04 \pm 0.33$ |
| Dune | 7 | $2.33 \pm 0.09$ | $0.71 \pm 0.03$ | $0.41 \pm 0.03$ | $3.99 \pm 0.29$ |
| Total | 10 | $2.31 \pm 0.10$ | $0.73 \pm 0.05$ | $0.42 \pm 0.02$ | $3.71 \pm 0.54$ |
| Las Vegas east | | | | | |
| Beach | 5 | $2.11 \pm 0.10$ | $0.76 \pm 0.03$ | $0.43 \pm 0.04$ | $2.79 \pm 0.41$ |
| Dune | 6 | $2.13 \pm 0.07$ | $0.74 \pm 0.02$ | $0.45 \pm 0.03$ | $2.85 \pm 0.30$ |
| Total | 11 | $2.13 \pm 0.09$ | $0.75 \pm 0.03$ | $0.44 \pm 0.07$ | $2.83 \pm 0.34$ |
| All beach swash | 12 | $2.10 \pm 0.17$ | $0.47 \pm 0.19$ | $0.09 \pm 0.18$ | $1.38 \pm 0.73$ |
| All middle and back beach | 11 | $2.06 \pm 0.16$ | $0.65 \pm 0.18$ | $0.38 \pm 0.24$ | $2.59 \pm 0.87$ |
| All beach | 23 | $2.08 \pm 0.16$ | $0.56 \pm 0.20$ | $0.20 \pm 0.21$ | $1.96 \pm 0.99$ |
| All dune | 26 | $2.11 \pm 0.20$ | $0.63 \pm 0.17$ | $0.30 \pm 0.18$ | $2.76 \pm 1.14$ |
| Pleistocene formations | 3 | $1.73 \pm 1.78$ | $1.02 \pm 0.75$ | $-0.05 \pm 0.40$ | $0.94 \pm 0.26$ |
The transect with the coarsest mean grain size is Parque del Plata east which lies immediately west of the entrance of Arroyo Solis Chico into the Rio de la Plata. The transect with the smallest mean grain size is the Las Vegas west transect which lies immediately east of the arroyo mouth. A comparison of the mean grain size of the swash zone to the middle and back-beach samples shows that the swash zone sands are slightly coarser. A comparison of the total mean for all beach samples to that of all dune samples shows that the dune samples are slightly finer.
4.7 Dispersion

Dispersion is a measure of the sorting of the sediments. The lowest values for dispersion (i.e. best sorting) occurred in the samples from the Parque del Plata west transect, where the values decrease from the swash zone to the back beach and then increased across the dune. The mean dispersion of the beach and dune samples is nearly equal at 0.31 and 0.33, respectively. The sediments of this transect are the best sorted of all transects and are classified as very well-sorted by Folk and Ward (1957).

Dispersion values generally declined from the swash zone across the beach to the dune in each of the other three transects. At the Parque del Plata east location, the dispersion value increases at the windward dune base and variably decreases to the crest and then increases at the leeward base (Figure 9). At both Las Vegas transects, the dispersion remains relatively constant across the dune. The mean dispersion of the beach sands is greater than that of the dune sands at the Parque del Plata, Las Vegas north and Las Vegas south transects. The mean dispersion for combined beach and dune sands for these transects is 0.66, 0.73 and 0.75, respectively (Table 7), which are categorized as moderately sorted (Folk & Ward, 1957).

Comparison of the beach swash zone to the aggregated middle and back-beach samples shows that the swash zone sediments are better sorted. Surprisingly, the beach sands are better sorted than the dune sands, but not within the range of statistical significance. The poorest sorted sediments are the gravel and sand fractions of the Pleistocene formation sediments with a mean of 1.02, which is classified as poorly sorted.

4.8 Skewness

Only minor differences in skewness occur across and between the transects (Figure 9; Table 7). Skewness varies between slightly negative and slightly positive (within −0.1 and 0.1 range) across the Parque del Plata west transect. The values are slightly negative in the swash zone and become slightly positive across the beach. Across the dune, the skewness is zero at the base, becoming slightly negative towards the crest, and then slightly positive at the leeward dune base. The difference in mean skewness values between the beach and dune sands at Parque del Plata, and the other transects, is not statistically significant.

