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RESEARCH PAPER

Facies architecture and origin of the Quaternary sand dunes of the Qazvin Plain, Iran

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Abstract
Sand dunes of the Quaternary age occupy large areas of Iran's semiarid and arid regions. In this study, some 33 sediment samples were collected from the crest, the lee and stoss sides of the linear dunes of the southern part of Qazvin plain. Sedimentological, geochemical, and mineralogical investigations were carried out in order to identify the origin and probable source of the aeolian dune sands. Grain size analysis of the sediments shows that most of the aeolian sands are generally fine-grained, moderately well-sorted, fine skewed and leptokurtic. The textural, mineralogical and the geochemical results supported by the statistical approach indicate that the dune sands were mainly derived from the Quaternary flood plain with a minor contribution from alluvial and fluvial sands. Facies study leads to the determination of 4 facies in 2 facies associations, including: 1) medium-grained lithofacies (Sdpc, Sdl, and Sdm), and 2) gypcrete facies (G). The studied aeolian sands are characterized by the predominance of gypsum and quartz, and stable minerals together with sedimentary, metamorphic, and volcanic fragments, and a few unstable pyroxene and amphibole minerals. The sand dunes of the Qazvin Plain record a semi-arid to arid paleoclimate and the relatively stable tectonic background characterized by the mineralogical and geochemical composition and gypcrete facies in the dunes.

Keywords: Sand Dune, Lithofacies, Sedimentology, Qazvin Plain, Quaternary.

Introduction

The highest sand dunes in the world are located in Iran, in the Lut desert (480 m), one of the most beautiful tourist attractions in the world. The linear dune is the most common of all inland dunes. These long, narrow sand dunes have sharp, steep crests resulting from the presence of a slip-face on both sides. Bagnold (1941) recorded linear sand dunes in Iran that were over one hundred kilometers long, two hundred meters high, and twelve hundred meters wide (Mangimeli, 2007). Many recent studies have focused on the interpretation and reconstruction of modern and ancient aeolian depositional systems. They consist of two types: wet and dry aeolian systems (e.g., Kocurek & Havholm, 1993; Mountney, 2006). Active and vegetation-stabilized aeolian dune fields are prominent features in many arid and semi-arid regions. Many of these landscapes originate from late Quaternary environmental conditions, and are important indicators of climatic and environmental changes including wind regimes and atmospheric moisture conditions (Muhs & Wolfe, 1999; Busacca et al., 2003). Recently, it has been noted that the aeolian deposits are intercalated with alluvial deposits, and foreset azimuths in cross-bedded sand under the influence of predominantly winds (Pavelic et al., 2006). Sand dune movements are considered to be a specific threat to irrigation networks, roads, urban areas, water resources, agriculture (Wahby,

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2004). Grain size variations in the desert and coastal dune sands have been used to infer transport and depositional mechanisms (Wang et al., 2003; Kasper-Zubillaga & Carranza-Edwards, 2005). Furthermore, geochemical and mineralogical studies of dune sands provide new insights into the evolution and origin of aeolian sand bodies (Muhs, 2004). The aeolian sand dunes occupy a significant portion of the Quaternary deposits of Qazvin plain. The way in which the Qazvin sand dunes are distributed reflects the paleoclimate, tectonic, and lithology of the plain. The aim of this paper is to describe and interpret the grain size attributes, geochemical and mineralogical differences between the sand dunes in the Qazvin plain. Furthermore, this paper provides information on the probable origin of these dune sands.

Geological setting

The Qazvin Plain, located adjacent to the Central Alborz Range in northern Iran, is a structural plain formed because of the activity of the north Qazvin and Ipak faults. This plain is filled by aggradation of various sedimentary processes such as alluvial fans, fluvial systems, playas, and aeolian deposits. The sediments of this plain are mainly composed of conglomerates, sandstones, and mudstones with local evaporate and calcrete deposits. The sediments thickness of the central part of the plain is up to 350 m; however, there is limited geophysical data about the plain basement depth. The only evidence on the plain basement is the outcrop of the Karaj Formation (Eocene) in the north and south of the Qazvin area (Berberian et al., 1993). This formation is comprised of a relatively thick sequence of well stratified green tuffs, sedimentary rocks, and volcanic lava and rare evaporative rocks (Annells et al., 1975). Rieben (1966) classified the alluvial sediments of the Qazvin Plain margins into four lithological units: Alluvial A, B, C, and D (from base to top, in the order of their appearance). The Qazvin aeolian sand dunes are composed of three parallel dunes with a northwest-southeast trend in the area between the floodplain and the alluvial terrace (Fig. 1). The Qazvin sand dunes are located between Bagherabad Turk and Qeshlaq-Aladaglu faults.

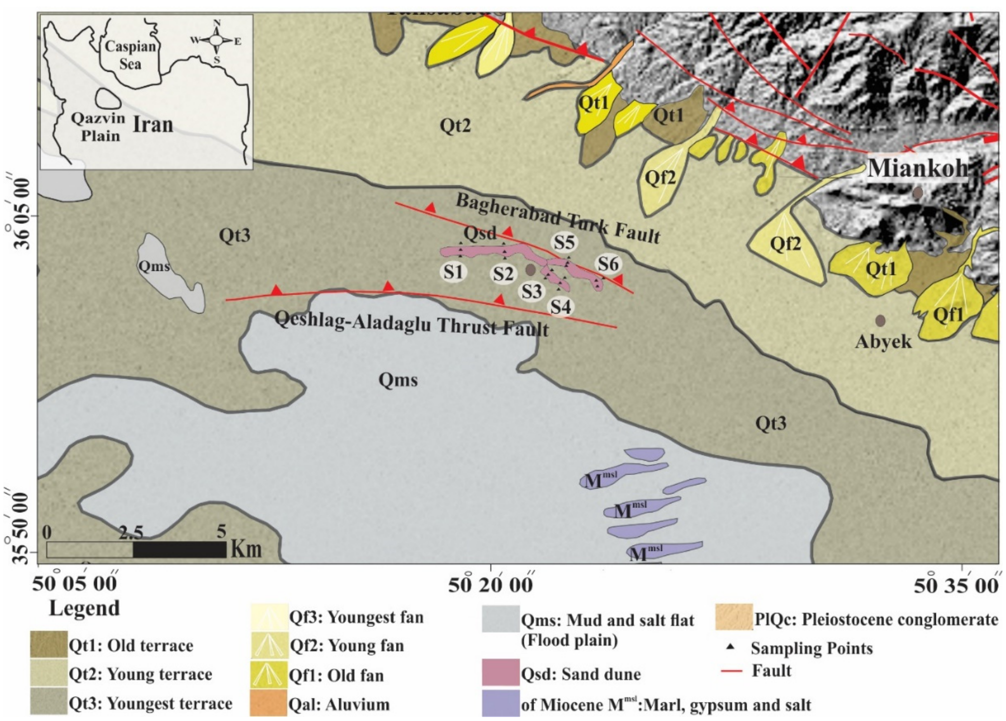

Figure 1. Location map of the Qazvin sand dunes. Sampling points and stations are marked with triangles and S1 to S6, respectively

Methods

In order to analyze the structure, textural variations, and origin of the sand dunes, two profiles were selected from each of the linear dunes (Fig. 1). For this purpose, 18 samples were collected from the crest and lee and stoss sides of the dunes (Table 1). Furthermore, 15 samples were collected for the study of gypcrete facies. The characteristics of representative samples including sedimentary structures, texture, bed geometries, and lithology were used to describe the dune facies based on Miall's (2006) code system. Foreset dip directions were measured in order to interpret the source area and palaeocurrent. In order to determine the prevailing wind direction of the study area, the annual rose diagrams (1986 to 2016) of the stations of Qazvin, Hashtgerd, Takestan, and Buin Zahra were drawn. The grain size of representative samples exposed in the different sedimentary facies units of the sand dunes were analyzed to aid in the interpretation of the variations in the grain-size parameters of aeolian sediments. Also, in order to study thin sections, 13 samples from the sand section and 10 gypcrete samples were prepared, respectively, in order to determine the origin of sediments and microscopic characteristics (Carver, 1971). Folk (1980) classification was used to name the dune sands. Modal analysis of samples was done by counting more than 250 points in each section based on the Gazzi-Dickinson method (Gazzi, 1966; Dickinson, 1970). Five powder samples have been subjected to a detailed mineralogical analysis for the bulk fraction. Mineralogical characteristics of representative bulk and oriented samples were investigated by X-ray diffraction (XRD) at Bu-Ali Sina University, Iran (Italstructures, 40 Kv, Cukα 30mA). Since the deposits of the sub-environments of the Qazvin plain are considered to be the main sources for aeolian dune sands, values of the elemental composition of representative samples of the sand dunes have been compared with those of other sub-environments of the Qazvin plain. For this purpose, X-ray fluorescence (XRF) was used to determine the elemental composition for 7 samples representing dunes and 34 samples from other sub-environments of the Qazvin plain (Table 3). XRF analysis was carried out using a Philips-PW1480 X-ray spectrometer in the Kanpajouh Laboratory of Tehran, Iran.

