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Biogeomorphology of mega nebkha in the Fahraj Plain, Iran: Sensitive indicators of human activity and climate change

Somayeh Zahabnazouri [a,*], Peter E. Wigand [b], Ahmad Jabbari [c]

[a] Manager Director of Supporters of the Lut Desert NGO, Kerman, Iran
[b] Division of Earth and Ecosystem Sciences, Desert Research Institute, Reno
[c] Remote Sensing and GIS, Tehran University, Iran

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ABSTRACT

The biogeomorphology of nebkha dunes, was investigated in the Fahraj Plain, which is located in southern part of the Lut Plain in southeastern Iran. Field investigations were performed to determine nature of nebkha dunes, whose genesis and growth involves the trapping of aeolian sand within the body of a plant. This study demonstrated that *Tamarix*, a shrub/tree in the Tamaricaceae family, has played a major role in reducing dust and sand storms in the region by trapping aeolian sediments and accumulating them in the form of nebkhas. In contrast, another tree/shrub that grows in the area, *Prosopis cineraria* (a variety of mesquite in the Fabaceae family), due to its structure seems not to have played an important role in aeolian sediment accumulation or in shaping any nebkha dunes in the area. Whereas previous investigations indicated that the highest nebkhas, which are located at the western margin of the Lut basin on the Takab plain, were no more than 12 m in height, our field investigations and measurements revealed that on the Fahraj plain there are nebkhas greater than 20 m in height. This would suggest that some of these nebkhas are among the largest and highest that have been reported in the world. Some were connected by rows of Tamarix and formed very long ridges more than 200 m in length. It seems that their form may be due to human activity.

During our survey of nebkhas in the region we observed ongoing and increasing degradation in the nebkha field that we were examining. This seemed to be due to current climate variability and human impact. Investigation of the past climate of this region reveals that the Indian monsoon is and has been a major factor. Examination of this history also reveals the relationship between climate and sand movement in the region, and the inferred past history of nebkha dunes. Past analogue conditions from that history can provide a scenario of future nebkha evolution, and reveal if their current, ongoing degradation is a long-term trend or simply a short-term cycle.

1. Introduction

Ecogeomorphological landscapes can be best understood through examination and understanding of both geomorphological and ecological processes and the feedback between them (Stallins, 2006). With the rise of biogeomorphology and growing interest in earth surface systems and perspectives, which integrate the biosphere, lithosphere, and hydrosphere, there has been increasing investigation of the relationships between landforms and vegetation, and in particular between geomorphic and ecological processes. Because vegetation change is ongoing and dynamic (Martin, 1993), its impact upon geomorphic features reflects this relationship through change as well.

Nebkha are a common feature in almost all dune fields found in arid and semi-arid areas in tropical humid regions and in coastal to continental environments (Hesp and Walker, 2013). Nebkha have also been called bush mounds, phytogenetic dunes and mounds (Cooke et al., 1993), vegetated dunes (Tsoar, 2001), coppice and shrub-coppice dunes (Melton, 1940) or hummocky dunes (Gile, 1966; Pye and Tsoar, 2009).

Nebkhas play an important role in the stabilization of the ecological environment in these areas (Du et al., 2010). In fact, many researchers regard nebkhas as vital in maintaining the stability of desert and arid and semi-arid ecosystems (Kidron and Zohar, 2015; Luo and Zhao, 2019). Nebkhas are a unique geomorphic association of plant and sand that form or when sand accumulates around plants (Tsoar, 2001). They

* Corresponding author.
E-mail address: zahabnazouri@gmail.com (S. Zahabnazouri).

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are therefore an excellent demonstration of the relationship between biological and geomorphological processes in arid environments. A nebkha is a biogeomorphological feature that forms as a direct result of the interaction of plants, wind and sediments, and is indirectly influenced by other factors, including climatic conditions, and anthropogenic activities (Khalaf et al., 2014). Regional topography and water table also obviously play a role.

All nebkha are topographical obstacles formed by the entrapment of sediments within the roots or branches of a plant (Cooke et al., 1993). They are usually formed as a result of ecogeomorphic feedbacks controlled by the interaction of vegetation growth and aeolian sedimentation (Nield and Baas, 2008). The origin and development of nebkhas is closely related to the local establishment of vegetation, sediment availability, and wind activity, and reflect dynamic changes in regional climate and the environmental (Kocurek and Lancaster, 1999). Vegetation has a critical role in the geomorphological development of many coastal, semi-arid and arid landscape features. Their distribution throughout these areas often determines the location of nebkhas dunes, foredunes, and parabolic dunes and even of blowouts, but eventually become crucial in the complete stabilization of dune fields as well (Mountney and Russell, 2009; Hesp, 2013; Mayaud et al., 2016). Although originally formed due to the active deposition of sediments around trees, shrubs and bushes, they can also become stabilized or fossilized aeolian landforms (Cooke et al., 1993). The initial colonization of vegetation and the stabilization of both coastal and desert dune fields correspond with nebkha formation (Hesp, 2013).

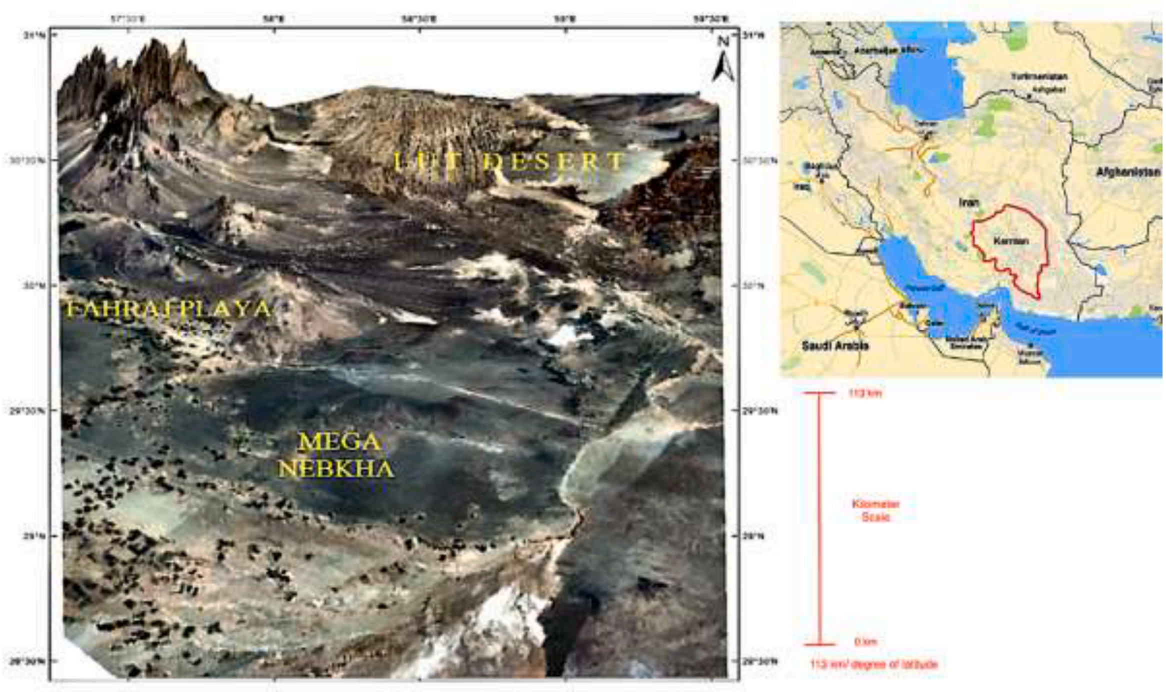
Because nebkhas, and other phytogenic dunes, are wide-spread in these regions, variations though time in the way they have accumulated can be used as a method of reconstructing environmental change and underlying climate change. Vegetated dune landscapes are sensitive to changes in overall plant vitality. For example, dormant dune systems may easily reactivate under worsening climate conditions (primarily drier global climate), and resulting decreased plant growth (Hugenholtz and Wolfe, 2005; Thomas et al., 2005).

Due to their important role in stabilizing the surface geology of arid areas, these features have been studied by many researchers (Du et al., 2010). The initial vegetation colonization and stabilization of both coastal and desert dune fields may begin with nebkha formation (Hesp, 2013). However, abiotic factors, such as water and nitrogen are the principal limitations on the growth of vegetation in desert regions Wainwright (2009). He suggests that the amount of nitrogen that is used by a plant to support its biomass and add new growth, varies linearly with rainfall. As such it is vital in the continuing ability of a plant to trap sand and maintain the growth of a nebkhas.

