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Identification of sand dune sources in the east Sistan, Iran by using mineralogical and morphoscopic characterization of sediments

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Abstract
Sedimentation in the dune fields of the Sistan Plain of Iran is the result of deposition of fine-grained sediment downstream of the Helmand River. Due to poor adhesion and low moisture content of soil particles, and the strong renowned Levar wind, dune fields mostly of Barchan and Nebkha types are created. This study aims to assess the physical, morphological and mineralogical characteristics of surface (S) and sub-surface (S-S) sediments and their genetic relationships with the aeolian sand surface. For this purpose, 48 S and S-S sand samples were prepared from Niatak Corridor (NC) east of Sistan and were analyzed to determine their physical and mineralogical properties by dry sieving, scanning electron microscopy (SEM) and optical microscopy methods. Results show that the physical characteristics of S and S-S sand particles, such as sorting, roundness, minimum elongation projection, Riley sphericity, morphoscopic and mineralogical characteristics, have no significant difference. The study of thin sections showed that all samples generally contain quartz, feldspar, calcite, gypsum and lithic components. This confirms that the source of S sand dunes is local and consists of the buried layers of sands in the close vicinity. Therefore, the Hamoun Lake are most likely not a source of regional sands. The local existence of Yardang also supports the conclusion of this research.
Keywords: *Wind Erosion, Sand Source, Mineralogy, Morphology, Sistan Plain*

1. Introduction
About 38 percent of Earth's land surface is influenced by desertification (Nunez 2010). Wind erosion is considered as one of the main indicators of desertification (Liu et al. 2007). Some factors, such as overgrazing, contribute to increased wind erosion, and some others, such as increased vegetation, reduce wind erosion process (Xu et al. 2010). Sand and dust storms have led to huge economic and environmental losses and affected the daily lives of around 5 million Iranians (Cao et al. 2015). Dry and hyper-dry conditions affect a large part of Iran with rainfall less than 150 millimetres per year, which has caused about 80 million hectares of Iran to be covered by desert areas, sand dunes and areas with sparse vegetation. From this region, about 13 million hectares are occupied by sand dunes and about 5 million hectares by active sand dunes, which strongly threaten infrastructure (Ekhtesasi 1996). According to the Food and Agriculture Organization of the United Nations (FAO), the rate of desertification in the world is an average 36 m2/s while in Sistan and Baluchistan provinces the rate is 50 m2/s (Negaresh and Latifi 2009). The Sistan region in Iran is the main source of sand and dust storms, especially in the summer season (Cao et al. 2015). Due to extremely strong winds, large amounts of dust and sand particles rise into the atmosphere above Sistan in Iran, Afghanistan and Pakistan (Rashki et al. 2012; Ekhtesasi and Ghorbani 2013; Cao et al. 2014; Alizadeh Choobari et al. 2014). East Sistan is particularly prone to sand and dust movements (Cao et al. 2015). Dust storms have an important effect on human health and causes respiratory disease (Goudie 2009; Higashi et al., 2014; Powell et al. 2015). As a result of the production and movement of sand on public facilities and residential properties, huge annual financial losses have been recorded (Cao et al. 2015). A method to identify the origin of sand and sand storms on a large scale can utilize satellite data and remote sensing. An effective methodology to determine the amount of sand dune movement is the study of wind regimes and identification of the erosive winds in sand dunes using meteorological data, especially that from anemometers (Mesbahzadeh and Ahmadi 2012). Indications left by the wind and moving sand dunes are sand dunes and Yardang landforms.

In the west of Sistan (Tasouki), the IRIFER experimental method (Ekhtesasi and Ahmadi 1996) used to identify the origin of aeolian sands determined that the distance between the source areas and the sands was 5 to 20 kilometers (Shahryary 2014). Therefore, the source of sediment is close to the sedimentation area. The east of the Sistan region, where the area of Niatak is located, is where one of the most critical centres of sand movement in Iran that has been identified, which might affect the settlements and public facilities.

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Based on previous studies, sources of aeolian sand in east Sistan are from 20 to 50 kilometers north of the region. The most important source of sand dunes in the Sistan plain are Lake sediments, abandoned agricultural land, bare land and local river beds (Negaresh and Latifi 2009; Abbasi et al. 2010). Negaresh and Latifi (2009) suggest a dual action of wind and water, due to the presence of roundish, low-angular and high-angular particles in Sistan wind deposits. Identification of the origin of wind-blown sediments can be important and plays a valuable role in monitoring and controlling wind erosion (Xiaozong et al. 2014).

The correct identification of source areas allows for controlling measures to be implemented there. Many attempts to control areas of perceived critical wind erosion have not been able to fix the problem due to lack of success in correct identification of the source areas. Experience has shown that the best way to combat wind erosion is to correctly identify the source of sands and the mitigation activities should be concentrated in these areas. The history of sediments in the Sistan basin is imprecisely known because of the paucity of studies on the stratigraphy of this remote area, and therefore subsurface geological data are not available (Whitney 2006). Most studies have focused on surface exposures and mention Hamoun Lake and river beds as the main source of eolian sand dunes (Negaresh and Latifi 2009; Abbasi et al. 2010). This study aims to assess morphological and mineralogical characteristics of the subsurface sediments and their generic relationship with the aeolian sand.

2. Study area

The Sistan region (30˚45'N–31˚20'N and 61˚20'E–61˚50'E) is located in SE Iran close to the Iranian borders with Pakistan and Afghanistan (Fig 1). The climate of Sistan is arid, with a low annual average precipitation of 55 mm and evaporation exceeding 4000 mm year (Rashki et al. 2013a). The Sistan plain has formed as a result of deposition of fine-grained sediment downstream of the Helmand River which is the longest river in Afghanistan (Fig 1 right). This region is mainly composed of Quaternary lacustrine silt and clay material as well as Holocene fluvial sand, silt and clay (Rashki et al. 2013a). Basin deposition took place concomitant with Oligo¬cene subsidence; Neogene and Quaternary sediment thickness is about approximately 1,000 meters (Schreiber et al. 1971; Whitney 2006). The Sistan beds consist of fluvial and aeolian sand units and lacustrine sandy and clayey silts, and beds of coarse to fine gravels. The gravel beds vary in thickness from around 1 to 15 meters, and they overlie the erosional surface (Whitney 2006).

The Levar wind (or 120-Days Wind) is the main cause of wind erosion and dust/sand storms (Rashki et al. 2012; Alizadeh choobari et al. 2014; Kaskaoutis et al. 2015; Dahmardeh et al. 2016). These strong winds blow continuously from the NW direction, eroding the Sistan lands and entraining finer sediment in the atmosphere. The Sistan basin is one of the most active sources of sand and dust and provides the materials for the formation of dunes and dust storms that spreads to west Afghanistan, west Pakistan and in rare cases, to the Arabian Sea (Middleton 1986; Rashki et al. 2012; 2013b; 2015; Kaskaoutis et al. 2015). There are three critical wind erosion corridors in the Sistan area: the Shile and Tasouki Corridors in west Sistan, the Jazinak Corridor in mid-Sistan, and the Niatak Corridor (NC) in East Sistan (red lines in Fig 1 left).