Table 1. Textural characters of the aeolian sand dunes in the lee side, crest and stoss side

Facies	Texture	Kurtosis (KG)	Skewness (SKI)	Sorting (ϕ) (Iσ)	Mod (Mo)	Mean (MZ)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Station Position	Station
Sdl	mS	0.61	0.49	3.37	0.5	3.38	6	29.3	64.7	0	Lee	
Sdm	mS	1.00	-0.33	1.50	4.5	3.64	7.59	47.51	55.1	0	Crest	SD1
Sdl	mS	0.66	0.59	2.93	2.5	4.15	7.8	28.2	64	0	Stoss	
Sdpc	mS	0.64	-0.34	1.46	4.5	3.15	5.8	38.1	55.9	0.2	Lee	
Sdm	sgsM	0.65	-0.20	2.62	6.5	6.08	12.5	67.5	31.6	0.9	Crest	SD2
Sdl	sgmS	0.58	0.30	3.14	1.5	4.66	11.4	38.3	49.9	0.4	Stoss	
Sdl	mS	2.43	0.52	1.85	2.5	2.68	2.7	14.4	82.9	0	Lee	
Sdm	sM	0.63	-0.15	2.76	2.5	5.73	10.4	45.4	44.2	0	Crest	SD3
Sdl	sgsM	0.66	-0.21	2.66	6.5	5.79	9.5	55.1	34.7	0.7	Stoss	
Sdl	mS	0.59	0.19	1.73	0.5	2.22	8.22	17.68	74.1	0	Lee	
Sdl	sM	0.92	-0.39	0.82	4.5	3.95	4.31	54.89	40.8	0	Crest	SD4
Sdpc	mS	0.82	-0.45	1.26	4.5	3.54	8.2	40.1	51.7	0	Stoss	
Sdl	mS	0.86	-0.67	1.56	4.5	3.36	10.17	47.23	42.7	0	Lee	
Sdl	sM	0.73	-0.57	1.67	4.5	3.11	12.83	34.37	52.8	0	Crest	SD5
Sdl	M	0.83	-0.66	1.48	4.5	3.45	9.1	50.6	40.3	0	Stoss	
Sdl	mS	0.48	-0.22	2.96	4.5	5.41	5.61	53.69	40.7	0	Lee	
Sdl	sM	0.64	-0.34	2.58	8.5	6.49	16	54.6	29.4	0	Crest	SD6
Sdl	sM	0.59	-0.19	2.71	2.5	5.88	11.8	46.6	41.6	0	Stoss	

Results and Discussion

Textural characteristics

The aeolian sediments of the Qazvin dunes are represented mainly by silt to medium-grained sand (Fig. 2) with an average value varying between 2.22Φ (lee side) and 6.49Φ (crest). Considering that the average grain size in the sand dunes on the stoss side is 4.57Φ and on the lee side is 3.36Φ; therefore, the grains are in the range of fine sand and are slightly coarser on the lee side than on the stoss side. The grain size of Qazvin dunes was divided into five categories: very coarse (2-3Φ), coarse (3-4Φ), medium (4-5Φ), fine (5-6Φ), and very fine (6-7Φ). The frequency of each category was measured in six selected stations (Fig. 1). The highest value of very coarse and coarse sand is observed in stations 1 (16.42%) and 5 (20.17%). However, in stations 4 and 6, the amount of very fine sand is more abundant. It represents the abundance of coarse sand is relatively higher in the western stations, which corresponds to the direction of the prevailing winds in the region (Fig. 3). Plotting the grain size against the sorting of the studied sands (Fig. 3 D) shows that there is a very weak positive relationship (R2=0.32) between grain size and sorting. The skewness of the studied dune sands ranges between -0.67 to 0.52 on the stoss side and between -0.66 to 0.59 on the lee side. Consequently, there is no significant difference between the lee and stoss sides of dunes (Fig. 3B). However, the skewness of the crest in stations 1, 5 and 6 is more negative than the lee and stoss sides. Also, there is no significant difference in skewness between the eastern and western parts of the dunes.

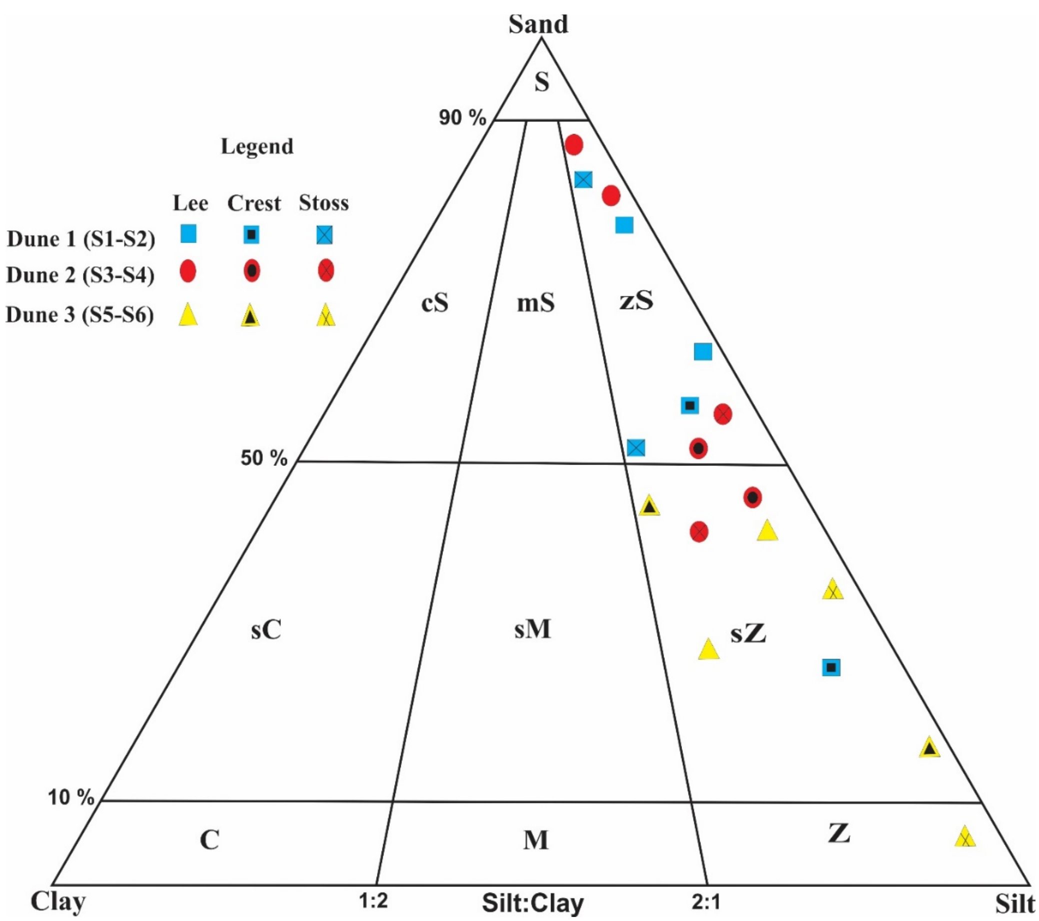

Figure 2. The textural triangle diagram of selected sediments of the Qazvin sand dunes based on Folk (1980)