Across the Parque del Plata east transect, the skewness remains quite close to 0.3 across the beach and becomes variable in the dune sands with a range of 0.25–0.40. The pattern of variation is similar in the Las Vegas west transect but the values are slightly higher, ranging from about 0.37 to 0.45. The general pattern of variation in the Las Vegas east transect is similar to that in the Las Vegas west transect.

Mean skewness decreases consistently from east to west in the down-drift direction. The inner bank of Arroyo Solis Chico has the highest measured value of 0.54 and the range of values in the Pleistocene sediment gravel and sand-sized fraction ranges from −0.5 to 0.40. Using the classification of Folk and Ward (1957), the skewness at the east begins as nearly symmetrical and becomes more positively skewed with distance away from the arroyo mouth to the west.

4.9 Kurtosis

There is a wide range in kurtosis values both within the transects and from one transect to another (Figure 9; Table 7). The lowest kurtosis values occur in the Parque del Plata west transect. The values start at about 0.98 in the swash zone, decrease landwards to about 0.8 and reach 1.04 at the windward dune slope, and vary within this range in the dune. The mean values for kurtosis in the beach and dune samples are close to 1.0.

Significantly higher kurtosis values occur in the Parque del Plata east transect in the swash zone beginning at near 2.5 and varying between about 2.5 and 3.2 across the beach. Within the dune, kurtosis values range between about 2.4 and near 4.0 at the crest. The mean kurtosis of the beach and dune sands is 2.81 and 2.72, respectively, which is not statistically significant.

The highest kurtosis values are found along the Las Vegas west transect. The values range consistently from about 2.6 in the swash to 3.9 at the windward dune base. The kurtosis increases to about 4.4 in the dune and decreases to 3.7 at the leeward dune base. The difference in the mean kurtosis of 3.04 for beach sands and 3.99 for dune sands is statistically significant.

Considerable variation in the kurtosis occurs across the Las Vegas east transect with beach sands having values ranging from about 2.2 to about 2.65 (mean average of 2.79) and dune sands having values between about 2.5 to 3.3 (mean average of 2.85).

Considering all samples, dune sands have a higher mean kurtosis of 2.76 compared to beach sands with a mean kurtosis of 1.96. However, the standard deviation is high. The inner beach at the spit has a kurtosis of 1.4 and the mean of the Pleistocene formation gravel and sand fractions is 0.94. Based on the classification of Folk and Ward (1957), the sediments are classified as mesokurtic (0.90–1.11) (Parque del Plata west transect), very leptokurtic (1.50–3.00; Parque del Plata east and Las Vegas west transects) and extremely leptokurtic (>3.00; Las Vegas west transect).

4.10 Comparative porosity and hydraulic conductivity of beach and dune sediments

A comparison of the variations in porosity and hydraulic conductivity in the transects from the beach swash to and over the dune is given in Figure 10 and statistical comparisons are given in Table 8. Porosity values occur within a narrow range
of 0.35–0.36 and any differences between transects and environments are not statistically significant with the exception of the sample collected in the inner bank of the spit across the mouth of Arroyo Solis Chico which has a value of 0.32 (Table 8).

The hydraulic conductivity variation in the beach and dune sands in the two Parque del Plata transects shows a generally similar pattern with a value near 24 m/day in the swash zone, an increase to the middle beach and then a decline to the dune edge (Table 8). Measured values of hydraulic conductivity are lower and show a different pattern of fluctuation in the two Las Vegas transects. The values increase from the swash to the windward toe of the dune in the Las Vegas west transect by about 27% and then decline within the dune by about 25% compared to the highest value. The hydraulic conductivity values range between about 18.5 and 23.3 m/day in the Las Vegas west transect while they range between 20 and 25 m/day in the Las Vegas east transect.

The mean hydraulic conductivity of the dune sands was greater than that of the beach sands in three of the four transects with the exception being the Las Vegas west transect where it was about equal. The transects lying west of Arroyo Solis Chico have a significantly higher mean hydraulic conductivity compared to the two to the east. The lowest mean value is found for the Las Vegas west transect where both the beach and dune samples show the lowest mean hydraulic conductivities. Within the beach environment, the swash samples had a higher mean hydraulic conductivity compared to the aggregated middle and back-beach samples. When all of the beach and dune samples are aggregated and compared, the dune sands have a slightly higher hydraulic conductivity compared to the beach sands. The inner spit sample collected at Arroyo Solis Chico had a low hydraulic conductivity similar to the values found in the Las Vegas east transect.