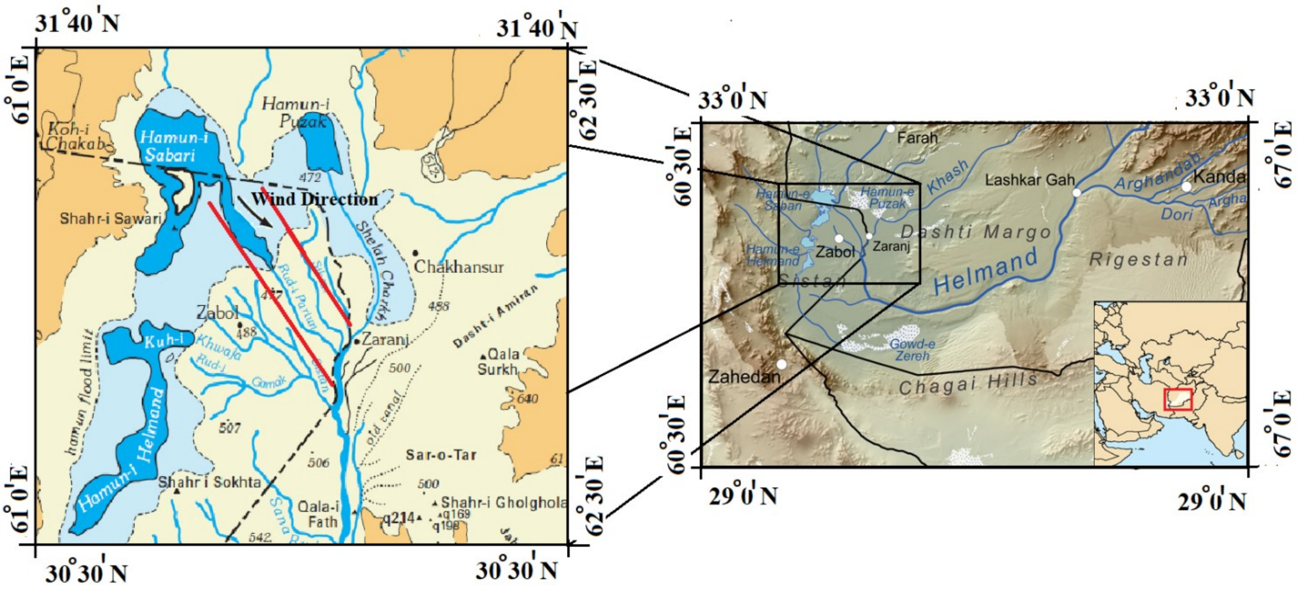

Fig 1. Geographical map of the Sistan region, showing the location of the study area (Niatak Corridor indicated between two red lines) (Source: Whitney 2006)

3. Material and methods

3.1. Sampling Methods

The NC is one of the main hotspots for sand movement in eastern Sistan (Fig 1 left). The Hamoun Lake is located to the north and NW of Niatak. The Helmand (or Hirmand) River is the main river feeding the Lake and, in contrast the wind direction, reaches the Hamoun Lake from the SE (Fig 1 right). Sandy sedimentary deposits in the NC in eastern Sistan consist of two parts: surface sands that are usually found on the surface of the sand dunes and barchans, and subsurface sands which are found at different depths underneath the surface, typically under an indurated layer of clay-silt of 1-2 meters thickness (Fig 2). To identify the source of sand for surface sediment in the study area, sampling was undertaken in two distinct sets. The first sampling set, which consisted of 24 samples, was taken from the surface of sand dunes (S samples). The second set of samples, which also consisted of 24 sand samples, was excavated from profiles or previously drilled profiles from sands in S-S (S-S or buried samples). Field observations, especially morphology of the ground surface, were taken to complement the laboratory results of the samples. Exposed soil profiles provided scope for sampling and allowed for determination of type and thickness of the sediments (Fig 2).

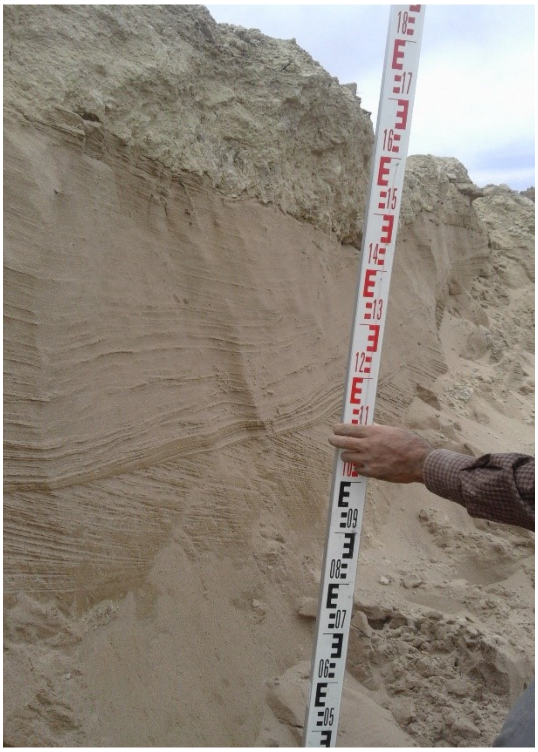

Fig 2. Excavated profile in a natural land at Zahedan Kohneh in the NC. In this profile, the Silt-clay layer that separates the surface from the subsurface is visible towards the top, with S-S sands visible beneath.

Depth of the S-S sand layers could be seen to differ in neighboring profiles. All the samples were prepared and transported to the laboratories to measure their particle size and determine their morphological and mineralogical characteristics. We then compared these characteristics to highlight similarities or differences and therefore assess potential genetic links between surface and subsurface samples.

3.2. Grain-size analysis

Soil gradation was determined by dry-sieve analysis at the Geology laboratory, Islamic Azad University, Zahedan branch. In order to study the grain composition of sand particles, 48 samples (24 S and 24 S-S) were prepared for comparison between S and S-S samples. Also, based on this study data, the statistical parameters including mean, median, and particle uniformity size were calculated using Inclusive Graphic standard deviation, skewness, or asymmetry of the curve by an Inclusive Graphic skewness method. In addition, four surface sand samples from an area up-wind of Niatak were collected to better understand potential origins of the samples (Fig 3).