2. The study area

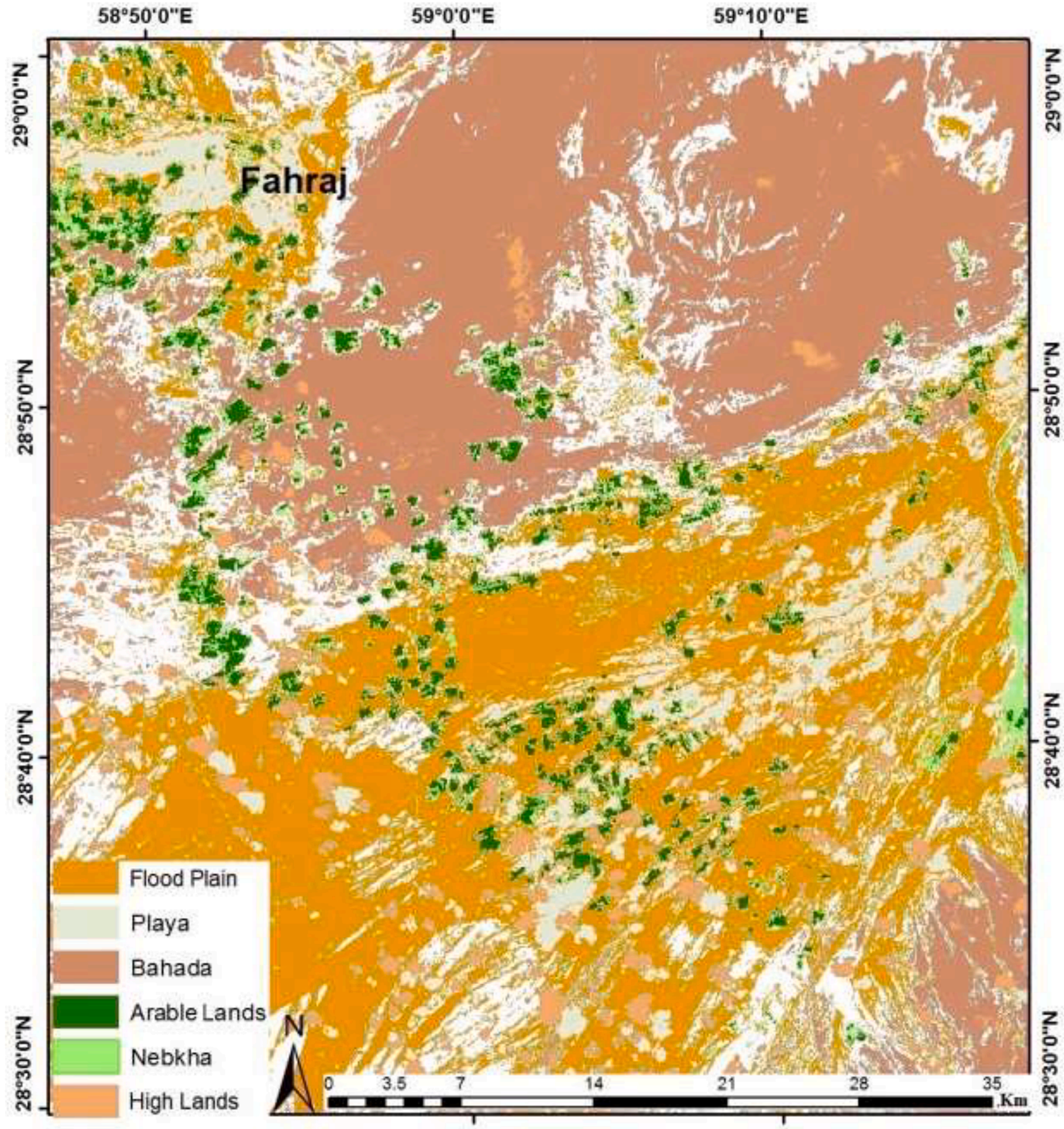
The Fahraj plain lies in the southeast of Kerman Province on the southern margin of the Lut Desert, which is locally known as Lut-e Zangi Ahmad (Fig. 1a). It lies ~62 km east of Bam, which was devastated during a very strong earthquake in 2003. Within the area there are two towns (Fahraj and Narmashir) and several tens of villages on this plain. The main road linking Kerman province to Sistan and Baluchestan provinces passes through this area and another major road extends from Narmashir towards the port of Chahbahar on the coast of the Sea of Oman. Citriculture and palm gardening are the main livelihoods of this region's residents.

The gross morphology of the study area is comprised of mountains, alluvial fans and bahadas and playa units. The Fahraj Plain is bounded on the north by low hills, which separate it from Lut Desert, and it is bounded on the south by the Jabal Barez, which has peaks up to 3700 m (12,140 ft) (Fig. 1). The Nesa Stream, which originates in these mountains, ends in a playa at the west end of the plain. The surface of the plain is primarily covered by sediments carried by this and other streams originating in the southern mountains. The fans originate at the foot of the mountains and are comprised of boulders and gravels at the mountain fronts and gradually become finer towards the middle of the plain, where they are primarily comprised of sands, silts and clays and intearfinger with the playa unit (Fig. 1b). The bahada, which is comprised of coalesced alluvial fans surround the medial playa. A major part of the bahada surface is covered by desert pavement. The distal zone bordering the bahada and playa is the main source of aeolian sands,



a.

Fig. 1. The Study Area: a. Three-dimensional view of the study area and its location in Iran south of the Lut Desert; b. land-forms in the Fahraj Plain study area.



b.

Fig. 1. (*continued*).

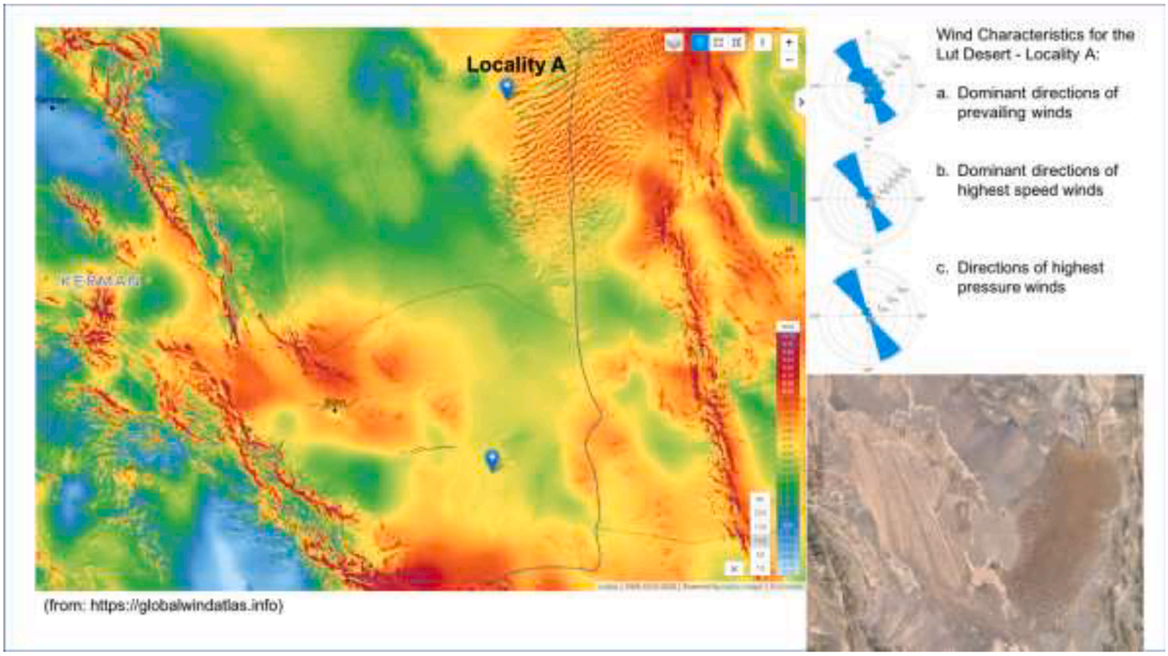
which have been transported along the playa surface and have formed the nebkhas. There is a mega nebkha field near one of the Fahraj villages named Hassan Abad Khoda Bandeh, we distinguish two main types of dunes in this region, 1) linear sand dunes whose morphology (Eric et al., 2009) displays a bimodal wind direction from the northwest and southwest, and 2) nebkhas (Fig. 1 b).

The average annual precipitation is ~70 mm (2.76 in) and the mean temperature is ~23 degreesC (73.4 degreesF) in the Fahraj Plain, reflecting an arid climate. Precipitation occurs mainly in winter and the driest season is during the summer when there are only negligible amounts of rain. The study area is part of a wind corridor stretching from north of Lut southeastward towards the Indian Ocean. A compass plot from between 1970 and 2003 of the annual wind direction and magnitude in the Lut Desert, north of the study area, reflects the predominance of unidirectional northwesterly winds (Ehsani and Quiel, 2008) (Fig. 2a and b). A regional wind system called "the wind of 120 days" predominates from May to September in east- central Iran (Goudie, 2007), and is best illustrated by the wind near the primary dune field north of the Fahraj Plain.