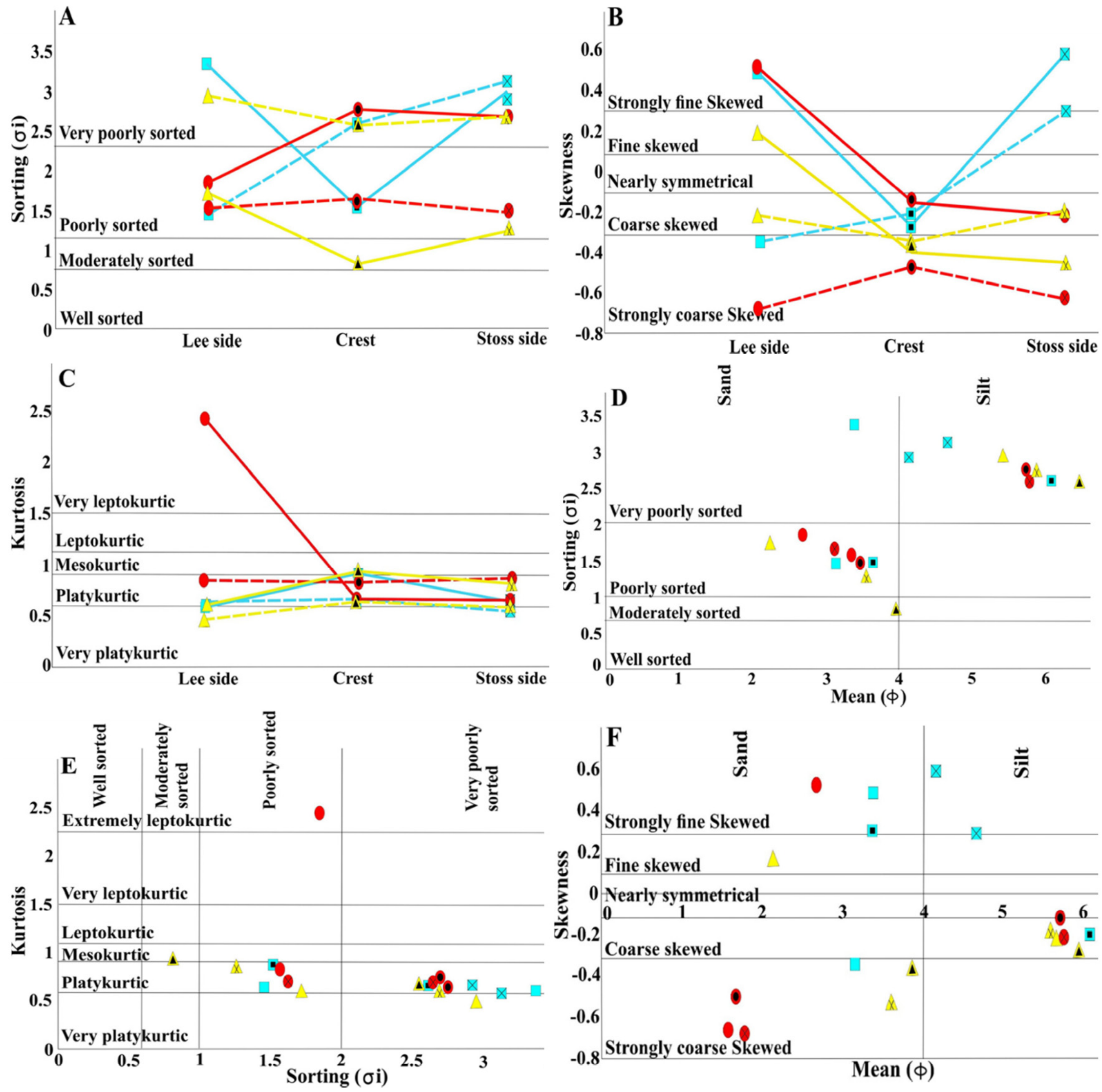

Figure 3. Biaxial graphs of the distribution of statistical indices of the studied aeolian sands: A) The mean sorting in the lee, stoss and crest of dunes; B) The skewness in the lee, stoss and crest of dunes; C) The kurtosis in the lee, stoss and crest of dunes; In figures A, B and C, the graphs of two stations of each dune are shown with similar colors; D) mean vs. sorting; E) sorting vs. kurtosis; F) mean vs. skewness. The legend is presented in figure 2

Histograms of the grain size distribution show three different grain size distributions in dune sands (Fig. 4): Sediments of sample SD1 from sand dune 1 with gravelly mud sand texture and very positive skewness, sample SD2 from sand dune 2 with mud sand texture and very positive skewness, and sample SD3 from sand dune 3 with sandy mud texture with and very negative skewness.

Mineralogical characteristics

The mineral assemblages provide valuable information about the history of aeolian sands and their sources (Besler, 2008). Ten representative samples of aeolian sands of the Qazvin plain have been subjected to a detailed mineralogical study for the mineral compositions (Table 2). The dune sands have a different composition from other sub-environments of the Qazvin plain, such as alluvial fans, flood plains (mud and salt flats), silty-clay flats, clay flats, and salt flats (Figs. 5-6). The studied aeolian sands seem to be more enriched in monocrystalline quartz (11 to 42%) than other sub-environments in Qazvin plain. The abundance of polycrystalline quartz is <1%. Plagioclase was observed with an abundance of 1 to 16% and potassium feldspar with an abundance of 1 to 8%. The abundant value of the volcanic rock varies from >1 to 19%. The most abundant sedimentary rock fragments include sulfate (gypsum), carbonate, chert, sandstone and siltstone. Sedimentary rock fragments (about 87%) are represented mainly by in situ and transported gypsum (10 to 67%), limestone fragments (3 to 13%), chert (1.3%), and sandstone (1 to 5%). About 1% of the samples consist of low-grade metamorphic rocks such as slate and phyllite. Heavy minerals were observed in dune sands with the amount of 1 to 3%, which are represented mainly by zircon, tourmaline and rutile.

In order to identify the mineralogical composition and origin of the sand dune sediments, selected samples of the sand dunes, alluvial fans, and flood plain were subjected to XRD analysis (Fig. 7). XRD micrographs of a bulk sample of the sand dune show the predominance of gypsum with a high-intensity peak at 31.20 2ϴ (2.93Å); the subordinate minerals are: quartz, chlorite, illite, feldspar and, amphibole. The composition of the sand dune sample is similar to that identified in the flood plain sample.

Table 2. Mineralogical composition of the sand dunes

Sample no.	Qm	Qp	P	K-F	MRF	VRF	PRF	CRF	Cht. RF	SS. RF	Gyps.	M&ch	HM
Sd1	36.4	0.7	8.0	6.9	0.9	17.3	0.0	6.6	0.7	2.1	17.73	0.0	2.6
Sd2	41.2	0.3	15.9	3.6	0.0	7.9	0.0	8.2	0.0	4.9	15.85	0.0	2.3
Sd3	35.8	0.9	10.2	3.1	0.0	14.5	1.9	5.2	1.9	2.6	22.27	0.2	1.4
Sd4	26.5	0.5	7.0	7.5	0.0	6.1	2.7	12.4	0.0	3.6	30.58	0.0	3.2
Sd5	11.6	0.0	1.3	1.1	0.0	0.0	0.0	1.2	1.2	0.0	81.47	0.0	2.1
Sd6	15.7	0.3	4.2	2.1	0.0	0.0	0.0	2.9	0.0	1.6	70.93	0.0	2.2
Sd7	32.8	1.0	4.3	8.0	0.6	6.0	5.4	10.9	2.5	3.9	23.09	0.0	1.4
Sd8	38.1	0.0	2.1	4.0	1.2	12.1	0.7	9.8	3.7	5.8	19.98	0.0	2.6
Sd9	29.8	0.0	13.3	4.4	2.3	10.0	1.2	12.3	2.1	3.7	17.67	0.0	3.3
Sd10	48.1	0.5	5.5	2.5	0.0	5.8	1.3	7.8	0.8	6.8	17.88	0.0	3.0
Mean	**31.6**	**0.4**	**7.2**	**4.3**	**0.5**	**8.0**	**1.3**	**7.7**	**1.3**	**3.5**	**31.8**	**0.0**	**2.4**

Table 3. Data values of the elemental composition of representative samples of sand dunes, compared with the mean values of other sub-environments of the Qazvin plain