3.3. SEM analysis and morphoscopic characterization of sediments

The shape of the sand particles was determined by scanning electron microscope (SEM, VEGA/TESCAN). The 48 samples of S and S-S sands from the NC were analyzed in a laboratory at Tehran Razi Metallurgical Research Center to assess the particles surfaces. The scale used by the SEM method to study particles was 200 μm. From the images prepared by SEM, 100 grains of S sand and 100 grains of S-S sand selected randomly from the samples and were studied in terms of geometric shape of grains including: sphericity (maximum sphericity projection, Riley sphericity and minimum elongation projection), roundness and grain surface texture.

3.4. Mineralogical analysis

Analyses of the mineralogical characteristics of sand particles are regarded as essential for clarifying the likely sources of sand dunes (Zarasvandi 2011). For this purpose, 48 thin section from S (24 samples) and S-S (24 samples) were prepared and analyzed in the laboratory of Azad University, Zahedan branch, to identify their minerals. To determine the mineralogical composition of sediments, the loose impregnation technique was applied to all the samples for preparation of thin sections for microscopic studies. Slabs of approximately 20 x 40 mm size and 5 mm thick were prepared using epoxy resin and hardener. Thin sections were prepared via vacuum impregnation with an epoxy resin/hardener for each sample and cut with oil to avoid damaging water-soluble minerals in the mortars. They were polished to the standard thickness of 30 μm, covered with a glass slip and examined with a polarized microscope. A Leitz Labrlux IZ Pols Polarizer Microscope was used for microphotographs of samples.

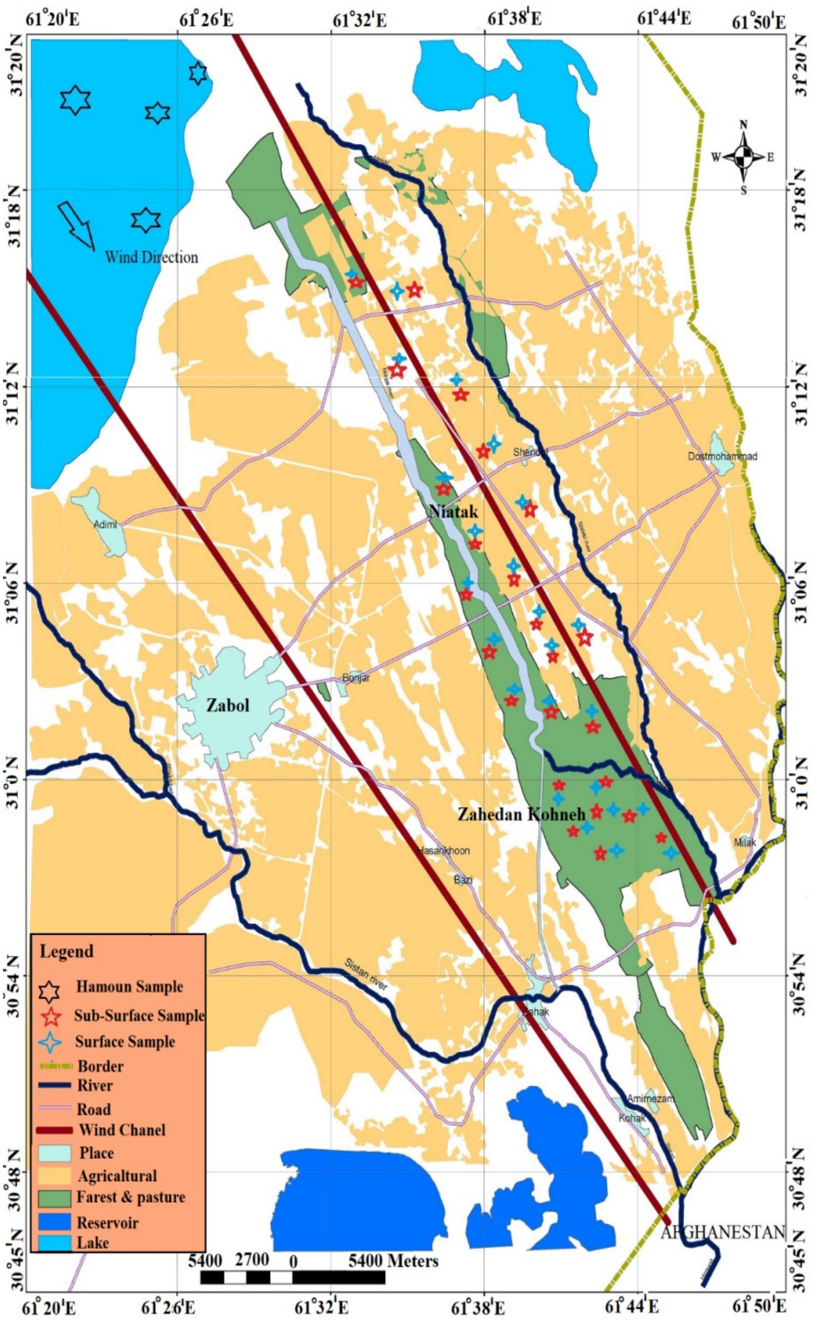

Fig 3. Location of NC and sampling locations.

4. Results

4.1. Grain size distributions

By analyzing the grain size distribution of samples from a sedimentary environment, the processes of its formation can be partly derived. In fluvial and lacustrine sedimentary environments, the most important factor of transport is water, while in dry and desert environments, the role of the wind is more pronounced.

The Sistan region is located at the end of the Helmand River basin where, due to its low topographic slope, the flow rate of water has decreased and most medium to fine grained sediment has been deposited. Changes in the rainfall regime in the upstream reaches of the Helmand River_lead to drought and wet periods and influence the sediments that accumulate downstream. In wet conditions, sandy sediments from the Helmand River bed enter and are deposited in the Hamoun Lake. In drought conditions, the Silt-clay sediments, although smaller, are more widely spread.

By virtue of the different sizes of the particles in the sediment, the different origins of the grains could to some extent be determined (e.g. Folk and Ward 1957).

Table 1 show the average results of 48 samples taken from the S and S-S sands in NC.

Using the data obtained from the sedimentary particles in sands taken from NC, the sand size variation curves of each of the S and S-S samples diagrams were drawn (Fig 4 and 5). Through comparison of these grain size distributions (Fig 4 and 5), we observe some natural variability but no obvious difference or anomaly between S and S-S samples. Peaks of normal distribution in the surface sands have ranges from 0.19 to 0.28 mm, indicating the coarseness of the particles. These values have ranges from 0.18 to 0.27 mm for S-S sands. Mean standard deviation in S and S-S sands is 0.025 and 0.028, respectively. Investigation and comparison of the mean grading curves of S and S-S sand particles in all samples of the NC shows a significant similarity in sediments (Fig 6). This similarity suggests that S-S sand deposits have a common origin with surface sands sediments.

The particles sizes are often in the range of medium sands (75%). So, with regard to the paucity of silt and clay particles passed through sieve No. 200 (74 µm), the studied samples were named "sand" based on the Folk's (1980) classification of coarse-grained sediments.