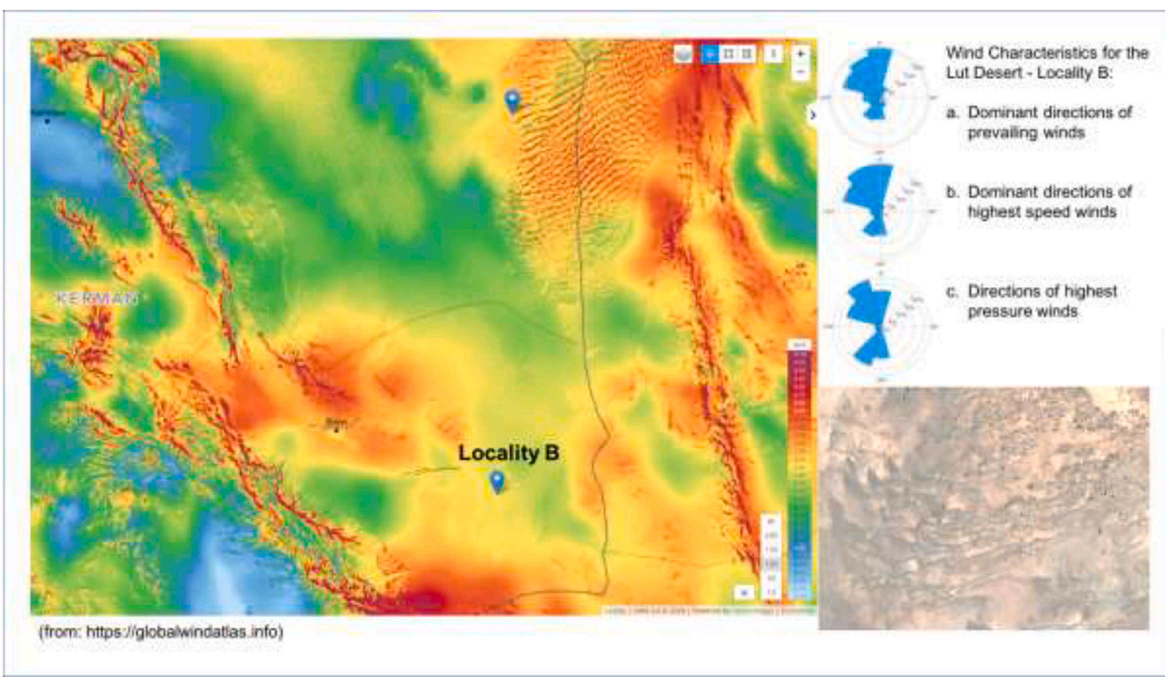
3. Methods

Remote sensing, and Bing and Google Earth imagery were used to conduct a preliminary study of the geomorphology of the study area and of the distribution of the dominant plant species. These were used to study the biomorphology of the nebkhas. Major geomorphological units were identified including: mountains, alluvial fans, playa surfaces, and streams.

To document the morphometrical parameters of the nebkhas, the maximum lengths, widths and heights of some large nebkhas were



a.



b.

Fig. 2. Wind characteristic of the Lut Desert and Fahraj Plain. Linear sand dunes show correspondence to the Wind Roses, a. Wind roses for Locality A in the center of the Lut Desert area, b. Wind roses for Locality, which lies in the Fahraj Plain study area.

randomly selected and measured in the field on randomly selected, and using SPSS software, their statistical characteristics were determined. Wind characteristics for the Fahraj Plain and the Lut Desert were derived from the https://globalwindatlas.info/ website, and correlated with the morphology of landforms in the study area.

In order to establish the potential Holocene history of Nebkhas for the Fahraj Plain-Lut Desert region of southern Iran the long-term regional record of monsoons in Iran and around the Indian Ocean must be documented. One of the authors (Wigand), who has worked in northeastern Africa, has contributed unpublished data from studies conducted in northwestern Sudan at Selima Oasis. The samples were collected by Dr. Peter J. Mehringer and Dr. C. Vance Haynes during field work The data consist of a record of sediment size analysis conducted in the Paleoecology Laboratory with Dr. Peter J. Mehringer (recently deceased) in the 1970s. Sediment grain size analysis was conducted on 50 samples from Selima Oasis using nested screens for the coarse fractions, and measurement of fine fractions using hydrometer measurements of samples added to 1000 ml graduated cylinders. Phi size measurements were calculated and mean, median grain sized distributions were calculated, as well as, sorting, skewness and kurtosis. Radiocarbon dates were run in the radiocarbon dating laboratory at Washington State University, and a deposition rate curve was calculated, and ages were assigned to each sample. Sediment parameters were plotted both by depth and by age.

4. Results

Measurements of Nebkha dimensions are presented in Table 1. The Length/Width Ration has also been calculated. The frequency distribution of the maximum widths, maximum heights and maximum lengths in meters of the mega nebkhas are shown in Fig. 3. The average length/width ratio is 1.25 indicating that they are conical nebkhas (Fig. 4).

Comparison of orientation of aeolian deposits within the Fahraj Plain study area and those of the central area of the Lut Desert with the wind roses derived from the https://globalwindatlas.info/ website show a strong correspondence (Fig. 2). Winds at the 1000 m elevation correspond with the direction of the regional wind system called "the wind of 120 days" which occurs in late spring through early fall. This correspondence is best demonstrated by the large linear and transverse dune fields that lie on the floor of the large basin of the Lut Desert proper (Fig. 2 a). In the Fahraj Plain the prevailing winds are more diverse, though still dominated by upper level winds from the northwest (Fig. 2b). The prevailing wind directions appear to reflect the orientation of the mountains flanking these basins.

Seven radiocarbon ages were obtained on carbonates by the Washington State University Radiocarbon dating laboratory (Table 2) from samples taken from Selima Oasis Hole 80–6. The radiocarbon dates were then converted to calibrated ages before the present (B.P.). These were then used to generate the deposition rate curve (Fig. 3). A two level polynomial curve fit was used to create the curve. Outlier ages were included in the generation of the curve. The deposition rate appears to increase upward.

The results of the analysis of sediment grain size are presented in Table 3. These data are plotted in Fig. 3a and b by depth and by age.

5. Discussion

5.1. Sand source

Our study shows that the main source of sediments, including sands, are locally derived from the distal ends of the alluvial fans bordering the playa. The mud-rocks comprising the yardangs also contain some sand, and these sands, which are released during aeolian sandblasting, are considered to be a second source of sand in this area.

Table 1
Morphometric parameters of mega-nebkhas in meters.

Sample	Height (m)	Length (m)	Width (m)	Length/Width Ratio
1	11.5	18.5	16.5	1.12
2	15	28	25	1.12
3	21	47	42	1.11
4	20.5	51	48.5	1.05
5	19.5	48	45.5	1.05
6	18	27	24	1.12
7	12.5	23	21	1.09
8	13	23.5	19.5	1.2
9	19.5	29.5	27	1.9
10	16	28	26	1.07
11	11	26.5	19	1.39
12	12	25.5	22.5	1.13
13	8.5	28	18	1.55
14	10.5	18	16	1.12
15	10	18.5	17	1.08
16	9	22.5	19	1.18
17	8	23	16	1.43
18	9	24	15.5	1.54
19	7.5	23.5	18.5	1.27
20	6	22	15	1.46
Mean	12.9	27.75	23.575	1.25
Standard Diviation	4.71	9.60	10.08	0.226

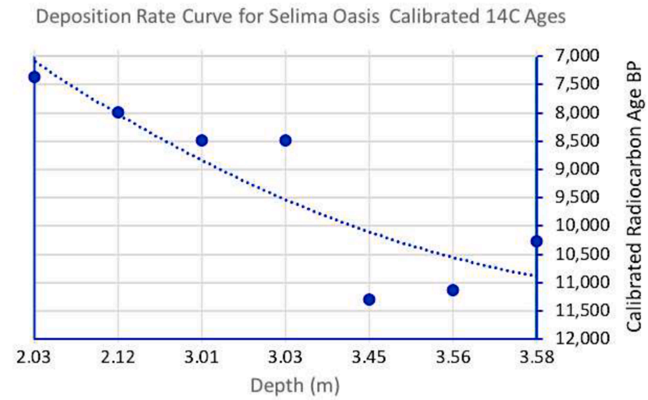


Fig. 3. Deposition rate curve for Selima Oasis Hole 80–6 generated from the calibrated ages in Table 2.

Given that the predominant winds blow from the southwest and northwest, the sands moving across the western alluvial fans must primarily come from the western bajada surface, and then form major sand dunes. Some of this sediment is then trapped by tamarix shrubs and forms nebkhas. In this region the nebkhas and parabolic dunes are very common landforms and reflect the complex interactions between vegetation, wind and sediment transport in the development of their classic shapes (Hesp, 2002)

5.2. Geomorphological characteristic parameters

Nebkhas are a type of phytogenic sand dune (Ardon et al, 2009) that commonly occur within the aeolian sand dunes of this region. In the Fahraj Plain they are found in the eastern, northern and western parts of the northern playa. According to the number of plants that occurs on the nebkhas, they can be classified into three different types: 1) single plant, 2) double plant and 3) grouped- plant nebkhas (Al-Dousari, 2017). The size and form of a nebkha depends on the size, density, and growth habit of the associated vegetation (Tengberg and Chen, 1998). Although nebkhas are with several different plant species, it is tamarix, which are native to the drier areas of Eurasia and Africa (Qong et al., 2002; Liu et al., 2008; Lang et al., 2013) that seems to be the most common plant associated with them on the Fahraj Plain.