Sub Environment	Sample no.	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	P_2O_5	MnO	S	LOI	BaO	SrO
Sand Dunes	Sd1	57.99	10.86	2.32	0.43	12.37	1.39	2.49	2.16	0.13	0.06	1.24	8.39	0.06	0.10
	Sd2	52.50	10.39	2.46	0.42	12.70	1.43	2.28	2.30	0.28	0.08	2.58	12.50	0.08	0.17
	Sd3	54.25	10.43	2.34	0.41	12.54	1.41	2.33	2.23	0.18	0.06	1.52	11.87	0.07	0.14
	Sd4	53.24	10.63	2.52	0.51	12.57	1.45	2.39	2.44	0.14	0.07	2.79	10.98	0.09	0.15
	Sd5	53.12	11.46	3.11	0.65	13.02	1.95	2.35	2.12	0.33	0.09	1.47	11.45	0.10	0.09
	Sd6	52.63	10.15	2.78	0.32	115.51	1.02	1.87	1.56	0.39	0.05	2.67	13.39	0.13	0.19
	Sd7	55.27	11.01	2.82	0.49	12.41	1.51	2.37	2.26	0.23	0.08	2.53	8.75	0.08	0.18
	Mean	53.42	10.99	2.62	0.46	13.44	1.45	2.29	2.16	0.28	0.14	2.71	11.05	0.08	0.13
Flood Plain	Mean	42.66	10.75	2.58	0.35	20.48	1.23	1.41	1.24	0.24	0.07	8.89	12.95	0.08	0.18
Young Terrace	Mean	49.49	12.74	4.47	0.72	13.34	1.98	1.45	1.96	0.48	0.18	<0.02	12.98	0.14	0.05
Old Terrace	Mean	46.60	11.73	4.18	0.86	15.48	1.57	1.41	1.81	0.49	0.60	<0.02	15.09	0.11	0.05
Alluvial Fans	Mean	48.49	12.72	4.73	0.78	11.97	2.36	1.23	1.89	0.32	0.16	<0.02	15.12	0.11	0.05

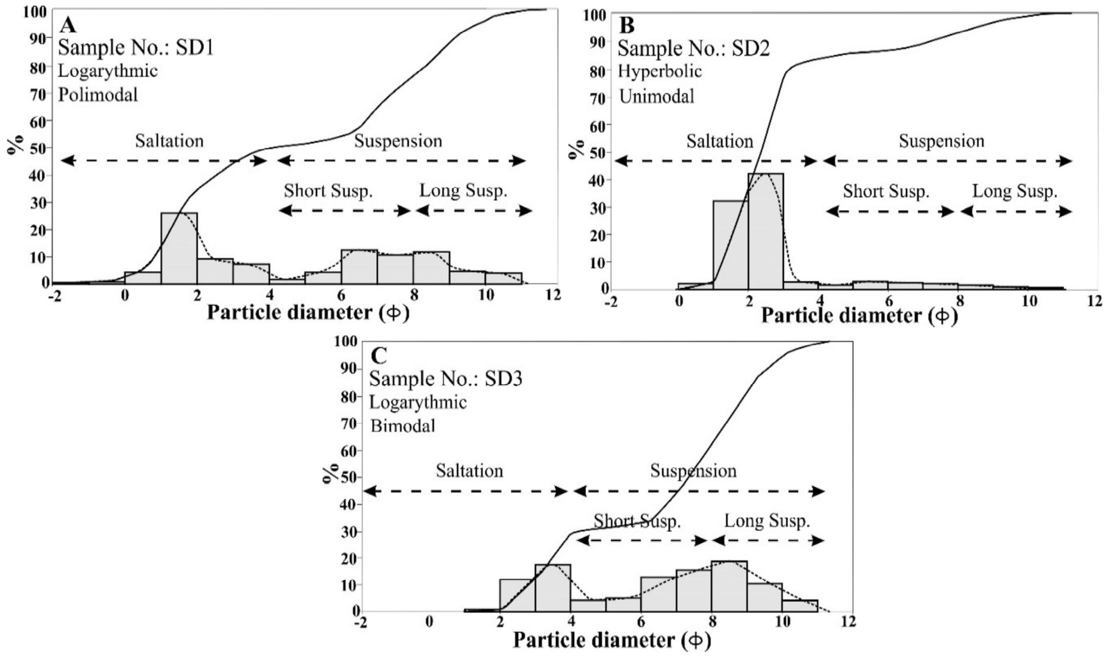

Figure 4. The grain size distribution for three representative samples of sand dunes

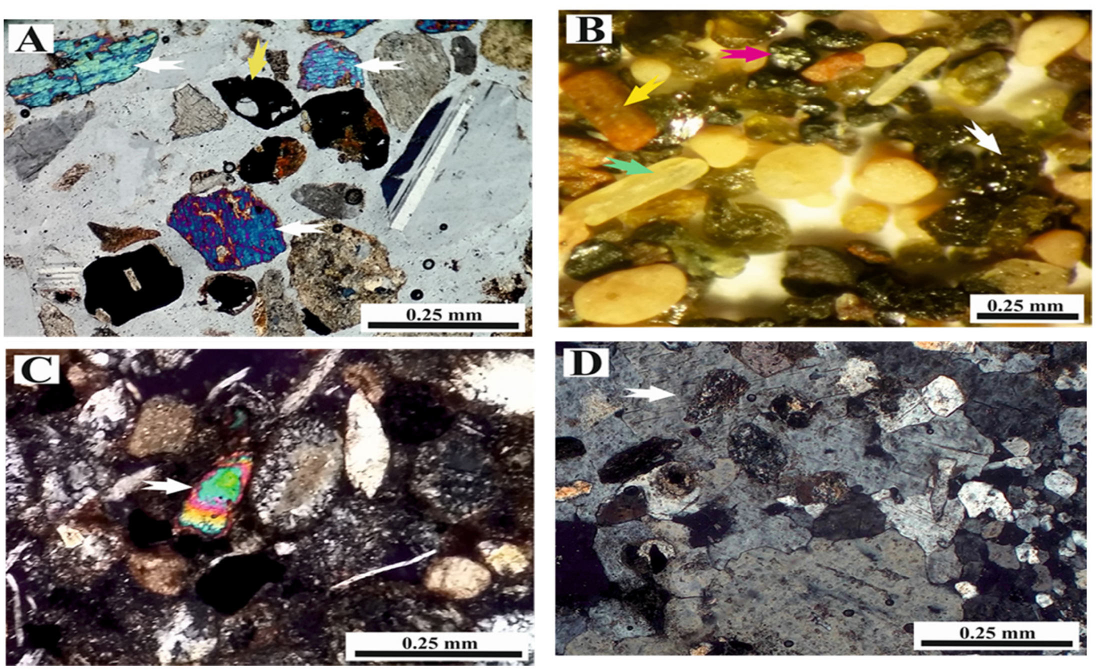

Figure 5. Microscopic images of the dune sand fragments: A) pyroxene (white arrow) and opaque mineral (yellow arrow); B) pyroxene (white arrow), magnetite (pink arrow), topaz (blue arrow) and hematite (yellow arrow); C) zircon (white arrow); D) Gypsum cement around igneous rocks (white arrow); Pictures A, C and D were taken in polarized light and pictures B were taken with binoculars

Geochemical analysis

The results of the analysis of the elemental composition of 41 sediment samples from different sedimentary sub-environments of the Qazvin plain are presented in table (3). The amount of SiO_2 in the samples varies from 24 to 63%. SiO_2 is the main oxide forming samples of the sand dunes, which ranges from 52.63% to 57.99%, averaging 53.42% of the whole composition and is higher than the average SiO2 values of other sub-environments. The amount of Al_2O_3 in the samples ranges from 6.91 to 16.2%, Fe_2O_3 from 13.2 to 7.73%, and CaO from 4.49 to 30.35%. The amount of other oxides (K_2O, Na_2O, MgO, BaO, MnO, P_2O_5 and TiO_2) in the analyzed samples is insignificant and their amount is less than 3.45% in total. The elements' values of the studied samples of the aeolian sand dunes and floodplain are nearly similar. The highest amount of S and Sr are found in the samples of the sand dunes and flood plain.

Facies analysis

Cross-bedded sandy Facies (Sdpc)

Facies Sdpc (Fig. 8D) comprises pale yellow to orange-colored, very-fine- to medium-grained sands. This facies is well-sorted, and its grains are well-rounded. This unit occurs as isolated cross-laminated sets interbedded within well-developed sub-horizontal to low-angle sets.