By comparison, the percentage of Silt-clay sediment in the dry bed of the Hamoun Lake dried bed is 98.9% and the sand-size sediments represent 1.1% of the total sample (Fig 7).

In order to obtain more precise data on the sorting and the frequency of fine or coarse-grained particle sizes, some statistical parameters were derived. In the present research, based on the existing data, the sedimentary statistical parameters including mean, median, sorting rate and the skewness and asymmetry of the curves for each of the S and S-S sands in NC were calculated (Table 2). The results show that there is a considerable similarity in the statistical parameters of samples in NC.

From Table 2, and based on Folk's (1980) classification, it is clear that there is a "very good" sorting among all the samples, indicating that the sediment underwent a similar history and formational conditions. Also, this finding corresponds to the similar equant shape of sedimentary sands particles shown for all the samples in Table 2. The skewness rate or the asymmetry of the curve in most of the sampled sediments turned out to be a negative and show severe asymmetry, indicating that there are populations of coarse-grained particles (0.60-60 mm). Generally, the very fine particles (less than 0.06 mm), as well as the medium sized grains,(0.06-0.6mm in diameter) are displaced and carried from their source to create the Dunes. Some of the more coarse sands are transported within the sandhills site, but most of the fine-grained deposits (silts) are removed completely. The sediments get more negative skewedness while being transported, whereas the original sediments (the remaining deposits) get more positive skewedness (Tucker 2001). Significant negative skewness in both types of S and S-S sand deposits show that the transportation factors (water and wind) have separated the fine particles from the coarse particles. The percentage of fine-grained clay particles in the S sand is lower than the S-S sand (Table 1), which is likely due to the re-loading of S-S sand and the separation of fine particles by wind.

4.2. Grain shapes

The grain shape characteristics of the samples were also determined, including sphericity, roundness and the grain's surface texture (Table 2).

Photomicrographs were taken in a laboratory with a scale 200 micrometres to determine the geometrical characteristics of the particles in the samples. Since it is not possible to study the particles two dimensions, we applied the Riley sphericity and minimum elongation projection to determine the sphericity of particles.

Table 1. Results of grain size analysis of 24 samples from the surface (S) and 24 samples from the sub-surface (S-S) in the Niatak Corridor (NC)

(phi)Ø		**Names of parts**		**Passing percentage**		**Weight passing (g)**		**Residual weight (g)**		**Sieve (mesh)**	**Sieve (mm)**
S-S	S	S-S	S	S-S	S	S-S	S	S-S	S		
-	-	-	-	99.7	-	498.5	-	1.5	-	40	**0.400**
1	1	Relatively coarse sand	Relatively coarse sand	96.84	99.92	484.2	499.6	14.3	0.4	50	**0.297**
2	2	Medium sand	Medium sand	35.44	22.32	177.2	111.6	307	388	70	**0.210**
3	3	Fine sand	Fine sand	10.74	9.26	53.7	46.3	123.5	65.3	100	**0.149**
6	6	Silt and clay	Silt and clay	2.62	0.96	13.1	4.8	40.6	41.5	200	**0.074**
						Pan=13.1	Pan=4.8	Sum=486.9	Sum=495.2		

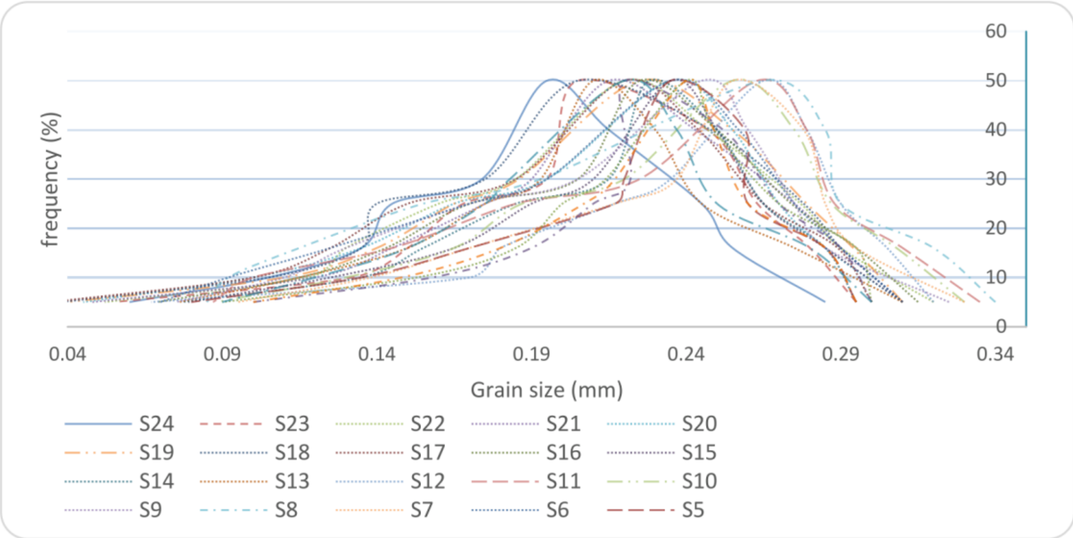

Fig 4. Normalized grain size distribution of 24 surface sand samples in the NC.

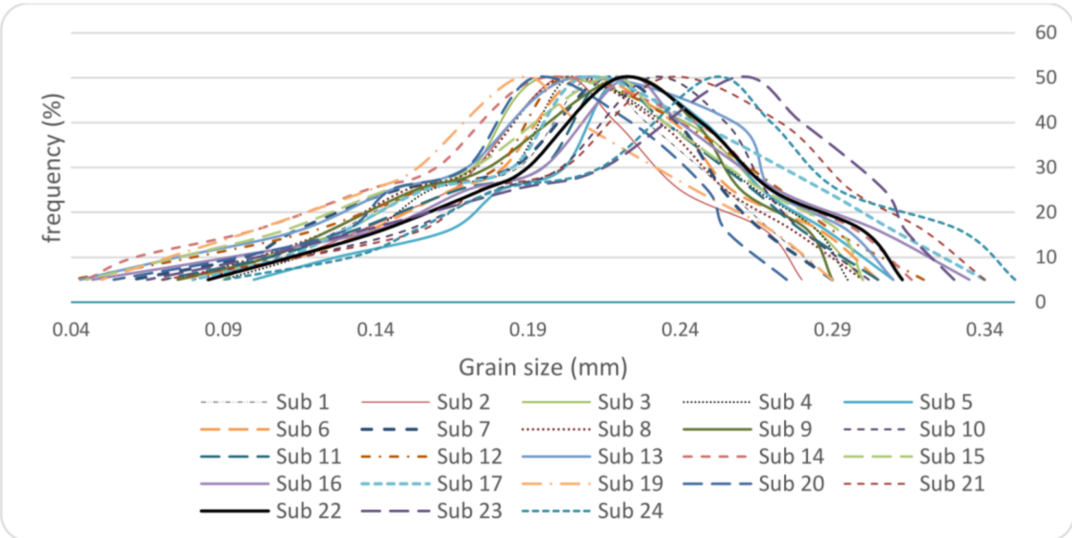

Fig 5. Normalized grain size distribution of 24 Sub-Surface sand samples in the NC.