5 | DISCUSSION

5.1 | Dynamic beach–dune–river interactions influencing the coastal geometry and sediment composition

The geometry of the beach–foredune system at the mouth of Arroyo Solis Chico (river) is impacted dynamically by the interaction of the beach–dune sediment transport system, the direction and rate of littoral movement of the beach sand (westward prograding spit), the influence of river sediments (tidal trapping and storm-related contribution of sediment), the current active erosion of the up-gradient shoreline to the east and the contribution of sediments from the erosion of Oligocene and Pleistocene formations on the beach and at the back-beach wave-cut cliff. The foredune complex on the west side of the river is relatively stable but becomes less so going further east where the dune has been largely removed to form a modern scarp that contains Pleistocene sediments (Libertad and Chuy formations). Although variations in the relative position of the beach, foredune and the orientation of the Arroyo Solis Chico mouth have occurred, the relative coastal geometry has remained rather constant over time (Figure 6). The active erosion of the scarp (cliff) is contributing sediment to the beach with an average estimated volume of 33,000 m$^3$/year (Goso et al., 2007, 2014). The contribution of offshore sediment to the beach and dune systems is unlikely to be significant because the offshore sand is muddy and the shoreline is generally regressing.

Contribution of sediment to the shoreline from Arroyo Solis Chico may occur only during extreme flood events but is probably not a large-scale contributor compared to the estimated erosion of the scarp area because there is no seaward extending accretionary beach-ridges, deltaic structure or a seaward deflection of the shoreline. The immaturity of the beach sands suggests Arroyo Solis Chico may have contributed some sediment, because it drains a large area of metamorphic and igneous rocks in its upper basin and cuts through continental
FIGURE 10  Plots showing the variation in porosity, and hydraulic conductivity along the four transects from the beach swash to the interior dune base.
outwash sediments in its lower basin. However, Arroyo Solis Chico has a low gradient with a constrained competence and, therefore, may not be a significant contributor of sand.

The Pleistocene (Libertad and Chuy formations) continental outwash and marine sediments contain significant quantities of immature-composition sand and gravel. They are soft and easily erodible as demonstrated by the rapid estimated recession rate (67–156 cm/year) and have a similar gravel and sand composition as the current beach sand with the exception of a greater plagioclase concentration. Erosion of these sediments is adding compositionally less mature sand and gravel to the beach which, in turn, is being transported from the beach via wind into the modern foredune. The young foredune areas contain less mature sand compared to the older foredune areas which may be a result of the modern erosion of the Pleistocene sediments.

5.2 | Roundness of the beach and dune sediments in comparison to the Pleistocene sediments

The roundness of the beach sand is largely controlled by the source sediment added to the beach (Picard & McBride, 1993; Resentini, Andò, & Garzanti, 2018). Associated coastal dunes can have an increased degree of roundness compared to the source beach sand based on selective transport (Reineck & Singh, 1980). This is indeed the case for the beach and dune sands found at this location. However, it is common for stream- or river-transported sands to have a lower degree of rounding compared to beach and marine dune sands (Clemens & Komar, 1988).

The beach and dune sand-sized fractions of the sediments indeed show that the dunes have a slightly higher degree of rounding compared to the beach sand at this location. However, the Pleistocene fluvial outwash sediments (upper two samples from the Libertad Formation) show a higher degree of rounding in the granule, coarse sand and medium fractions compared to the beach and dune sands. There is a considerable number of unusually well-rounded grains in this sediment which is being directly added to the beach sand and indirectly added to the dune sand. Therefore, it is probable that the eroded sediments based on the measured roundness values reported have had considerable influence on the overall degree of rounding within the beach and dune sediments at this location. This is also another line of evidence that suggests that the erosion of Pleistocene sediments is influencing the composition and properties of the beach and dune sand.

5.3 | Evidence for addition of sand eroded from the Pleistocene formations to the beach

Pleistocene formations crop out on the beach both to the east and west of the Las Vegas east transect. These formations contain compositionally immature sediment with variable percentages of quartz, feldspar and rock fragments within the gravel and sand-sized fractions. The lower samples from the Libertad Formation are particularly enriched in plagioclase compared to the upper unit and the modern beach sand. There is a tendency for the beaches to have a greater percentage of feldspar in the vicinity of the outcrops and some enrichment in plagioclase in areas where the new sediment is accumulating. This is illustrated by observing the changes in the feldspar percentage and $F_{k}/F$ ratios in the beach sands moving in the direction of transport from east to west (Table 9). The loss of feldspar moving down-drift away from river sources is similar to that found along the Texas shoreline in the Gulf of Mexico by McBride, Abel-Wahab, and McGilvery (1996).