In some regions nebkaha dunes may reach 10 m in height (Warren, 1988). But the height, long axis length, and short axis length of *Tamarix chinensis* nebkhas have been reported to reach 15 m in height, 50 m in length, and 25 m in width (Lang et al., 2013). The plan view of the typical nebkha can range from elliptical to nearly circular, and may be up to 5 m high and 25 m in length (Wainwright, 2009), and hemispherical in their elevation view (Wu et al., 2008). Normally, nebkhas evolve through three developmental stages: 1) initiation of the nebkha when aeolian sands are blocked by a shrub, 2) simultaneous growth of the nebkha and its associated shrub(s), and finally, 3) erosion of the nebkha and after the deline of the associated shrub for various reasons, i.e., drought, disease, human disturbnce (Tengberg and Chen, 1998). In the field, Nebkha morphology can be highly variable, but it depends primarily upon, primarily, the type and density of its vegetation cover (Al-Awadhi and Al-Dousari, 2013). However, it is the morphology of the associated plant species that is the primary factor in its efficiency to trap sand (Khalaf et al., 1995)

In the Fahraj Plain, sand forms range in size from small sandy mounds to huge nebkha dunes comprised of several shrubs with some nebkhas reaching more than 20 m in height, and up to 50 m in length. The dominant shrub is tamarix, and according to field evidence, the needle-like leaves, and density of the branches of these shrubs as well as their sticky exudations play a major role in stabilizing the shifting sands

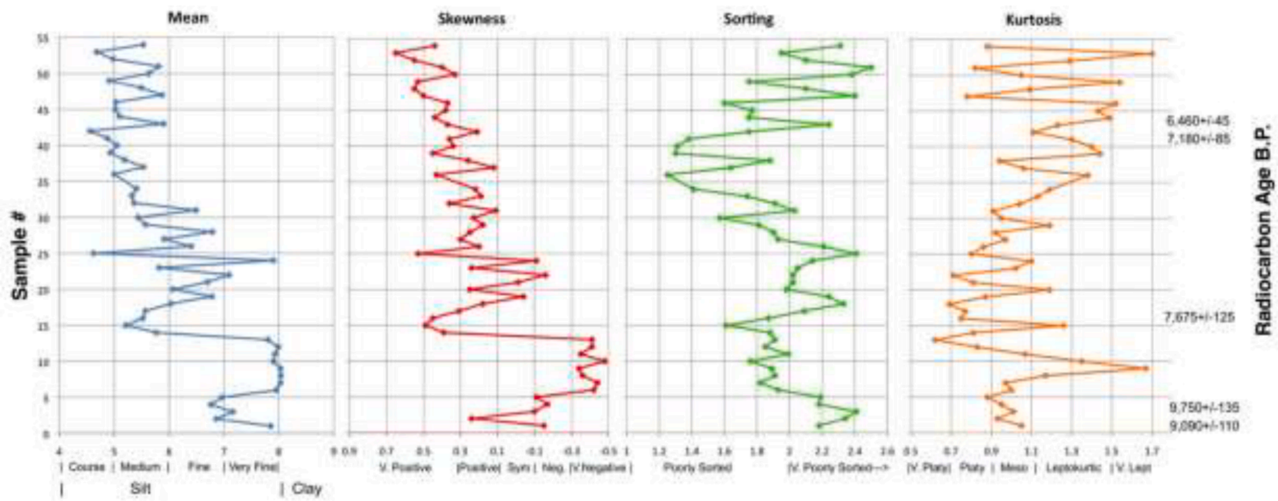


Fig. 4. Selima Oasis grain size parameters plotted by sample number from the base of the exposure.

Table 2
Radiocarbon Ages in Selima Hole 80–6.

Depth (m)	Laboratory #	Material Dated	C14 Age	Standard Deviation	Calibrated Age
2.0325	WSU-2599	Carbonate	6460	±45	7368 cal. BP
2.1150	WSU-2614	Carbonate	7180	±85	7997 cal. BP
3.0125	WSU-2510	Carbonate	7675	±125	8481 cal. BP
3.0300	WSU-2610	Carbonate	7680	±130	8487 cal. BP
3.4500	WSU-2603	Carbonate	9850	±90	11288 cal. BP
3.5600	WSU-2602	Carbonate	9750	±135	11127 cal. BP
3.5800	WSU-2601	Carbonate	9090	±110	10262 cal. BP

and growth of the nebkhas.

To document the morphometrical parameters of the nebkhas, the maximum lengths, widths and heights of some large nebkhas were randomly selected and measured in the field (Table1). The frequency distribution of the maximum widths, maximum heights and maximum lengths in meters of the mega nebkhas are shown in Fig. 3. The average length/width ratio is 1.25 indicating that they are conical nebkhas. The bimodal distribution of these graphs might suggest two generations of nebkha formation separated by a few decades or perhaps even hundreds of years. On the other hand, two different but major wind directions might be indicated. These might be seasonal in nature.

According to the IUCN Evaluation Report, 2016, nebkhas can reach up to 12 m or more in height, arguably among the highest in the world. However, our field measurements in the Fahraj Plain nebkha field revealed that there are considerably higher nebkha dunes in this region (Table 1; Fig. 5). The maximum height of 20.5 m, length, maximum length of ~ 51 m, and width of 48.5 m. Obviously these measurements do not cover the entire area and it seems that there maybe larger nebkha in this region. However, these data provide an indication of the nature of the nebkhas in this area. A more detailed description of the nebkhas of the Fahraj Plain will have to await additional field investigation.

Therefore, the aeolian geomorphology of the Fahraj Plain is comprised of a mega nebkha field that has an average maximum height of ~12.9 ± 4.71 m, and also a series of linear dunes. Nebkhas seem to be best developed wherever there is a sandy-gravel cover layer over the playa mud-rocks. In this situation a relatively impermeable layer (the playa mud-rocks) slows the percolation of water into deeper sediments, and the sandy-gravel unit allows water to percolate down to the impermeable layer where it becomes available to plants. The sandy-gravel unit also allows water to move laterally through it under the ground surface. In addition, evaporation is slowed by the sandy gravel unit as well (Fig. 6).

Development of nebkha forms primarily depends upon the density, distribution, height, and coverage of its plants and the speed or transport capacity of the wind (Hesp, 1983). In the Fahraj Plain it is apparent that nebkha vegetation, in this case tamarix and prosopis, obstructs the flow of the wind and reduces its speed so that sedimentary particles are forced to settle, because the wind velocity is slowed below that needed to keep them in motion (Table 4). The sediment is immediately deposited and begins accumulating within the branches of the plant that served as a biotic sand trap (Cooke et al., 1993). Therefore, the vegetation of the nebkhas winnow sand out of the wind and become the natural locus for inhibiting sand movement, and thereby effectively trap and hold wind eroded sediment (Du et al., 2010). Through time the plants continue to grow to avoid being buried by the accumulating sand and in doing so, generate the nebkha. As nebkhas grow they assume another role in the prevention of aeolian erosion.

In order for wind to erode and lift or entrain sand, it needs to reach critical velocities (Table 4). It is at that point that dunes and especially nebkhas play a second role in preventing aeolian transport. To reach the wind velocities required for erosion (shear) and entrainment, an unobstructed path or fetch is needed for wind to reach the required velocity. In desert or semi-desert regions the length of unvegetated patches, the potential fetch length, is the most important variable affecting aeolian erosion (entrainment) (Whitford, 2002/2020). If dunes or nebkhas lie within and obstruct the fetch, the wind cannot reach the critical velocities needed either to erode (reach wind shear) and entrain (transport) the sediment particles. Citing unpublished data by Herrick, Whitford indicates that in mesquite coppice dunes in the Chihuahuan Desert, in areas with high degrees of roughness due to the varying heights of coppices and dunes, the minimum fetch length for saltation was ~5 to 20 m with threshold wind velocities ranging between 18 and 35 km/h (Whitford, 2002/2020 Figure 4.1).

Whitford (2002/2020) indicates that reduction in canopy height and vegetation cover, and disturbance of the soil surface by grazers in these areas, especially during reduced rainfall or drought results in the creation of erosion cells, which when they grow large enough will have sufficient fetch length for wind speeds to reach velocities that will exceed the entrainment threshold speed. Once begun, and with ongoing drought, these patches will grow and sand deflated from their surfaces will bury vegetation on downwind dunes. Eroded patches will coalesce and become a major source for aeolian sediment. Flooding and subsequent erosion of these areas by streams emanating from the surrounding mountains will also enlarge them.