Table 2. Mean geometry parameters of 24 samples and mean statistical of 240 grains from 24 samples of S sands and 240 grains of 24 samples of S-S sands selected in a completely random in the NC

Local		**Samples**	**From**	**Riley Sphericity**	**Minimum Elongation Projection**		**Roundness**	**S Texture of the Grain**	**Textural Maturity**
NC	geometry	S	Equants	0.777	0.731		0.237	Limited dissolution, fracturing and haze	Mature
		S-S	Equants	0.754	0.728		0.246	Limited dissolution, fracturing	Mature
	STDEV	S	-	0.007	0.054		0.016	-	-
		S-S	-	0.019	0.051		0.014	-	-
	statistical		Mean	Median	Inclusive Graphic Standard Deviation		Inclusive Graphic Skewness		
					Numerical Value	Sorting	Numerical Value	Kind of Skewness	
		S	0.23	0.225	-0.383	Very good	-0.245	Coarse Skewed	
		S-S	0.23	0.25	-0.381	Very good	-0.24	Coarse Skewed	
	STDEV	S	0.004	0.010	0.039	-	0.149	-	
		S-S	0.004	0.007	0.036	-	0.186	-	

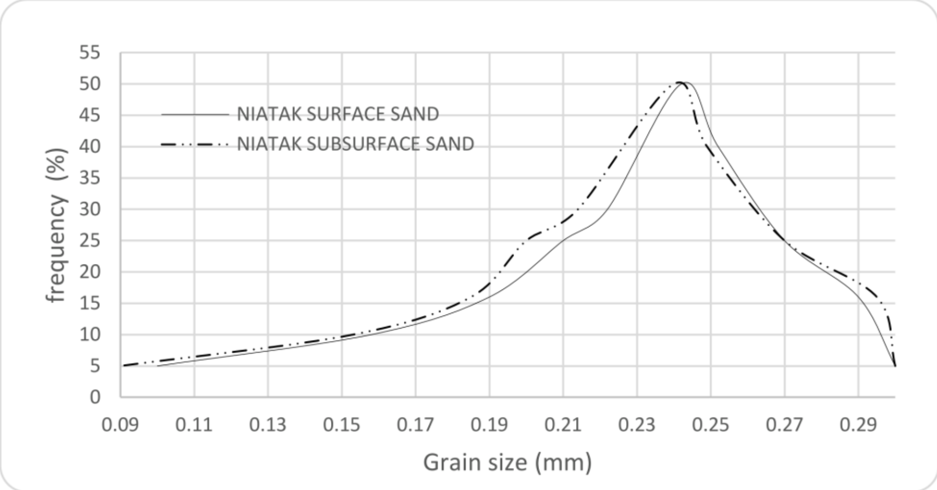

Fig 6. Mean gradation curves of S and S-S sand particle in the NC.

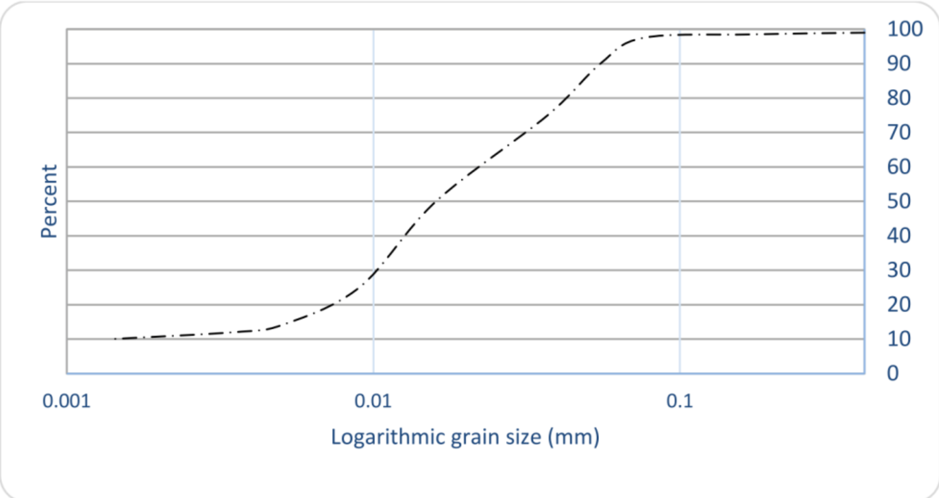

Fig 7. Mean Logarithmic gradation curves of four samples from the Hamoun Lake bed upwinds of the NC.

In order to calculate the sphericity Index, 200 sand grains which selected in a completely random, were selected on the photographs, and two circles encompassing the particles were chosen, one circle with the longest diameter and one circle with the shortest diameter in accordance with the calculated scale. Also, in order to calculate the width and the length of each of the 200 selected particles, rectangles were drawn around the particles and then by measuring the ratio of width to length of grains and determine of their mean diameter, the average diameter of the particles was calculated. The results showed the samples had the same diameter.

The average radius of the circles that intersected the particles corners and the radius of the largest circle that confined the particle for the 200 selected particles were measured to determine the particle's roundness. Our results show that the sand particles of all the samples are semi-angular and angular with a high sphericity.

In addition, the surface of some of the sand particles were examined with a high magnification (2 micrometer scale) in order to determine the topology of the surface. The results showed that there were traces of fracture, solubility and opacity in all of the samples whereas the opacity was greater in the sands taken from the Dunes (Fig 8 and 9).

4.3. Mineralogical composition

Microscopic analysis of the thin sections taken from the samples and identification of the mineral components of each of the S and S-S sands in NC showed that there was no any considerable difference between samples from different locations, indicating that the S and buried sands in all places of Niatak had a common origin (Fig 10). Fig 11 and 12 shows samples of the profiles of all places in NC S and S-S sands. Also, Table 3 shows mean minerals of 24 samples S and S-S sands and standard deviations in the NC.