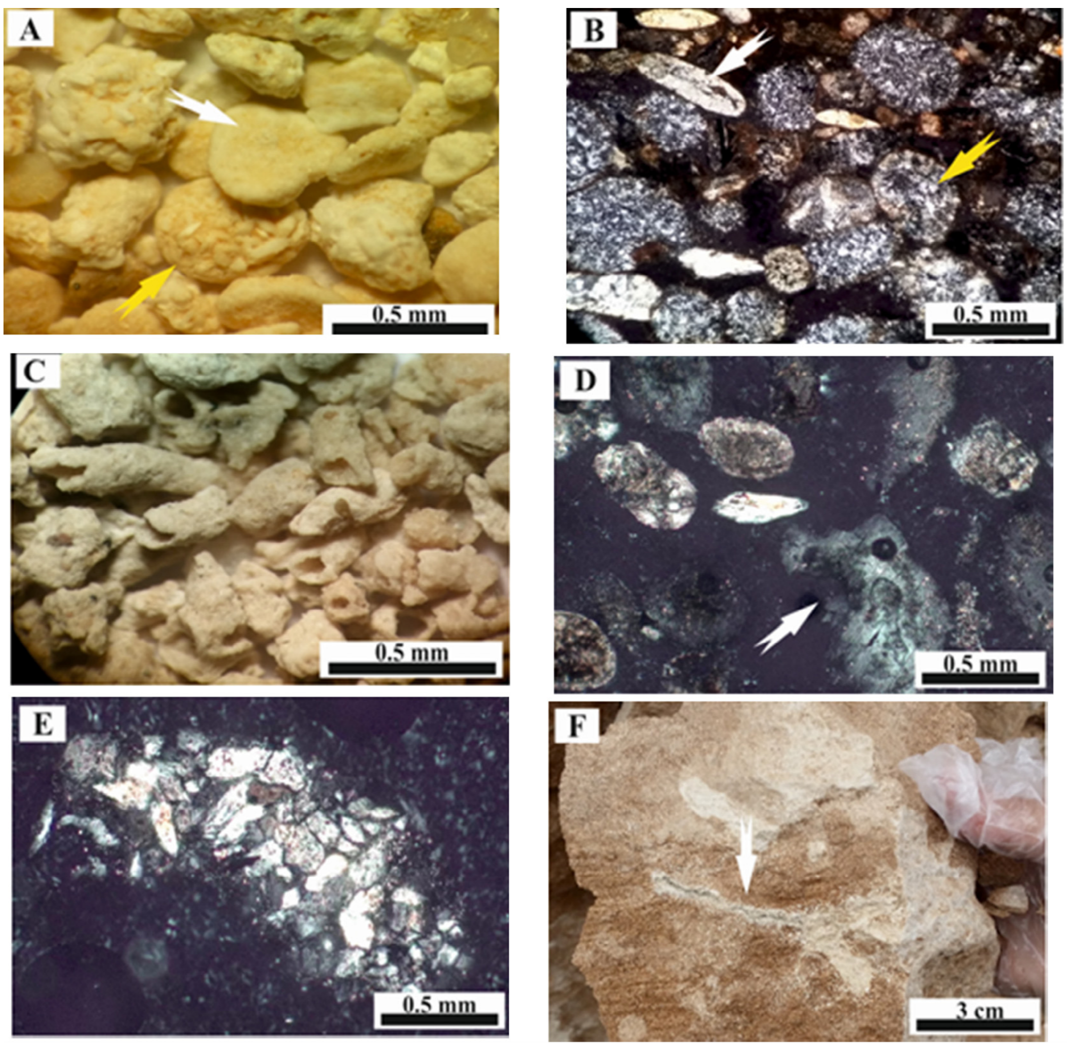

Figure 6. -A) Microscopic image (binocular) of flaky gypsum (white arrow) and cumulative gypsum consisting of lens-shaped gypsum (yellow arrow, sample Sd2L); B) Microscopic image of gypsums of image A (XPL); C) Microscopic image (binocular) of tubular gypsum (sample Sd5L); D and E) Microscopic images of tubular gypsums of image C (XPL); F) growth of plants and bioturbation of horizontal laminations (white arrow, sample Sd6L)

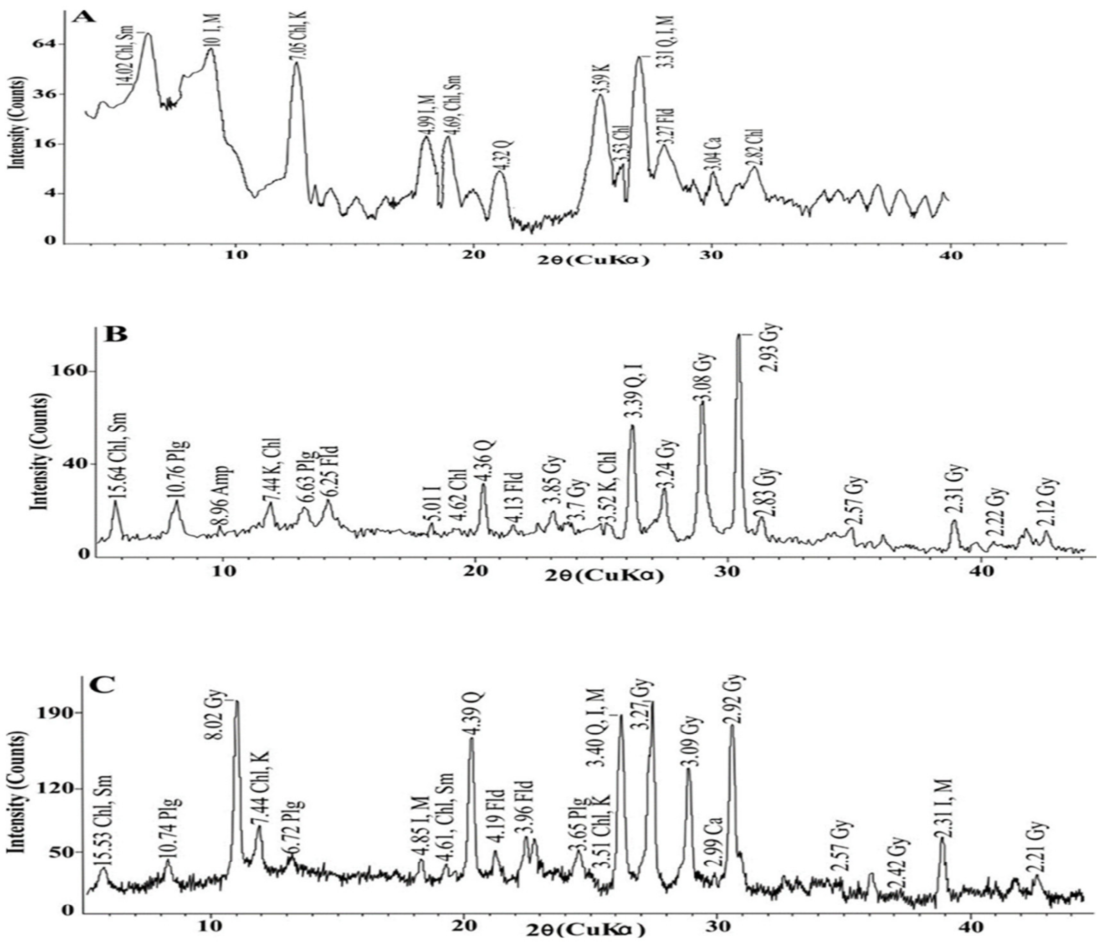

Figure 7. Representative examples of XRD patterns from bulk sample of: A) Alluvial fan; B) sand dune; C) floodplain. Abbreviations: Chl: chlorite; Sm: smectite; Plg: palygorskite; I: illite; M: mika; K: kaolinite; Fld: feldspar; Ca: calcite; Gy: Gypsum; Q: Quartz; Amp: amphibole

It is characterized by tabular foresets. Usually, they form units composed of tabular 40–80 cm thick sets with lateral extension between 4 and 9 meters. The foresets exhibit moderate to high dip angles usually between 14° and 38°, and the dip azimuths are towards a mean direction of 60° to 125˚, i.e. to the northeast to southeast. At some places scattered and thin pinching out cross-laminated sets develop within sub-horizontally laminated sandy sets.