Therefore, dunes, and especially their vegetation, act both to stop

Table 3
Selima Oasis Age Dates and Sediment Data. Radiocarbon dated sediment units are marked in yellow highlight. (Unpublished data Mehringer and Wigand).

Selima Oasis, Sudan: Ages and Sediment Size Parameters							
Depth	Radiocarbon Age	Calendar Age	Mean	Median	Sorting	Skewness	Kurtosis
0	0	0	5.53	6.21	2.31	0.44	0.88
1.585	5037.687577	5761.367774	4.68	5.53	1.95	0.65	1.7
1.635	5196.605166	5943.114391	4.98	5.76	2.1	0.55	1.29
1.685625	5357.509225	6127.132841	5.81	6.6	2.5	0.4	0.82
1.736875	5520.399754	6313.423124	5.63	6.12	2.38	0.33	1.05
1.788125	5683.290283	6499.713407	4.91	5.47	1.75	0.53	1.54
1.839375	5846.180812	6686.00369	5.49	6.24	2.1	0.55	1.09
1.8975	6030.922509	6897.284133	5.87	6.75	2.4	0.5	0.78
1.955	6213.677737	7106.292743	5.03	5.35	1.6	0.37	1.52
2	6356.703567	7269.864699	5.02	5.36	1.77	0.38	1.43
2.0325	6460	7388	5.1	5.53	1.75	0.44	1.49
2.0575	6678.181818	7572.242424	5.9	6.32	2.24	0.37	1.23
2.085	6918.181818	7774.909091	4.56	4.63	1.75	0.21	1.11
2.115	7180	7996	4.87	5.14	1.38	0.36	1.3
2.155	7202.061281	8016.947075	5.05	5.27	1.31	0.34	1.4
2.205	7229.637883	8043.130919	4.93	5.21	1.3	0.45	1.44
2.255	7257.214485	8069.314763	5.19	5.46	1.88	0.26	0.94
2.305	7284.791086	8095.498607	5.53	5.55	1.64	0.12	1.06
2.355	7312.367688	8121.682451	5	5.24	1.25	0.43	1.38
2.4	7337.18663	8145.247911	5.4	5.54	1.41	0.22	1.19
2.431	7354.284123	8161.481894	5.32	5.4	1.74	0.19	1.13
2.493	7388.479109	8193.949861	5.36	5.8	1.91	0.36	1.04
2.525	7406.128134	8210.707521	6.49	6.55	2.03	0.11	0.91
2.58	7436.462396	8239.509749	5.43	5.61	1.57	0.23	0.95
2.625	7461.281337	8263.075209	5.57	5.7	1.81	0.18	1.19
2.6425	7470.933148	8272.239554	6.79	7.05	1.9	0.25	0.92
2.6525	7476.448468	8277.476323	5.91	6.31	1.93	0.3	0.97
2.6775	7490.236769	8290.568245	6.4	6.69	2.21	0.2	0.86
2.7075	7506.78273	8306.278552	4.62	5.5	2.41	0.53	0.8
2.738875	7524.087047	8322.708914	7.9	7.73	2.14	-0.11	1.1
2.783	7548.423398	8345.816156	5.82	6.12	2.05	0.24	1.02
2.81	7563.314763	8359.955432	7.09	6.82	2.02	-0.16	0.71
2.835	7577.103064	8373.047354	6.7	6.68	2.02	-0.01	0.81
2.865	7593.649025	8388.75766	6.07	6.36	1.98	0.25	1.19
2.89	7607.437326	8401.849582	6.78	6.63	2.24	-0.04	0.87
2.9175	7622.604457	8416.250696	6.03	6.29	2.33	0.18	0.69
2.95	7640.529248	8433.270195	5.57	6.06	2.09	0.31	0.77
2.9825	7658.454039	8450.289694	5.52	6.11	1.87	0.45	0.75
3.0125	7675	8466	5.21	5.68	1.61	0.49	1.26
3.0425	7788.69863	8613.39726	5.77	6.22	1.88	0.39	0.81
3.075	7911.872146	8773.077626	7.8	7.12	1.91	-0.41	0.62
3.1025	8016.09589	8908.191781	7.99	7.3	1.85	-0.41	0.83
3.135	8139.269406	9067.872146	7.93	7.27	1.99	-0.35	1.07
3.1675	8262.442922	9227.552511	7.9	7.15	1.76	-0.48	1.35
3.2025	8395.091324	9399.515982	8.03	7.43	1.89	-0.34	1.67
3.2425	8546.689498	9596.045662	8.04	7.36	1.91	-0.36	1.17
3.2775	8679.3379	9768.009132	8.03	7.36	1.82	-0.44	0.97
3.3125	8811.986301	9939.972603	7.95	7.3	1.93	-0.42	1
3.365	9010.958904	10197.91781	6.96	6.7	2.19	-0.11	0.88
3.435	9276.255708	10541.84475	6.76	6.33	2.18	-0.17	0.95
3.5025	9532.077626	10873.48858	7.16	6.84	2.41	-0.1	1.01
3.56	9750	11156	6.86	7.25	2.34	0.24	0.93
3.6025	9911.073059	11364.81279	7.85	7.57	2.18	-0.15	1.05

sediment that is already in motion, and they actually prevent sediment from being eroded and entrained by shortening the wind fetch. However, occasionally extremely high winds can entrain sand from the tops of dunes despite a shortened fetch. These concepts are critical for what we have observed is happening on the Fahraj Plain.

The change in desert ecosystems vegetation in is primarily influenced by climate, i.e., effective rainfall (rainfall and temperature), hydrogeological conditions, i.e., groundwater recharge, and, soil nutrients i.e., geology and organic productivity (Peng et al., 2004; El-Bana et al., 2002; Xu et al., 2017). Nebkhas are normally formed where the level of underground water is high or there is enough humidity for vegetal life (Bourke et al., 2009). Variability in the depth to the groundwater table directly impacts the vegetation in the study area today and has in the past. Previous studies have revealed that dune vegetation dies when the level of the groundwater drops beneath the root length of the vegetation growing on the nebkhas (Peng et al., 2004) If the groundwater supply is adequate, tamarix biomass will increase with branches rapidly growing new shoots and branches, which will provide more traps for sand, and accelerate the development of tamarix nebkha communities. These become more widely distributed over a larger area, and become densely clustered keeping ahead of burial by shifting sand (Li et al., 2010). Nebkha dune formation has a different growth function that requires vegetation that can tolerate large-scale sedimentation (burial) events in comparison to a pioneer grasses or successional shrubs (Melton, 1940). Because tamarix roots can sprout new branches continuously the during the formation of the nebkha, the age of tamarix nebkhas may approach or exceed more than a thousand years (Li et al., 2010). Therefore, giant tamarix nebkhas are the unique bio-geo-morphological landscape typically found in arid region deserts.

It seems that on the Fahraj Plain, the long-term establishment of vegetation in dune fields is related to depth to ground water below the ground surface. Vegetation establishment obviously occurred during periods of higher water table. During periods when the water table lowered, the vegetation died and the dunes became active again or were buried by active aeolian sands because vegetation growth could not keep up with the sedimentation rate (Fig. 7).

Prosopis (mesquite), a multipurpose tree or shrub, that provides a variety of products to people on the Fahraj Plain and supports various services to local communities, has in some cases negatively impacted the arid lands of Fahraj. According to field observations in the Fahraj area, no nebkhas seem to occur around Prosopis. On the Fahraj Plain we have found that soils in the arid region *Prosopis* jungles are cemented having a low water penetration capacity. Therefore, they seem to enhance flood events. Also, the surface sediments are active in *Prosopis* jungles, which suggests that this species does not play a major role in sand stabilization in the Fahraj region (Fig. 8). It is its branchless stem which prevents it from being an effective sand interceptor. In addition, *Prosopis* seems to exclude other plant species, decreasing the diversity of plant species associated with it. It also has other adverse effects affecting crop yields, as well as animal and human health. Despite its negative effects on the Fahraj Plain, *Prosopis* has potential uses as a fuel, charcoal, fodder, food, bio-char, bio-control, windbreaks, shade, construction and furniture materials, and soil stabilization (Abdulahi et al., 2017).

Therefore, we could say that this species does not seem to function in slowing aeolian sediment transport, and is especially does not aid in decreasing sand storms. Dust storms and shifting sand due to 120 days' wind are serious problems in Rigan, Fahraj and Narmashir in Kerman province, having caused damage to rural communities, properties and infrastructure (Middleton, 1986; Kaskaoutis et al., 2016; KNRWMO, 2016). They occur during the warm season, mid-May and continuously until mid-September (McMahon, 1906), due to the pressure gradient between the Turkmenistan (Hamidianpour et al., 2017; Kaskaoutis et al., 2016) or Hindukush high pressure (Alizadeh-Choobari et al., 2014) and the low pressure system common over the Rajistan Desert.