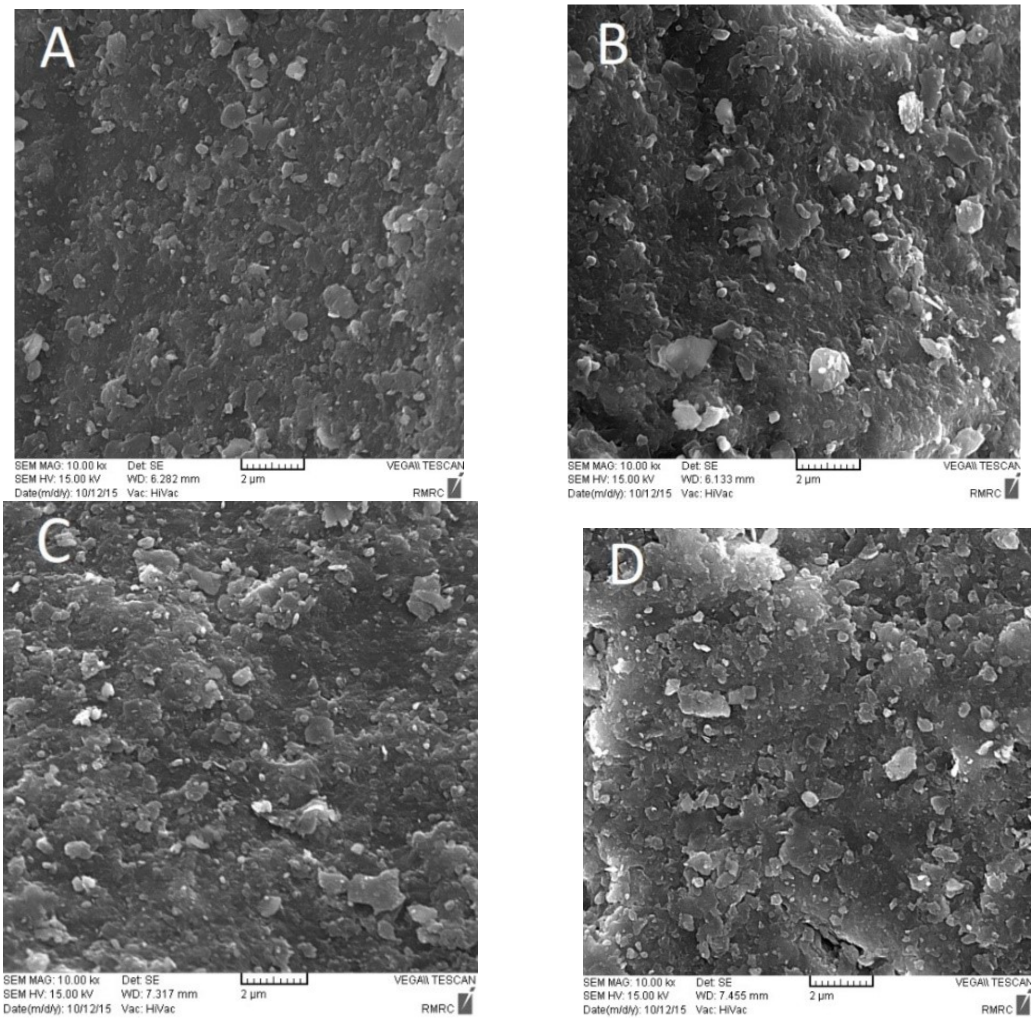

Fig 8. Scanning electron microscope of four randomized grains from S sand in the NC. Images show adsorption of particles in clay size on the surface of sand grains made of different minerals.

5. Discussion

Work on the origin and identification of aeolian sands in the Sistan has been undertaken by researchers in the recent years. Based on the results presented by Negaresh and Latifi (2009) and Abbasi et al. (2010) the origins of the sediment in the Sistan sand dunes are thought to be the Hamoun bed sediment and nearby rivers (92%), implying a transport distance of 20-50 km from the deposit. This present study has focused on the origin of the NC sands in the eastern of Sistan. The aim of this study on the NC is to determine the origin of the sand deposits, carried by the wind and formed as sand hills and barchan dunes. Primarily, we seek to understand the relationship between S and S-S sand. To achieve this goal, analysis of grain size, morphoscopy and mineralogy of S and S-S sand were carried out in the NC.

According to the physical analysis of S and S-S sand grains, the average amount of fine particles (silt and clay) by sieve 200 in the S sand was lower than the S-S sand (Table 1). The reason for this decrease is the wind's action leading to the displacement of sand grains and separation of clay silt particles in the form of dust. Increasing the percentage of low-adhesive silt particles makes it possible to double (Fig 7). But the S-S sand has been protected from the wind.

Similarity in size of S and S-S sand particles (Fig 4, 5 and 6) shows that there is a genetic relationship between these sediments. In other words, S-S sand deposits either have the same source as the S deposits, or are the main supplier of the S deposits. This is also shown by studying the statistical and geometric parameters of S and S-S sand sediments. The results show that the statistical and geometric parameters between these sediments are very similar (Table 2). Differences in the sediment properties of the Hamoun Lake (Figure 7) with the NC sediments indicated that the Hamoun Lake bed is not the origin of the NC sediments, if there is a possibility to be transported the Hamoun sediments with northern winds.