As sediment moves down-drift onto the beach of the Arroyo Solis Chico spit, the overall percentage of feldspar decreases, but the ratio of potassium feldspar to total feldspar ($F_{k}/F$) also decreases, which indicates the influx of plagioclase from erosion of the Pleistocene sediments. The inner shore of the spit has particularly high feldspar percentages and the lowest $F_{k}/F$ ratios found in the study. The percentage of feldspar decreases further moving west to the east Parque del Plata transect and reduces again at the Parque del Plata west transect. The change in the percentage of plagioclase is quite significant over a distance of only about 3 km between the source outcrops and the beach at the Plaque del Plata west transect. The change in the percentage of plagioclase is probably caused by the combined loss of the fine fraction to the offshore and dilution moving away from the source sediments. The plagioclase is most abundant in the fine fraction of the sediment and may be more subject to transport into offshore waters during storms (Clifton, 2006). The fine-grained fraction of plagioclase may be more susceptible to dissolution in sea water or alteration to clay minerals in the dune environment (Arnorsson & Stefansson, 1999; Mack, 1978; Stefánsson & Arnórsson, 2000).

5.4 | Comparison of the composition of the modern beach and dune sediments to the work of Potter with implications regarding provenance and tectonics

It has been suggested that there is a distinct relationship between the composition of beach and other sands, and the tectonics of their source terranes (Dickinson & Suczek, 1979; Dickinson et al., 1983; Potter, 1986; Valloni, 1985). The composition of the sand is related directly to the source area (Garzanti, 2017; Johnsson, 1993). This concept has been clearly demonstrated in studies of modern island-arc sands and active continental margins (Packer & Ingersoll, 1986; Pirrie, 1991). At the continental scale, the composition of beach sand should be related to the tectonic provenances such that the leading-edge beach sands should be rich in
volcanic rock fragments and the trailing-edge sands should have a greater percentage of quartz sand where not influenced by major river influx of sediment with an immature composition (Potter, 1986). This pattern has been demonstrated to be generally correct over large areas where there is primarily influx of quartz sand from river and stream transport of sediments to the shoreline (Potter, 1978, 1984). For example, the small streams providing sand to the Brazilian coast contain very high percentages of quartz (Potter, 1986). The assumption that beach sands occurring along the trailing-edge of a continent should be close to quartz arenites with minimal percentages of feldspars and rock fragments is not always correct, especially in geographically immediate areas where local rivers transport immature materials to the shoreline (Potter, 1978, 1984). For example, the small streams providing sand to the Brazilian coast contain very high percentages of quartz (Potter, 1986).

The assumption that beach sands occurring along the trailing-edge of a continent should be close to quartz arenites with minimal percentages of feldspars and rock fragments is not always correct, especially in geographically immediate areas where local rivers transport immature materials to the shoreline. In his study of South American beaches, Potter (1986) found that the beach sands of coastal Argentina are quite rock fragment-rich (mostly volcanics), similar in composition to leading-edge tectonic province beach sands found in Chile (primarily volcanic clasts). The beach sands in Brazil are primarily very quartz-rich arenites that typically reside on the trailing-edge or passive margin of continents. The beach sands of Parque del Plata and Las Vegas, Uruguay contain a greater content of feldspars and rock fragments compared to the Brazilian beach sands and fewer rock fragments compared to the Argentinian sands (Table 10). In addition, the rock fragments are primarily metamorphic and igneous rock fragments and not volcanic. These compositions are in contrast to the very quartz-rich sediments recently studied in the Uruguay River which is a big river that episodically provides sediment to the nearshore system of Uruguay at the headwaters’ area of the Rio de la Plata (Missimer et al., 2017).