The shape of nebkha dunes in deserts also seems to be influenced by the changing sediment level around the nebkha (Wang et al., 2006) The dune formed within a plant roughly approximate cones, hemispheres or a dome (Nield et al., 2014; Al-Awadhi and Al-Dousari, 2013; Gillies et al., 2014). Some research suggests that during formation, the morphologic characteristics of nebkhas exhibit linear sand ridge, isosceles triangle-shapes, oval, and nearly circular stages (Zhu and Chen, 1994). Lines of nebkha form in some coastal and desert regions and may in some cases lead to the formation of vegetated linear dunes (Tsoar, 2013).

As we have indicated above, vegetation is the focus for dust deposition, because the flow resistance caused by the plant's branches, slows the wind flow and increases the rate of settling (Grantz et al., 2003). In addition, Whitford (2002); 2020) suggests that the shape of a shrub also affects the wind turbulence around it (Figure 4.2). He indicates that

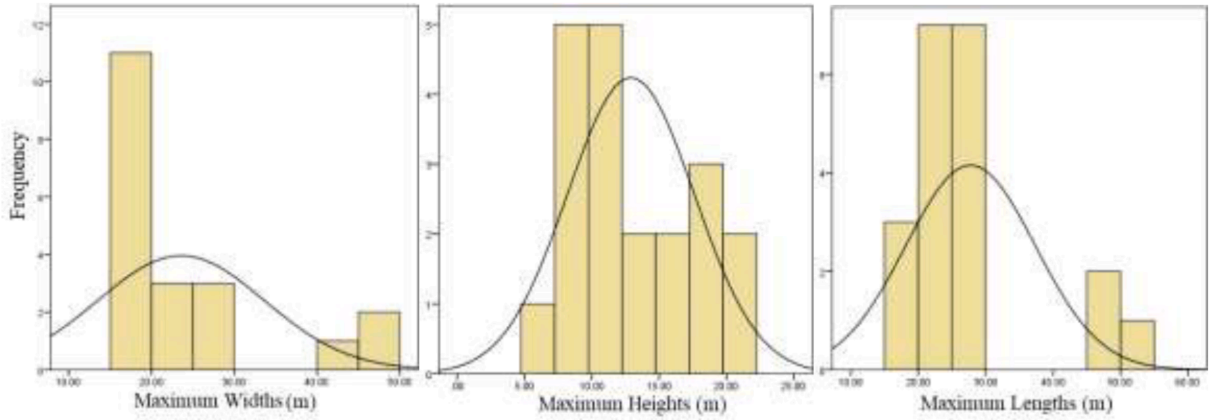


Fig. 5. Frequency distribution for the Maximum Widths, Maximum Heights and Maximum Lengths (m) of mega nebkhas.

Fig. 6. Nebkha more than 20 m high with a sandy-gravelly interdunal layer.

Table 4
Critical Wind Velocities During Nebkha Formation. Critical Wind Velocities Needed to Erode Sands, Maintain Sands in Motion, and Wind Velocity below which Sands are Deposited (.

Particle Size			Wind Velocities for Lower and Upper Range for each Size Class		
Wentworth Class	Krumbein phi (ϕ) scale	Size range (μm)	Wind Velocity above which Shear/ Erosion Occurs cm/sec	Entrainment Wind Velocity Range cm/sec (lower & upper limits)	Wind Velocity Below which Deposition Occurs cm/sec
Very coarse sand	0 to −1	1000–2000	38 to 53	5.9 to 37 9.8 to 50.5	5.9 to 9.8
Coarse sand	1 to 0	500–1000	25 to 38	3.5 to 27 5.9 to 39	3.5 to 5.9
Medium sand	2 to 1	250–500	21 to 25	1.8 to 20.5 3.5 to 27	1.8 to 3.5
Fine sand	3 to 2	125–250	19 to 21	0.90 to 20 1.8 to 21	0.90 to 1.8
Very Fine sand	4 to 3	62.5–125	21 to 19*	0.45 to 21 0.90 to 20	0.45 to 0.90

*These values are reversed because it takes a higher wind velocity to mobilize these particles than larger ones.

wind turbulence, due to interruption of the wind stream of low shrubs with a shape close to the ground, causes the deposition of litter and sand in the eddies on the downwind side of a shrub with a hemispherical crown. Shrubs with a conical shape and high profile let the wind flow relatively uninterrupted, resulting in sand and litter to be entrained into the wind stream, resulting in little or no sand deposition.

The dominant plant species found on nebkhas are all very capable of capturing aeolian sediments that are swept through the dunes from adjacent areas, and will promote the formation of nebkhas. However, it is clear that the size of a nebkha varies greatly depending upon the plant species found on them. This is, of course the result of the different sand trapping capacity of their associated plant species (Khalaf et al., 1995). The flow field structural changes caused by tamarix growing on the upper part of the nebkhas, plays a significant role in interrupting and even blocking the flow of sand. This focuses the area of dust settlement, and results in maintaining and promoting the development and growth of the nebkha (Li et al., 2010).

The properties of nebkha seem also to be influenced by other natural or anthropogenic landforms. In many cases human activities seem also to have had an effect on the development of regional nebkhas (Tengberg and Chen, 1998). They occur in unique shapes and sizes when distributed along irrigation channels, on abandoned farmland, and along the borders of cultivated lands in the overflow area of the transitional zone in the Fahraj Plain (Fig. 9). Previous studies have noted the impact of anthropogenic activity on nebkhas (Wang et al., 2006), e.g., extensive nebkhas have developed on arable lands in northern China (Wang et al., 2006).

Li et al. (2010) has indicated that *Tamarix* nebkhas are one of the

Fig. 7. Degraded and dead nebkhas caused by increased aeolian sand activity in the *Prosopis* jungle.

Fig. 8. This shows significant degradation of *Tamarix* nebkhas and active sand dune in an area dominated by *Prosopis* jungle.

most widespread type of nebkha. Field observations in this area as well as other areas in the Kerman region, e.g., in the Lut Plain (Maghsoudi et al., 2013) and in the Rafsanjan plain (Abbasnejad & Zahabnazouri, 2013) confirm that in these desert areas, *Tamarix* bushes are the main species establishing nebkhas wherever there is a coarse (usually sandy) layer overlying a clay layer. The main locations having such conditions are playas having a cover of shifting sands. Under such conditions the clay layer acts as an impervious layer over which porous sands allow water to accumulate and provides water for the establishment of vegetation that begins the formation of vegetative dunes.

An investigation of the variation of vegetation over different space and time scales, might better reflect the effects of interactions between ecology and geomorphology in complex earth surface systems (Nield and Baas, 2008). Once the nebkah has been established, shifting sands accumulate around and in its vegetation. This explains how a nebkha takes form. The shrub(s) will continue growing to avoid being buried by the sands, and the sands will continue to accumulate around the growing plant.

As a result of the presence of the nebkha, the underlying playa will be preserved from wind erosion. However, the surrounding bare surfaces are subjected to wind erosion, mainly by the process of sand blasting. As a result, with the passage of time, the surface of playa around the nebkha is gradually lowered. This then exposes the roots of the *Tamarix* and leads to its gradual drying, a process that takes many years. Afterwards, the sands that had been stabilized by the *Tamarix* erode and the exposed playa will be higher than nearby less exposed surfaces. Its initial height is gradually reduced due to renewed exposure to erosion. Sandblasting and deflation will eventually give it a very aerodynamic shape that becomes even more aerodynamic with time. This is the same process that forms yardangs.

5.3. Holocene history of southern Iranian dunes

Nebkhas clearly have some age in the region and examination of the past record of climate and records of sand movement in the Fahraj Plain and beyond indicate that cycles of dune formation, and most likely of nebkhas have characterized much of the last 14,000 years or more in the region (Vaezia et al., 2019). Cycles of periodic summer rainfall (periods of Indian Ocean monsoon intrusion) were followed by drought brought on by retreat of the monsoons and weak southward movement of Mediterranean westerly flow climate pattern. Shallow lakes formed and streams carried fresh sediments on the the valley floor during periods of monsoon intrusion. Droughts that followed evaporated the lakes and left salts and sands and silts to be eroded by the winds.

The record of Holocene monsoon incursions is well studied in

Fig. 9. Linear sand ridge nebkhas along arable land borders and abandoned irrigation channels on the Fahraj Plain.

northeastern Africa (Haynes, 2001; Pachur et al., 1990; Pachur & Hoelzmann, 1991; Hassan, 1997). Haynes (2001) compiled a list of the timing of Holocene lake duration in northeast Africa, that provides a detailed record of the timing and the latitudinal position of the monsoon in northeastern Africa during the Holocene (Fig. 10).

It is clear that northward movement of the monsoon was not gradual, but occurred almost simultaneously in the area between 16 and 25 degrees north latitude. The entire period of monsoon penetration during this period was centered between 12,500 and 9,000 cal. B.P.