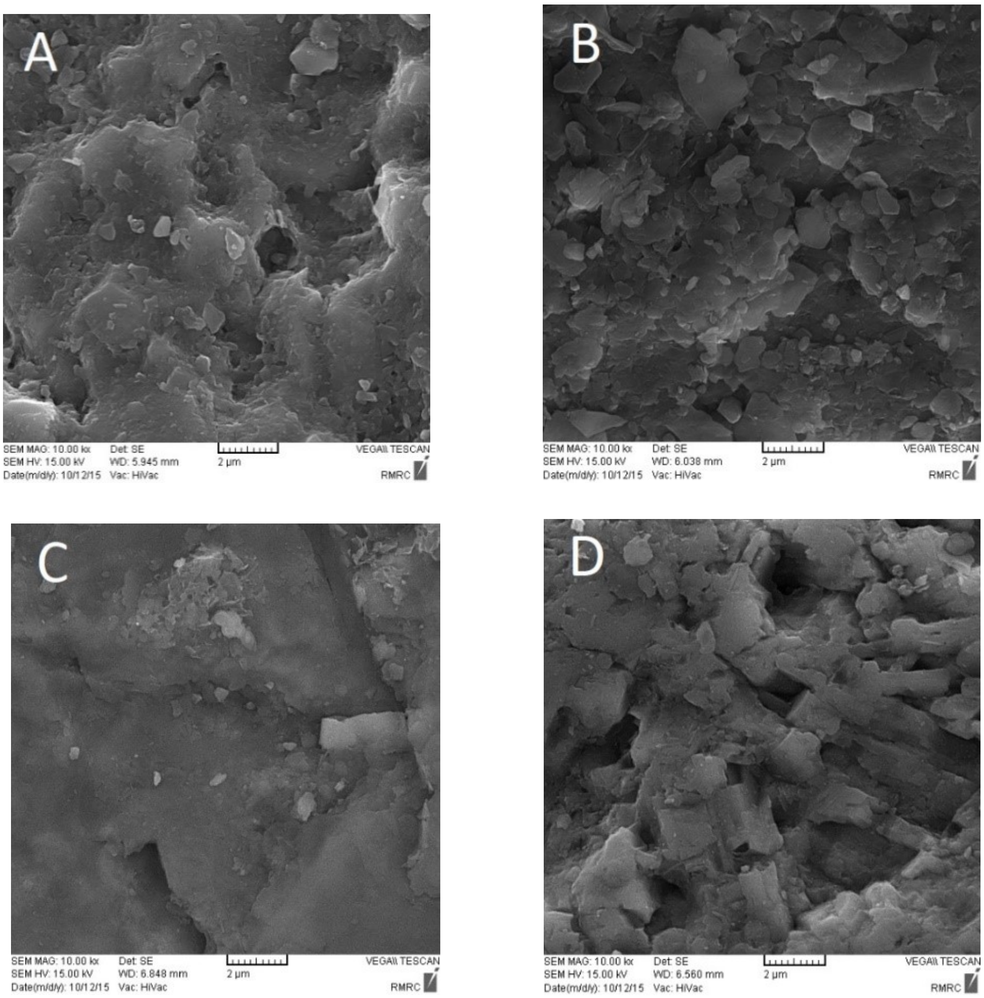

Fig 9. Scanning electron microscope of four randomized grains from S-S sand in the NC. Images show solubility traces on the particles surface of calcareous minerals due to the high groundwater level and sufficient moisture.

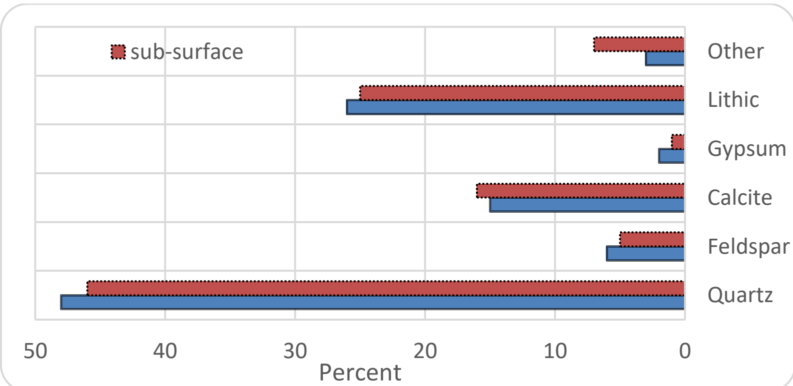

Fig 10. Mean percentage of minerals based on 24 thin sections of S sand and 24 thin sections of S-S sand samples at the NC

Table 3. Mean minerals of 24 S and S-S sands samples and their standard deviations in the NC

Local	Sample	Quartz	Feldspar	Calcite	Gypsum	Lithic	Other
NC	S (mean)	48	6	15	2	26	3
	S-S (mean)	46	5	16	1	25	7
	S STDEV	1.351	0.722	0.933	0.323	0.885	0.406
	S –S STDEV	1.769	0.978	0.780	0.198	0.933	0.885

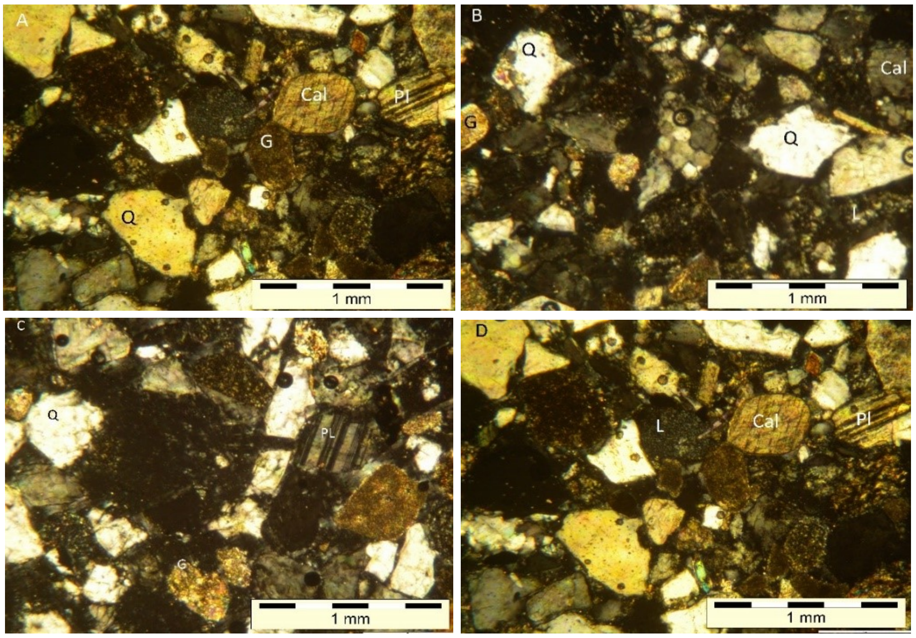

Fig 11. Four thin sections from S sand samples in the NC. The sections show that the main components of the sand formation are Monocrystalline and Polycrystalline quartz (Q), Lithic (L), Calcite (Cal) and Plagioclase (Pl) minerals.

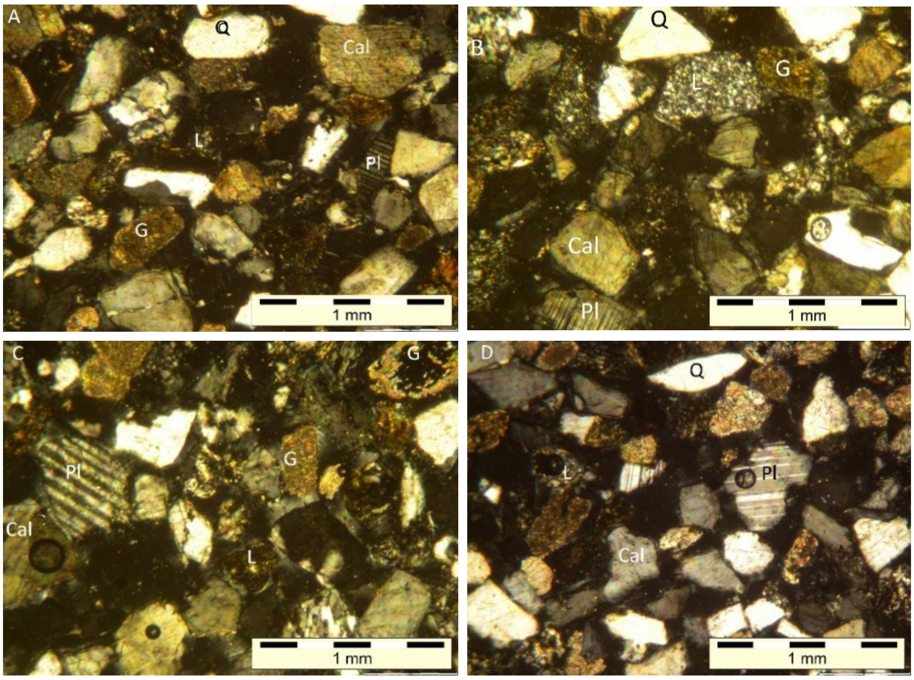

Fig 12. Four thin sections from S-S sand samples in the NC. The sections show that the main components of the sand formation are Monocrystalline and Polycrystalline quartz (Q), Lithic (L), Calcite (Cal) and Plagioclase (Pl) minerals, as in S samples.