An interesting observation is that the percentage of mean total quartz in Uruguay is similar to the Brazil beach sands, 82.5%–90%, respectively, but when the composite quartz grains are added to the rock fragments, the Uruguay sands have monocrystalline quartz contents in the range of 67.5%–86%. Feldspar and rock fragments are significantly more abundant in the Uruguay beach sands compared to the Brazil beach sands. It should be noted that to be comparable, the composite quartz compositions were used for the Uruguay beach sands.

### Table 9

| Location                        | Grain-size category | Feldspar % | $F_k/F$ |
|---------------------------------|---------------------|------------|---------|
| Pleistocene formations          | Granule             | 0          | 0       |
| (outcrops)                      | Coarse              | 6.7        | 0.76    |
|                                 | Medium              | 4.5        | 0.52    |
|                                 | Fine                | 13.4       | 0.24    |
| Las Vegas east transect         | Coarse              | 11.8       | 0.88    |
|                                 | Medium              | 5.0        | 0.92    |
|                                 | Fine                | 9.2        | 0.98    |
| Las Vegas west transect         | Coarse              | 10.0       | 0.91    |
|                                 | Medium              | 7.0        | 0.94    |
|                                 | Fine                | 16.0       | 0.93    |
| Arroyo Solis Chico Spit east    | Granule             | 6.3        | 1.0     |
|                                 | Coarse              | 9.4        | 0.77    |
|                                 | Medium              | 6.0        | 0.57    |
|                                 | Fine                | 9.2        | 0.43    |
| Arroyo Solis Chico Spit West    | Coarse              | 6.4        | 0.44    |
|                                 | Medium              | 1.8        | 0.33    |
|                                 | Fine                | 8.2        | 0.54    |
| Arroyo Solis Chico spit inner shore | Granule       | 5.6        | 0.25    |
|                                 | Coarse              | 6.8        | 0.68    |
|                                 | Medium              | 10.2       | 0.43    |
|                                 | Fine                | 13.4       | 0.30    |
| Parque del Plata east transect  | Coarse              | 6.2        | 0.87    |
|                                 | Medium              | 9.6        | 0.83    |
|                                 | Fine                | 11.2       | 0.95    |
| Parque del Plata west transect  | Coarse              | 0.7        | 1.0     |
|                                 | Medium              | 4.2        | 0.80    |
|                                 | Fine                | 9.6        | 0.98    |
This suggests sands currently being added to the beach sediments in Uruguay have had insufficient time to become quartz arenites based on mechanical erosion. This supports the contention that the erosion of Pleistocene-age sediments along the shoreline and small-stream transport of these sediments to the beach are adding feldspar and rock fragment-rich sediments. If any sand is being added to the Rio de la Plata system from the Paraná and Uruguay rivers, it would be very quartz-rich which is not what is found at the location studied that is situated a great distance from the headwaters of the Rio de la Plata.

While Potter (1986) did not report any compositional data on the adjacent dune sands in South America, the Uruguay dune sands show an increased percentage of quartz with decreases in both the feldspar and rock fragment percentages compared to the beach sands. This is to be expected for two reasons, the first of which being that the rock fragments in the beach sand tend to be in the coarser fractions that are transported by wind at lower rates and the second, that freshwater percolation through the sands tends to chemically erode some of the feldspars. The plagioclase tends to be more quickly removed by dissolution and there is a tendency to increase the ratio of k-feldspar to plagioclase which is more probable to be transported offshore (Arnórsson & Stefánsson, 1999; Feth, Roberson, & Poizer, 1964; Garrels & MacKenzie, 1967, 1971; Stefánsson & Arnórsson, 2000). In addition, the climate of Uruguay is humid-temperate which is favourable to the chemical erosion of all feldspars in soils (and dunes) (Cleary & Connolly, 1971; Suttener et al., 1981).

5.5 | Impacts of sediment addition and pass dynamics on grain size and hydraulic conductivity of the beach and dune sands