Fine to medium grained dune sands with very uniform grain size, distinct cross-bedding, steep upper foresets, and the pale yellow to orange coloration indicate aeolian deposition without organic matter (cf. Hunter, 1977; Kocurek, 1991). The lack of bioclasts supported this interpretation, that may indicate subaerial deposition. Moderate- to high-angle foresets may have been formed by two kinds of flow. The steeper foresets, are interpreted as deposited by sandflows, causing avalanching on steep slipfaces in aeolian dunes (McKee, 1966; Hunter, 1977; Kocurek, 1991). Less steep foresets indicate flow separation over the crest and grainfall deposition on the smooth leeward of the dune (Kocurek, 1991). Surfaces truncating the foresets may have been produced by periodical partial erosion of the lee side caused by shifts in wind directions (cf. McKee, 1966; Hunter, 1977; Kocurek, 1991). Due to their occurrence within thick units, the thin sandy units can be interpreted as secondary bedforms, small dunes formed on the slipfaceless slopes of large, primary bedforms which carried superimposed, faster migrating secondary bedforms (cf. Hunter, 1977; Kocurek, 1991).

Low angle to Sub-horizontally laminated sandy facies (Sdl)

The deposits of facies Sdl (Figs. 8E-F) are also pale yellow to orange-colored, very-fine- to medium-grained sands. These deposits are characterized by well-sorted and well-rounded grains. The lamination of the facies is planar or rarely slightly concave-up at some places. The thickness of the laminates varies from 4 to 6 cm. The angle of dip is 3–8°, and in a few places up to 14°, with a mean direction changing towards the east and the north-east. Laminates, rich in flake gypsum and laminates with less gypsum, are interlayered. Parts of the sub-horizontally laminated facies are structureless (massive), or the lamination is discontinuous. At some places laminates are pinching out laterally in others. Sdl facies is the most abundant facies in the sand dunes.

The pale yellow to orange coloration of the facies Sdl, in addition to the well sorted and well-rounded grains, represents an aeolian source (Gough, 2015). The sub-horizontally laminated sandy sets may be compared with planar laminated aeolian sands (sensu Hunter, 1977) and are probably wind-ripples deposits on the lee-side of aeolian sand dunes (Kocurek, 1991).

Massive to crudely stratified sandy facies (Sdm)

The deposits of facies Sdm are yellow to orange-brown, very fine-grained sands with a muddy matrix lacking in any internal architecture or structure or with a crude stratification. At some places the cross-bedded set is strongly destroyed. This facies is often observed in the upper parts and crests of the sand dunes (Fig. 8C) which are commonly highly bioturbated, and an abundance of rhizoliths can be observed. In the upper parts of the dunes, centimeter-sized vertical and horizontal tubes are abundant.

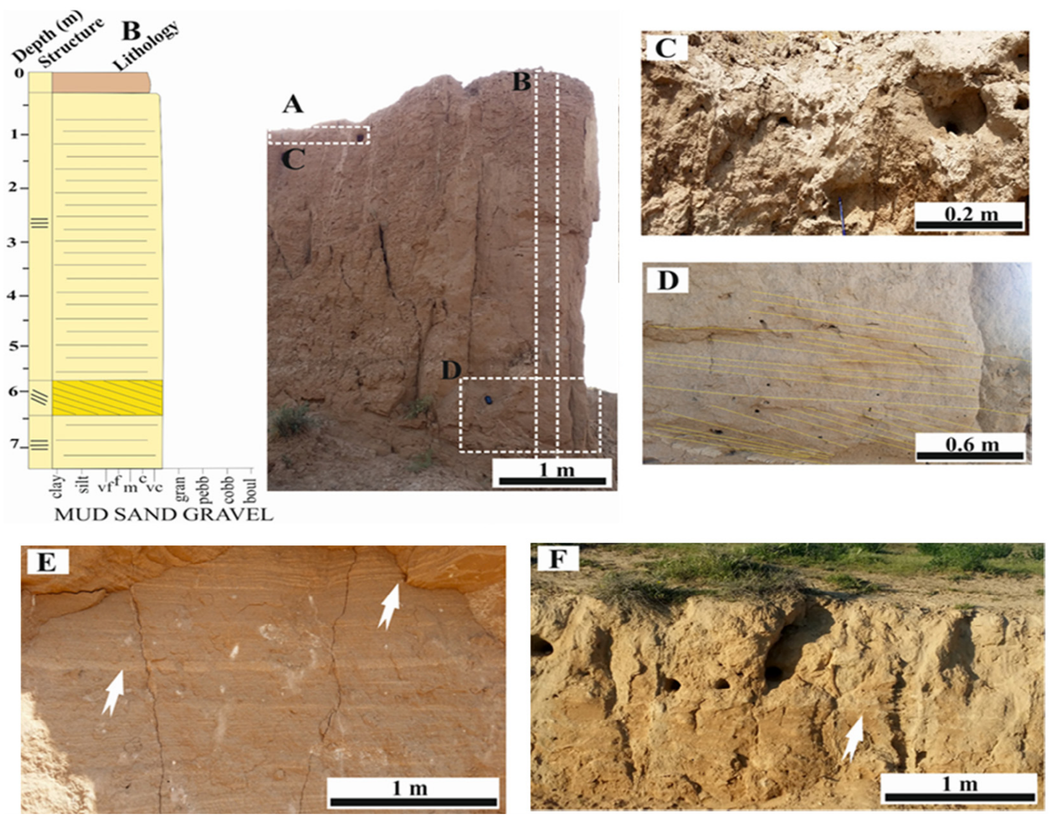

Figure 8. A and B) Sedimentary profile and field image of facies of sand dunes; C) massive sandy facies (Sdm); D) Cross-bedded sandy Facies (Sdpc); E and F) Low angle to Sub-horizontally laminated sandy facies (Sdl); note the white gypsum-rich horizons (white arrow)

This facies can be caused by disturbance due to the activity of vegetation and living organisms. Intense bioturbation represents pedogenesis that has defaced any primary sedimentary structure (Ghinassi & Ielpi, 2016).

Gypcrete facies (G)

The deposits of facies G are white to pale yellow (Fig. 9) within the host mud- to- sand-grade deposits, with rhizoliths occurring throughout the column of the facies. The facies never exceed 9cm in thickness, and are commonly powdery and vertical, thin, millimeter-sized laminar in appearance. The facies occurs sporadically in the study area. The most prominent internal feature is an abundance of rhizoliths, which occur throughout the facies.

The facies is indicative of poorly to well-developed palaeosols. The rhizolith-rich layers represent periods of tectonic stabilization (Alonso-Zarza, 2018). The light color of the facies is the result of a secondary alteration of the deposits (Gough, 2015). The development of gypsum facies represents the relatively stable tectonic background and arid to semi-arid climate (Alonso-Zarza, 2003). Consequently, the relatively stable tectonic background and arid to semi-arid climate (Reeves, 1983; Wright & Tucker, 1991) may be considered as the main reasons for the development of gypcrete in the studied area.

Palaeocurrents

The prevailing wind direction of the studied area was identified using meteorological data of four stations in Qazvin Plain (Fig. 10). The palaeoflow measurements thus represent a dominance of westerly and southerly winds generating sand deposition and dune migration. Moreover, a total of 113 foreset dip directions were measured in the sand sets in order to interpret the source area and palaeocurrents. Foreset dip directions of the bedforms are mainly towards northeast to southeast with a narrow spread around the mean value. Therefore, internal bedding and orientations of dunes show that the dunes were developed by winds blowing from the same direction as present-day wind regimes.

Discussion

Sediment texture

The results of granulometric studies showed that the abundance of coarse sand is higher in the western stations.