In addition to the results of the S and S-S sand in NC, the existence of deep eroded places in the NC showed that buried alluvial sand are sources for sand dunes.
Accordingly, the results of the analysis of thin sections of S and S-S samples confirm the previous results: it was found that minerals making up sands on the surface and sand buried under the clay-silt layers are nearly identical in terms of the type and relative proportions in the samples (Fig 10, 11 and 12).
All of these results indicate that S-S sand either has the same source as the S deposits, or is the main source of S sands carried by wind. The latter may occur if the silty layer which covers the natural surface is eliminated in some areas, exposing S-S sands to the wind. The factors that make the natural clay-silt layer more susceptible to erosion include poor soil texture, low clay content, low adhesion, low vegetation, low soil moisture during drought and human degradation due to undesirable exploitation of the land. Due to the exposure of the S-S sand layers along the beds of old rivers that flowed to Hamoun Lake, there is expansion and the possibility of creating sand dunes in these areas. Consequently, the excavation and transportation of sand occurs everywhere from the old rivers. This would suggest a local source and short distances of transport of the S sands.
Flow direction of the rivers reaching the Hamoun Lake is SE - NW, which is contrary of the wind direction (Fig 3). Field observations, from the numerous excavation profiles along the NC, have shown that with proximity to the Lake, the thickness of the sand layers is reduced and the thickness of the clay silt layer is increased. The results of four samples taken from the Hamoun dry bed show that these sediments contain 98.9% fine particles and 1.1% sand grains. These sediments are severely damaged by the northern winds (120 days) during drought condition, leading to the production of dust in the area, due to poor adhesion related to the low amount of clay in proportion to the silt (Fig 13). The amount of sand grains in these sediments is so insignificant that we suggest it does not play a decisive role in the production of sand compared to the old river beds that make up the S-S.
In order to find out the relationship between sand from dunes on the surface and buried sand and, in addition, to identify the factors of transport and deposition for the S-S sand sediments, laboratory analysis and several field observations were carried out. Results have shown that S-S sand sediments have several important characteristics that distinguish them from S sands:
1- The existence of silt-clay layers between the sand deposits (Fig 14).
2- The presence of stones with different diameters (with a maximum diameter of 3 cm) within the sand deposits.
3- The existence of armoured mud balls between S-S sand deposits in NC (Fig 15).

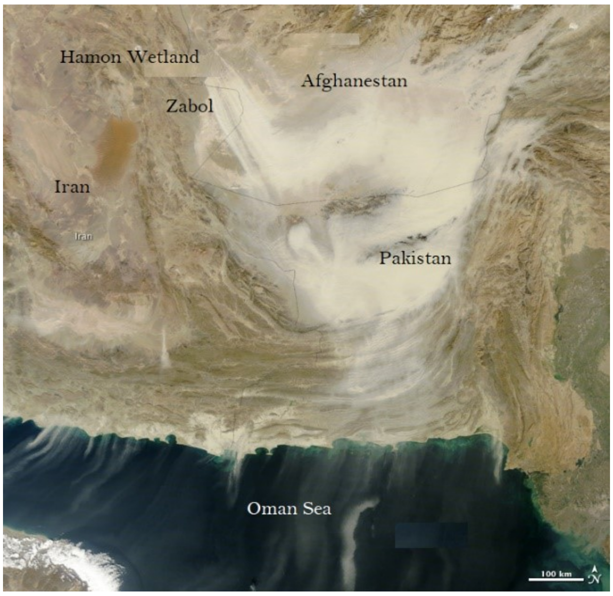

Fig 13. The Moderate Resolution Imaging Spectroradiometer (MODIS) from the Terra satellite. The dust storms in the Sistan which carry dust up to 100 kilometers away across southern Afghanistan and Pakistan on December 20, 2011.

Fig 14. Trough cross-bedding in alluvial sands in NC. We see several sets of cross-beds with tangential bases which formed during the migration of lunate dunes.

4- The existence of ripple marks with ripple index of 8 to 10 in the S-S sand deposits, indicating that the ripples are of the type of aqua ripples (Fig 16).
The presence of armoured mud balls in sandy sediments and low index ripple in S-S sand indicate with certainty that these sand sediments formed by river flow which, in the past, entered the Hamoun Lake from the SE to the NW.

Fig 15. Armoured mud balls in the S-S sands in Niatak

Fig 16. Cast of current ripples on the bottom surface of silty sediments.

The presence of scattered stones in the S-S sands was due to the separation of rocky grains from the armoured mud balls. In fact, the armoured mud balls are formed by the detachment of clay fragments from the clay deposits and their transportation through the sandy river bed. The origin of the stony particles in the S-S sand deposits are the armoured balls, the stony particles of which have been detached during flowing and been inserted between the sand deposits. These particles have origin from upstream of the rivers.

Consequently, we infer that the cause of creation of S sand sediments has been wind, and cause for the transport and creation of S-S sediments has been water. According to our laboratory studies which showed the close relationship between the S and S-S sand components and the lack of sand in the Hamoun Lake bed, it can be clearly stated that the main source of S sand in east of Sistan is alluvial S-S sand sediments from the same area and that this sand has not been carried far. In_contrast to earlier studies, this work demonstrates that the Hamoun Lake bed has not played much of a role in the supply of sediments in the East of Sistan.

6. Conclusion

The results of sand particle analysis in the Niatak Corridor (NC) showed that most of the particles in terms of size are medium and that the surface particles (S: sand dunes) and subsurface particles (S-S: alluvial) are of the same size. The statistical parameters and geometrical forms of the particles are very similar in the S and S-S samples in the NC: the particles in all places have similar mean, median, sorting, Riley sphericity, equidistance and roundness. Studying the thin sections of sand (S and S-S) showed that the constituent minerals are alike and include the minerals quartz, feldspar, calcite, gypsum, mica, lithic carbonate, sandstone and chert in comparable proportions. From the laboratory results and field studies, it is inferred that the origin of sand dunes in eastern Sistan are local and that Hamoun Lake sediments do not have much of a role in sediment supply to the sand dunes. The spread of sand dunes in the form of sand hills and barchan sand dunes is a result of the deterioration of the subsurface clay-silt layer by wind and the exposure to wind erosion of the S-S alluvial sand layer. Therefore, the drift, displacement, transit and sedimentation all are limited and local. There is sufficient mineralogical and morphoscopic evidence that the archaeo-alluvial sedimentary sand particles in eastern Sistan are the source and main origin of the region's wind deposits.

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