The pattern of variation of the mean grain size and the hydraulic conductivity are consistent with the input of sediment from erosion of the Pleistocene formations and the possible sediment input from Arroyo Solis Chico. The mean grain size, and the corresponding mean hydraulic conductivity, generally decreases from east to west from the Las Vegas east transect to the Las Vegas west transect from the outcrop area to the shore adjacent to Arroyo Solis Chico (Tables 6 and 7). The finest sands and corresponding lowest hydraulic conductivity values occur along the Las Vegas west transect which lies immediately east of Arroyo Solis Chico. This is the area which receives the longshore drift of the new sediment from erosion of the scarp and Pleistocene formations and any fine-grained sediment that may be carried to the Rio de la Plata by streamflow. The hydraulic conductivity along the Parque del Plata east transect shows a winnowing of the finer sand with a resulting higher hydraulic conductivity, but there is variation in the mean grain diameter with a slight decrease between the Parque del Plata east and west sites (1.84±2.1 0). The trend continues to increase at the Parque del Plata west transect. The overall changes in hydraulic conductivity go from an average in the beach samples from 21.92 to 19.92 to 24.23 to 25.00 m/day over the four down-drift transects. This pattern shows subtle differences that can be expected to occur in similar geological settings at other locations and in the geological record.

5.6 | Low degree of measured porosity variation in the beach and dune sediments

A very low degree of porosity variation was observed in the beach and dune sediments included in this study. Pryor (1973) found the same result from a large number of closely spaced samples collected from beach sands on the Gulf Coast of the United States.

| Table 10 | Comparison of composition of beach and dunes sands at Parque del Plata and Las Vegas, Uruguay to those measured in Argentina and Brazil by Potter (1986) |
|-----------------|-------------------------------------------------|------------------|------------------|------------------|
|                 | Uruguay beaches (6)                              | Uruguay Dunes (5) | Argentina beaches (22) | Brazil beaches (88) |
| **A. Average proportions and SDs** | | | | |
| Q                | 82.5 ± 3.6                                       | 86.2 ± 2.4         | 28 ± 10.5         | 90 ± 11.8         |
| F                | 8.0 ± 2.1                                        | 5.5 ± 1.5          | 14 ± 9.9          | 5 ± 7.6           |
| Rf               | 9.6 ± 3.1                                        | 8.5 ± 1.6          | 58 ± 16.8         | 5 ± 7.5           |
| **B. Selected ratios** | | | | |
| Qm/Q             | 0.82 ± 0.03                                      | 0.87 ± 0.03        | 0.75              | 0.95              |
| Qc/Q             | 0.18 ± 0.03                                      | 0.13 ± 0.03        | 0.25              | 0.05              |
| Fk/F             | 0.78 ± 0.22                                      | 0.83 ± 0.14        | 0.33              | 0.71              |
| **Average proportions and standard deviations of recombined variables** | | | | |
| Qm               | 67.5 ± 5.1                                       | 75.0 ± 3.7         | 21 ± 11           | 86 ± 16.3         |
| F                | 8.0 ± 2.1                                        | 5.5 ± 1.5          | 13 ± 9.8          | 4 ± 6.2           |
| Rf + Qc          | 24.5 ± 5.0                                       | 19.3 ± 3.7         | 65 ± 18.1         | 10 ± 12.7         |
6 | CONCLUSIONS

Potter (1986) suggested that the grain composition of recent and ancient beach sands can be used as an indicator of tectonic provenance with the active margin containing predominantly volcanic rock fragments and the passive margin containing quartz arenites and/or generally compositional mature (quartz-rich) sands. His investigation of South American beaches showed that the relationship was about 75% accurate with the sands from the shorelines of Argentina and Uruguay being an exception in that they have relatively high percentages of rock fragments and feldspars despite a passive margin setting.

It is concluded that for the investigated area along the coast of Uruguay, a lower ratio of quartz to feldspars and rock fragments compared to passive margin sediments in Brazil (67.5/8/24.5 vs. 86/4/10 in Brazil for the composite composition) can be attributed to the combined influx of sediments in Uruguay containing larger percentages of feldspars and rock fragments derived primarily from small rivers and streams and from erosion of Precambrian outwash deposits derived from erosion of the interior Precambrian craton. Sediments from the major rivers feeding the Rio de la Plata, the Paraná and Uruguay rivers, are predominantly quartz arenites and do not influence the current beach and dune sand composition in the study area. Therefore, use of beach sediments to assess the tectonic provenance at the continental scale must be used with caution based on the volume and composition of the sediments feeding the beach and the length and duration of beach and coastal dune transport.

At the smaller scale, textural changes produced by the inflowing sediments and their changes during transport influence the hydraulic properties of the beach and dune sands. Sediment balance changes have a minimal impact on porosity. Changes in hydraulic conductivity (permeability) are significant in areas where the inflowing sediments impact the grain-size distribution which in turn influences the hydraulic conductivity.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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