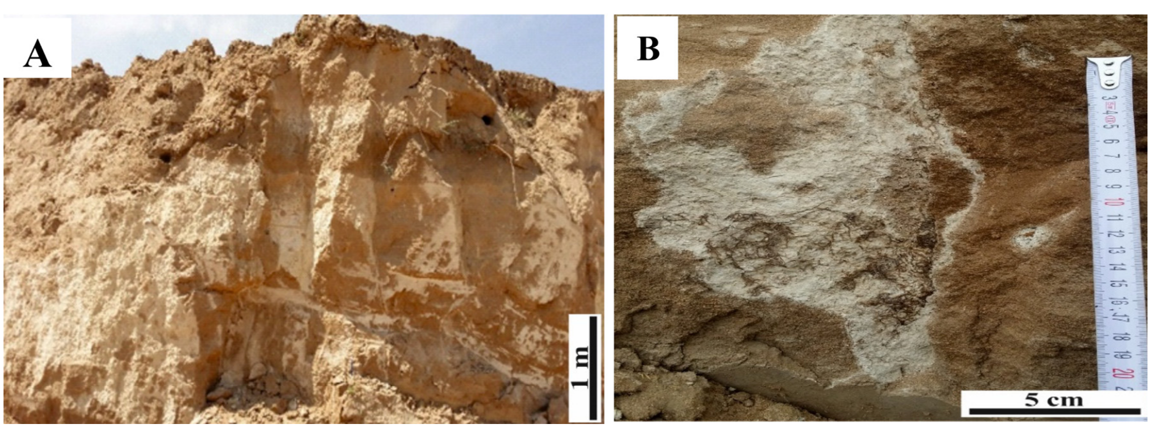

Figure 9. Field image of gypcrete facies A) laminar gypcrete; B) rhizolith-rich gypcrete

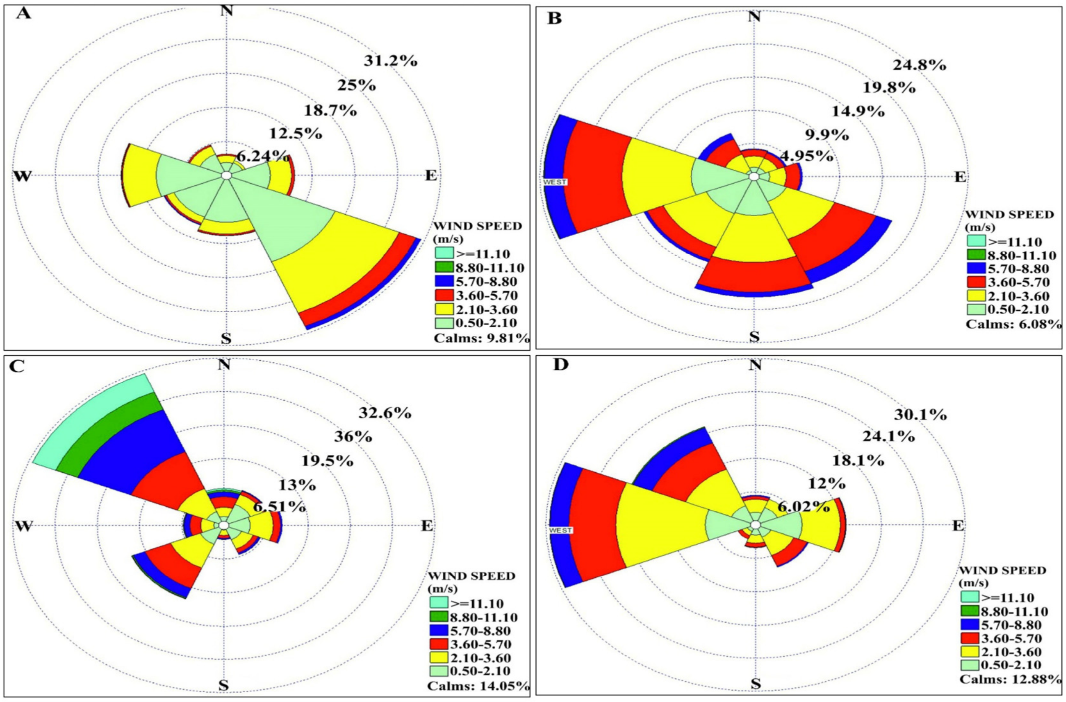

Figure 10. The annual rose diagrams (1986 to 2016) of stations of: A) Qazvin; B) Hashtgerd; C) Takestan; D) Buin Zahra

In general, the three modes of the grain transportation by wind sands are: (1) suspension for grains finer than 0.9 mm (3.5Φ); (2) saltation for the grain size range from 0.25 to 0.125 mm (2 to 3Φ) and (3) surface creep or rolling for grains coarser than 0.35 mm (1.5Φ) (Visher, 1999).

In the dunes of Qazvin plain, the sands were transported in all three different modes. The transportation of sands in the western part took place in three modes: suspension, saltation and rolling, but towards the east, grains larger than 1.5Φ were left and the sands continued to move mainly in two modes: suspension and saltation. Therefore, in the eastern part, the sands are relatively finer. Table (1) shows the sorting of the studied dune sands at different points. Therefore, among the studied stations, only the sediments in stations 1, 5, and 6 are less sorted at the crest of the dune compared to its lee and stoss sides. Also, there is no significant difference between the skewness of the lee and stoss sides and deposits on the crest are better sorted compared to those on the lee and stoss sides. There does not appear to be any significant difference in sorting and skewness from west to east. Also, the kurtosis of the lee side is relatively better than the stoss side, and the kurtosis of the crest of the dune is more than the stoss side but less than the lee side. On the other hand, there is no significant relationship between the kurtosis of the eastern dune sediments compared to the western dune.

Generally, three categories have been presented for the deposits of sand dunes in sorting: 1) finer crest dunes with finer-grained crests, in which the dune crests have finer grains, better sorting and more positive skewness than their sides (Lancaster, 1981; Watson, 1986; Wang et al, 2003). These dunes are formed by the slow movement of larger grains towards the crest (Bingqi and Jingjie, 2013); 2) coarser crest dunes in which the crest of the dunes have coarser grains, but they are better sorted than the sides. These dunes have been investigated in Simson's linear and longitudinal dunes by Watson (1986) as well as the southwest Kalahari dunes (Lancaster, 1986; Livingstone, 1989). The development and formation of these dunes are the results of the selective transportation of grains based on the grain size, shape or density (Folk, 1971); and 3) The third type is interpreted as "No difference patterns" (Lancaster, 1986), in which there is no significant difference in grain size distribution between different parts of the dune (Lancaster, 1986). This type has been reported in the dunes of the Sinai desert of Egypt and also for a part of the southwestern Kalahari Desert (Livingstone et al., 1999). At present, these three patterns are used to describe the sorting of dune sands. These studies show the importance of sorting in sand dunes all over the world. However, no attention has been paid to the importance of studying the grain size and sorting in the linear dunes of the Qazvin plain; therefore, in this article, an attempt has been made to provide a comprehensive model for the linear dunes of the Qazvin Plain by examining the convergence of different points of the dunes in relation to each other and finally comparing it with other study (Fig. 11). Consequently, the sand dunes of Qazvin plain are of the third type of dunes, and compared to other places, the average size of their grains is smaller (3.54%). The standard deviation (2.17) is much weaker than the dunes mentioned in other parts of the world and this characteristic is the indicator of the linear dunes of Qazvin plain.

Provenance

The main mechanisms controlling the formation of sand dunes include wind regime, sediment supply and physical barriers. Wind regimes control the orientation of dunes and physical barriers affect dune migration, such as rivers (Wasson & Hyde, 1983) and active floodplains, which have the potential to secondary change the orientation, spacing, and degree of order of sandbars (Fitzsimmons, 2007). However, barriers are not needed for aeolian sand accumulation. Sand has the power of self-accumulation. This power results from two processes: 1) the drag effect of saltating sands on wind velocity, and 2) the differential speed of saltating sand over non-sandy versus sandy surfaces (Mangimeli, 2007).

Tsoar (1983) worked on a linear dune in the Negev Desert. He argued that any wind flow crossing the crest of the dune obliquely would be subjected to a separation of flow from the surface of the dune, and would be diverted along the lee slope. The separation of the wind flow would lead to a reversal of flow at the lee side. Dune sands could be prevented from leaving the downwind side of the dune, and sand transport would be parallel to the crest of the dune. Tsoar believes that lee side eddies and the flow diversion could account for the maintenance of the linear form of the dune. Therefore, in the linear sand dunes of Qazvin plain, the initially inclined winds are deflected at the crest of the dune, which leads to the formation of a sand flow on the lee side, which is along the dune parallel to the crest (Fig. 12).