Selima Oasis, located in northwestern Sudan, contains both a sediment and a pollen record (Mehringer and Wigand unpublished data; Haynes et al., 1989). The sediment record from Selima Oasis clearly records fluctuation in lake depth between 11,500 and 7,250 cal. B.P. (Fig. 11). Finer sediment is an indication of the expansion and contraction of the lake as well as of depth. During wetter episodes sediments were finer, because the sample location was more distant from what would have been the lake shore. At those times mainly finer sediments reached the site. During dry episodes when the sample location would have been nearer shore, or even exposed, aeolian sands were deposited at the site. Pollen counts from this record (Mehringer and Wigand unpublished; Haynes et al., 1989) indicate that vegetation during this period alternated between wet episodes characterized by grass and dry episodes in which grass is either rare or even disappears.

The monsoonal record from Iran should compare favourably with that of northeastern Africa. A Macrophysical Climate Model (MCM) reconstruction of Kerman's climate for the last 14,000 years indicates when monsoonal intrusions occurred in the region. This climate model was derived by Reid Bryson of the University of Wisconsin (Bryson, 1992). It is basically a heat-budget model predicated upon orbital forcing, variations in atmospheric transparency, and the principles of synoptic climatology (Bryson and DeWall, 2007). The climate of the last 39,000 years is reconstructed at 100-year intervals for the location of the weather station whose data were used in the model. The model input data include: mean monthly precipitation, mean monthly high temperature, mean monthly low temperature, and mean monthly temperature from the local weather station in the area of interest for the period of record or the thirty-year averages from 1971 to 2000. However, other monthly data can be entered into the model including: average monthly snow fall, monthly days below 0 degrees centigrade, monthly number of rainy days, as well as monthly evaporation data.

Comparison with the paleoenvironmental record from Jazmurian playa about 154 km south of the Fahraj Plain, indicate at least 17 episodes of Indian Ocean Monsoon intrusion followed by periods of aeolian activity (Vaezia et al., 2019). Comparison of the MCM climate reconstruction with the dated sediment record from Jazmurian Playa has some significant gaps in the sediment record, the longest one occurred during the middle Holocene between ~9,400 cal. B.P. and ~5,250 cal. B.P. and then a shorter one between 2,800 cal. B.P. and ~150 cal. B.P. (Fig. 12). The lacustrine sediments that accumulated in lakes during these periods most likely comprise the dune fields of the region today.

The middle Holocene lacustrine record that is missing from Jazmurian must be represented in dunes that were formed after ~5,200 cal. B.P. These sediments would also be included in the aeolian sands of the Jazmurian record between ~5,200 and ~2,700 cal. B.P. And finally, the hiatus in the sediment record from ~2,700 to just a hundred or so years ago, is probably present as reworked sands in today's dunes around Jazmurian Playa today.

It is clear that sands that have been washing into Jazmurian Playa throughout the Holocene have probably been reworked numerous times. Sometimes they were incorporated as dunes downwind of the playa lake and also as dune sands accumulating in the bottom of the dry playa ephemeral lakes that filled the playa.

The same pattern would have characterized the playas of the Lut Desert and Fahraj Plain to the north. Episodes of wetter climate were

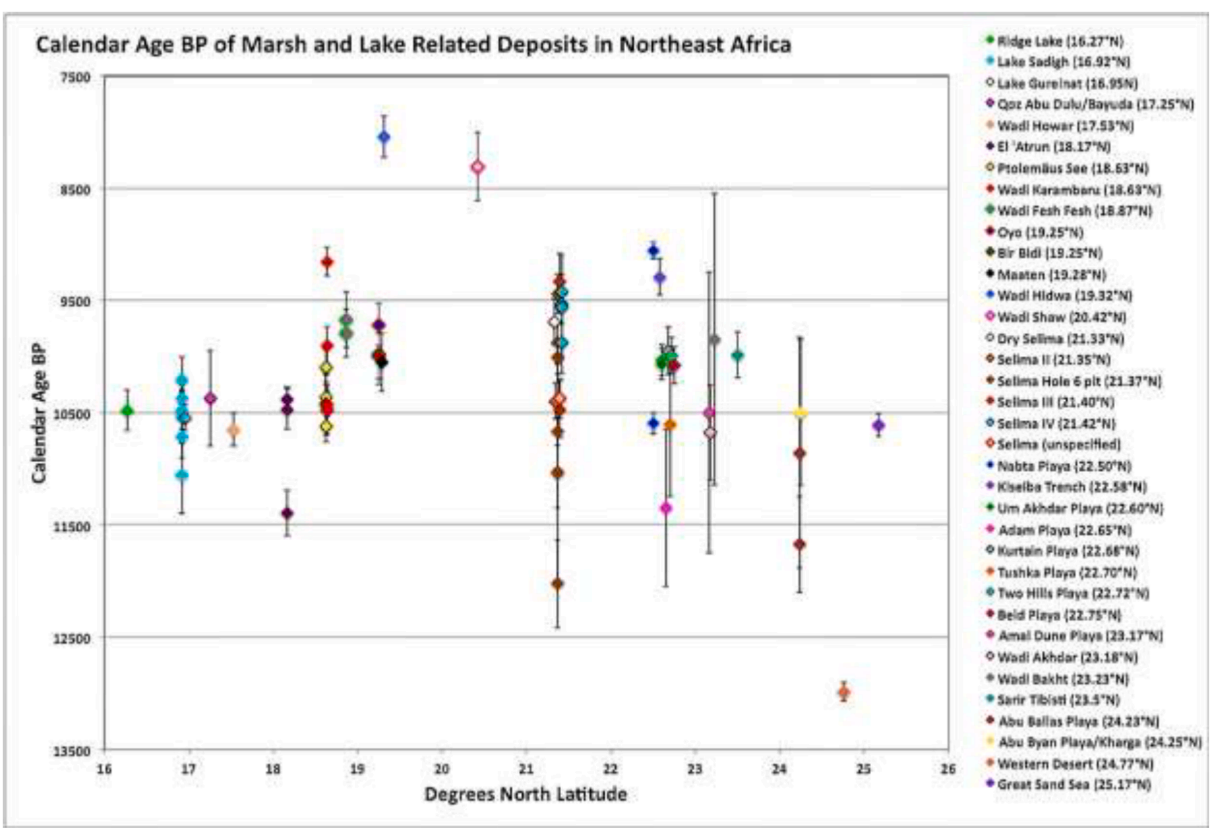


Fig. 10. The mean calendar age and duration of lake and marsh deposits in Northeastern Africa plotted by their position in degrees north latitude (data from Haynes, 2001; Pachur et al., 1990; Pachur & Hoelzmann, 1991; Hassan, 1997).