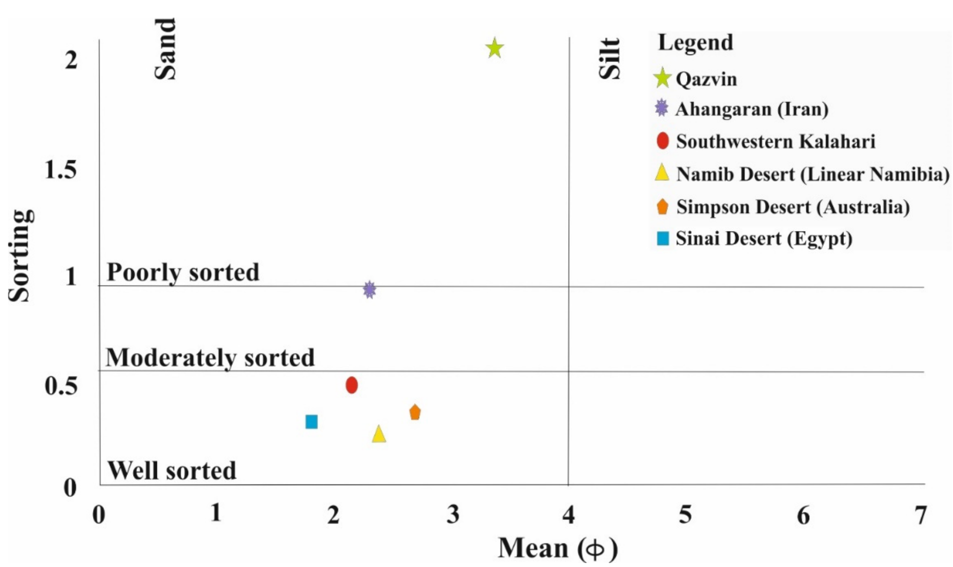

Figure 11. Sorting versus mean of the Qazvin sand dunes in order to compare with the data of Kalahari sand dunes (Lancaster, 1986), Namib desert (Lancaster, 1981), Simpon desert (Folk, 1971), Sinai desert in Egypt (Tsoar, 1978) and Ahangaran in Iran (Rezazadeh et al., 2016)

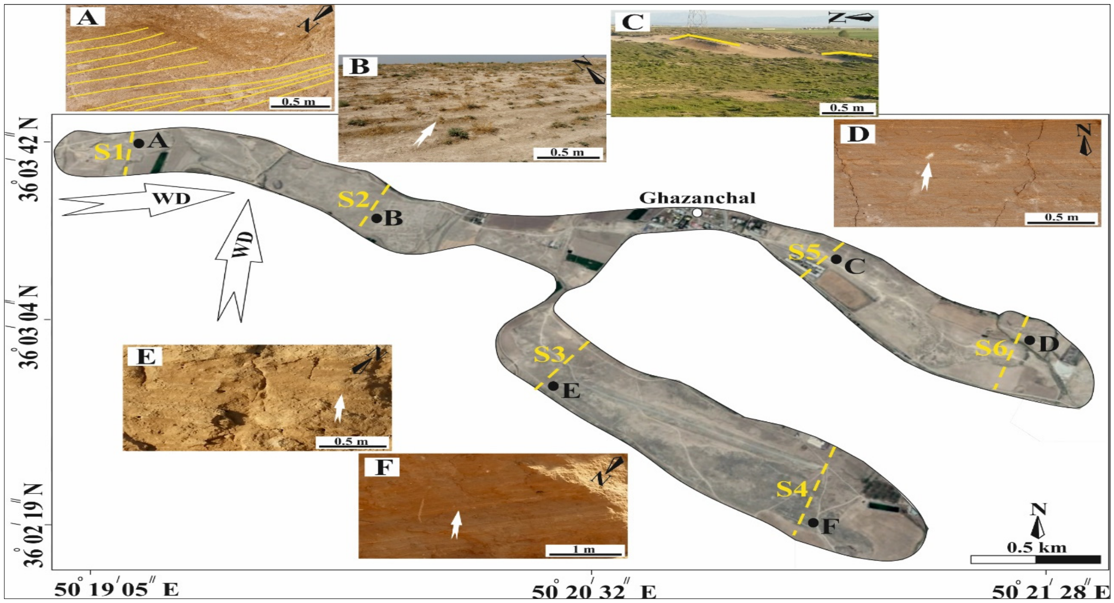

Figure 12. Field image of sand dunes and sampling stations (S1 to S6); A) Sdl facies; B) asymmetric ripple-marks on the dune surface; C) small dunes on the dunes or larger dunes whose steep slope is towards the north; D, E and F, Sdl facies with laminae rich in flaky or powdery white gypsum (white arrow). Note the wind direction (WD)

On the other hand, the modal analysis indicates that the dune sands were derived from weathering of different rock types. Quartz grains, feldspars, and plagioclase are probably derived from acidic magmatic rocks. The predominance of transported and in situ gypsum indicates that older gypsum rocks were the main sediment source. Plagioclase, potassium feldspar, and phyllite were derived from igneous and metamorphic rocks. Limestone, siltstone and sandstone fragments suggest weathering residues of various sedimentary rocks. Weathered chert provided a lesser portion (1.3%) of detritus. Ultrastable transparent heavy minerals such as zircon, tourmaline, rutile, and sub-rounded and rounded quartz grains represent partial recycling of older sandstones. Amphiboles, pyroxenes, garnet, and epidote may suggest weathering residues of various metamorphic or magmatic rocks. Well-rounded grains and good sorting are representative of textural maturity, suggesting longer transport of sediments. However, the presence of unaltered feldspars, the prevalence of limestone lithoclasts, and the dominance of chemically unstable pyroxenes and amphiboles amongst transparent heavy minerals suggest that the dune sands are mineralogically highly immature. The heterogeneous composition of the sands indicates a lithologically complex provenance. Dune sands that are composed of sedimentary (especially gypsum), igneous, and metamorphic rock fragments, and relatively short transport, suggest that a flood plain was the source area. This is supported by dominating winds blowing mainly from west and south-southeast, i.e. from the salt flat, clay flat, and river flood plain, and by the position of sand dunes, in the proximity of the potential provenance area. Moreover, the deflation of the alluvial fans and terraces probably triggered the formation of the sand dunes. In different parts of the world, desert deposits have been introduced as the provenance of aeolian sands because desert fields are fine-grained and due to the presence of alkaline salts, desert sediments are usually scattered easily (Madole et al., 2008; Alles, 2013). Moreover, the high amount of S in the samples of sand dunes and flood plain is due to the presence of hydrous calcium sulfate (gypsum) in the form of grains or cement in these sediments, which originates from the evaporate layers of the upper Red Formation and the brine. The origin is the brines from which gypsum was deposited and the difference in its value is a function of its concentration in the original brine (Aljubouri, 2011).

Climatic controls on the development of sand dunes

Mineralogical and sedimentological data indicate that the sand dunes were strongly controlled by climate as an extrabasinal factor (Muhs, 2004). The debris flow-dominated fans of the Qazvin Plain recorded a semi-arid to arid paleoclimate characterized by the formation of non-cohesive debris flow and calcrete (Davoudi et al., 2019). This climate is also represented by some sedimentary features such as red-coloration, interbedded mudflow, polygonal mud cracks, salt facies, and, gypcrete facies (Clyde et al., 2010) throughout the Qazvin plain. The scarce presence of plant root traces in the sand dunes represents conditions unfavorable for vegetation growth, presumably prevailing dry conditions. During dry periods, large amounts of sand were transported by winds from sub-environments of the Qazvin plain towards the central part of the plain.

Conclusion

During the Quaternary, gypsiferous aeolian sediments were deposited on the central part of Qazvin plain. The Qazvin sand dunes are composed of silt - to medium-grained deposits with moderately well sorting, fine skewness, and leptokurtic with no marine bioclasts. From sorting point of view, the deposits of Qazvin sand dunes are similar to "No difference patterns" proposed by Lancaster (1986). The studied aeolian sands are characterized by the predominance of gypsum and quartz, and stable minerals together with sedimentary, metamorphic, and volcanic fragments, and a few unstable pyroxene and amphibole minerals. The similarities in mineralogical, textural, and geochemical composition between the studied dunes and flood plain deposits indicate a genetic connection between them, which is confirmed by the direction of the prevailing winds. Consequently, the fine-grained sediments of the floodplain and the young terraces can be introduced as the main source of the sediments of the sand dunes. Also, due to the heterogeneous composition of the sediments of sand dunes, other sub-environments of the Qazvin plain can contribute to their formation. Gypcrete facies represents the relatively stable tectonic background and arid to semi-arid climate.

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