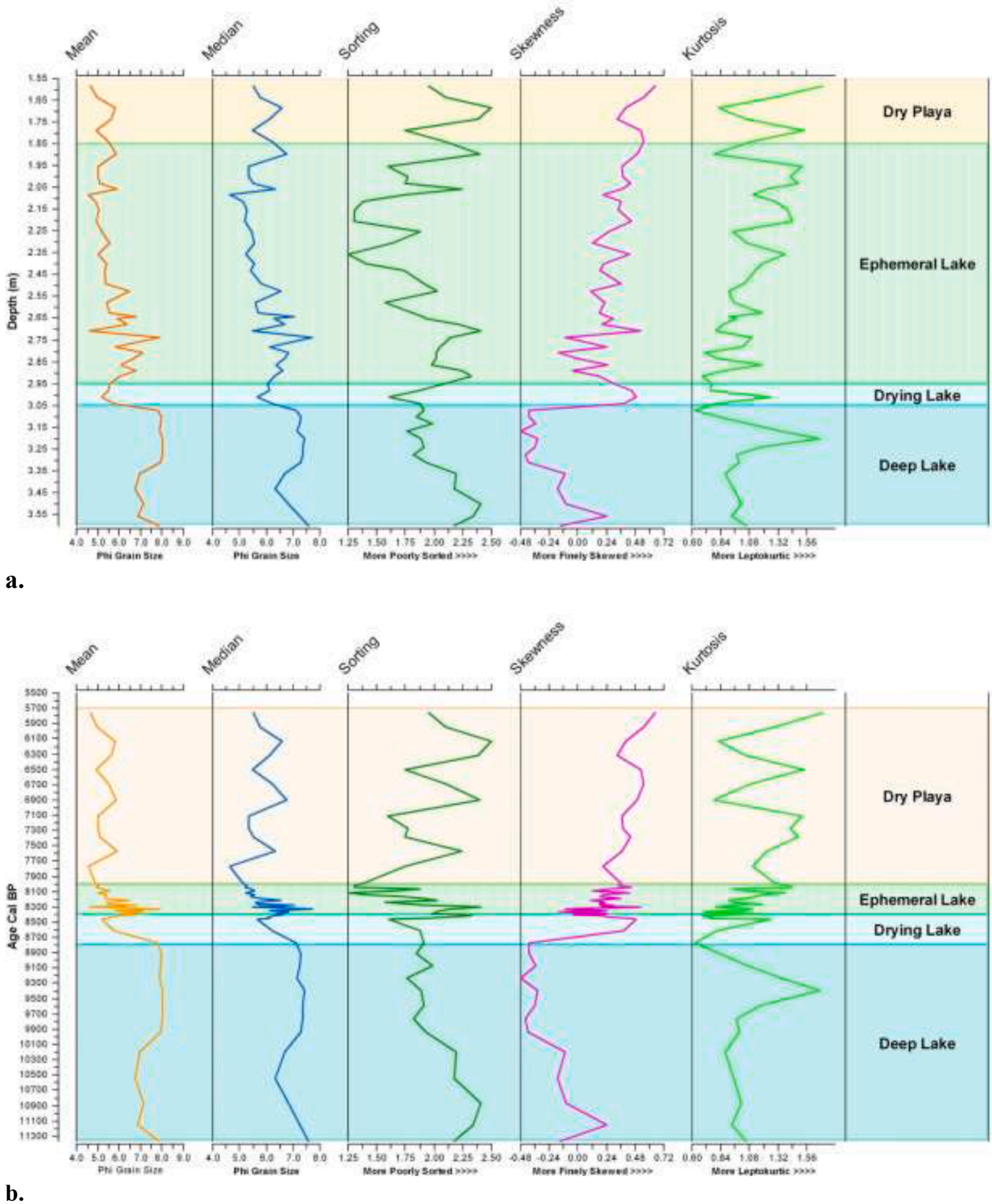


Fig. 11. Grain size parameters plotted by depth (a) and by calibrated age before the present (b).

probably characterized by stabilization of dunes, whereas dry cycles were characterized by the demise of dune vegetation cover, and remobilization of their sands. The only thing that would have halted the ongoing deflation of these basins would have been layers of carbonate or salt cemented sediments, such as those that today serve as the bottom of perched water tables today.

Although many of the dunes may represent reworked sands that have been washed into the basin throughout the Holocene, there may be some dunes, that due to their size and stability, preserve older dune units in their cores. Dating of these deposits may coincide with some of the older aeolian units that appear in the Jazmurian Playa record, or some may also date to the periods of aeolian activity hinted at in the mesoscale climate model from Kerman in Fig. 12.

Macrophysical Climate Model reconstructions of the Holocene

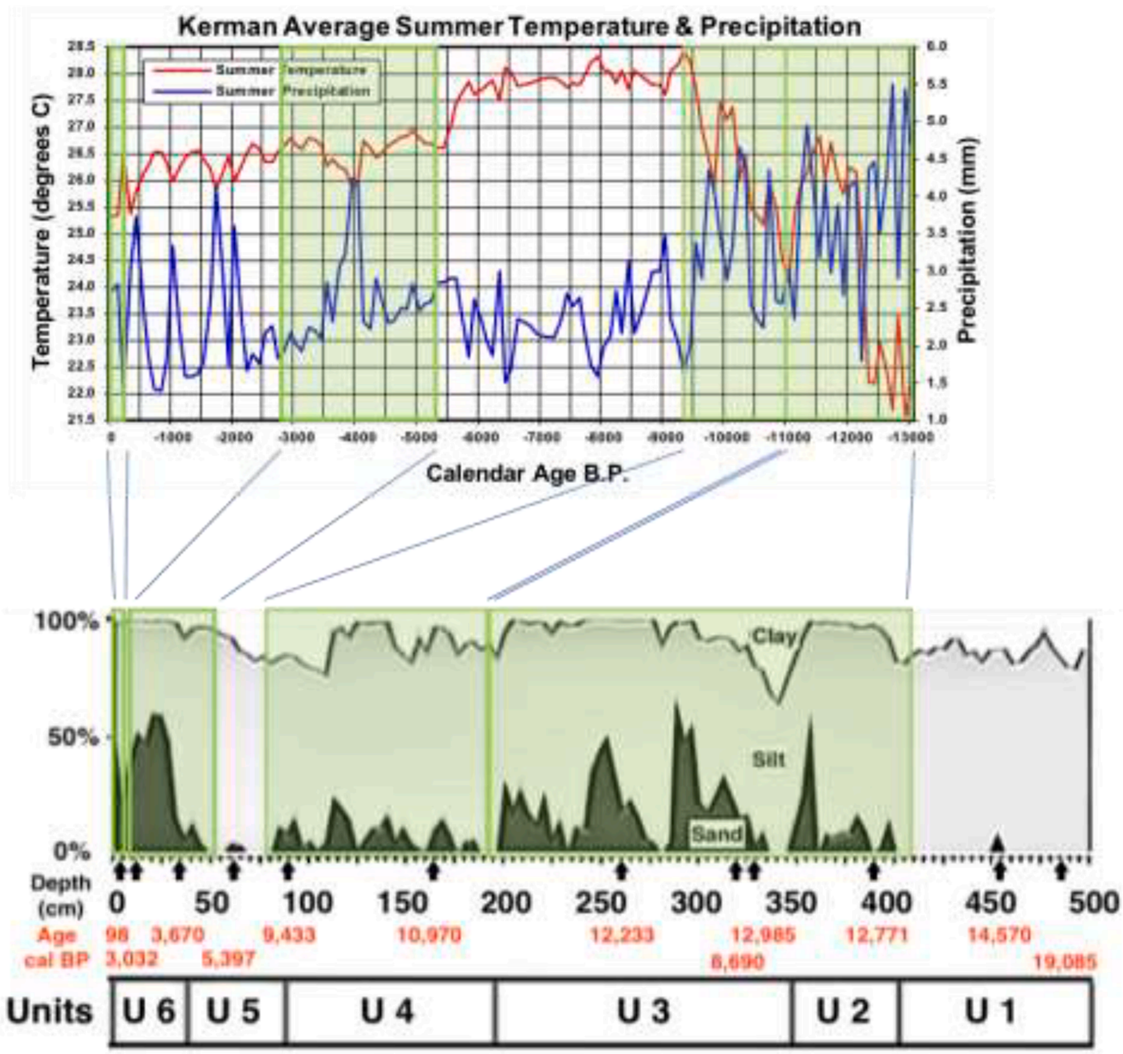


Fig. 12. Comparison of the MCM modelled climate of Kerman with the sediment record from the Jazmurian Playa. Areas in the MCM model reconstruction at the top are not represented in the sediment record of the Jazmurian Playa sedimentary record, they have been deflated.

climate of western Iran, and records of grass pollen abundance recovered from lakes in western Iran as far north as Lake Urmia reveal a Holocene climate record that tracks the northward movement of the monsoon front, and incursion of Mediterranean storms from the west (Figs. 12 and 13).

The monsoon clearly began after 14,000 cal. B.P. years ago in western Iran and lasts until about 9,000 cal. B.P. The magnitude and duration of the monsoon episodes are dependent upon topography, and proximity to the Indian Ocean, but it does appear that it may have reached as far north as Hamedan, but not to Tabriz. Tabriz's early Holocene wet episodes seem to have been related to storms sweeping into Iran from the west across the Near East from the Mediterranean (Fig 14).

Grass Pollen (as a measure of moisture) records from three lakes in western Iran, Lake Mirabad, Lake Zeribar, and Lake Urmia also reveal Holocene wet episodes and the MCM reconstructions of climate (Fig. 12).

Clearly the time span of the Lake Zeribar grass abundance record compares well with the time span of the MCM model reconstructions from western Iran for the period of monsoon dominance, and the Lake Mirabad record does cover the last part of the Zeribad monsoon record. The Lake Urmia grass pollen record compares favourably with the MCM reconstruction for Tabriz's climate as well.

Although dating of aeolian activity in Iran will require great effort, the evidence of episodic monsoonal penetration into Iran from the south suggests that cycles of lake alternating with dune formation has characterized the region for much of the Holocene. Although episodes of late Holocene monsoon seem to have only have penetrated into the southern portion of Iran, it may clearly have been responsible for formation of the dunes that are seen on the landscape today. However, beneath these dunes may lie much earlier dunes. A record of the magnitude of these cycles would provide a reliable estimate of what might be expected under future scenarios of global temperature warming. The decline in the dunes of the Fahraj plain seem to be due to the combined impacts of both highly variable monsoon penetration and of well drilling which deprives the deeply penetrating roots of both Tamarix and Prosopis of water.

6. Conclusions

As suggested in the article, there are significant relationships between the size and distribution of nebkhas developed on abandon arable land or close to cultivated land. Nebkhas developed in rural areas close to farmland and irrigation systems are far higher than those developed in other areas. It is apparent that the greater concentration and height of nebkhas established close to rural area are provided with a sufficient water supply to support *Tamarix* vegetation. In addition, palm gardens act as wind barrier reducing wind speed, which reduces the sediment carrying capacity of the wind and therefore allows more aeolian

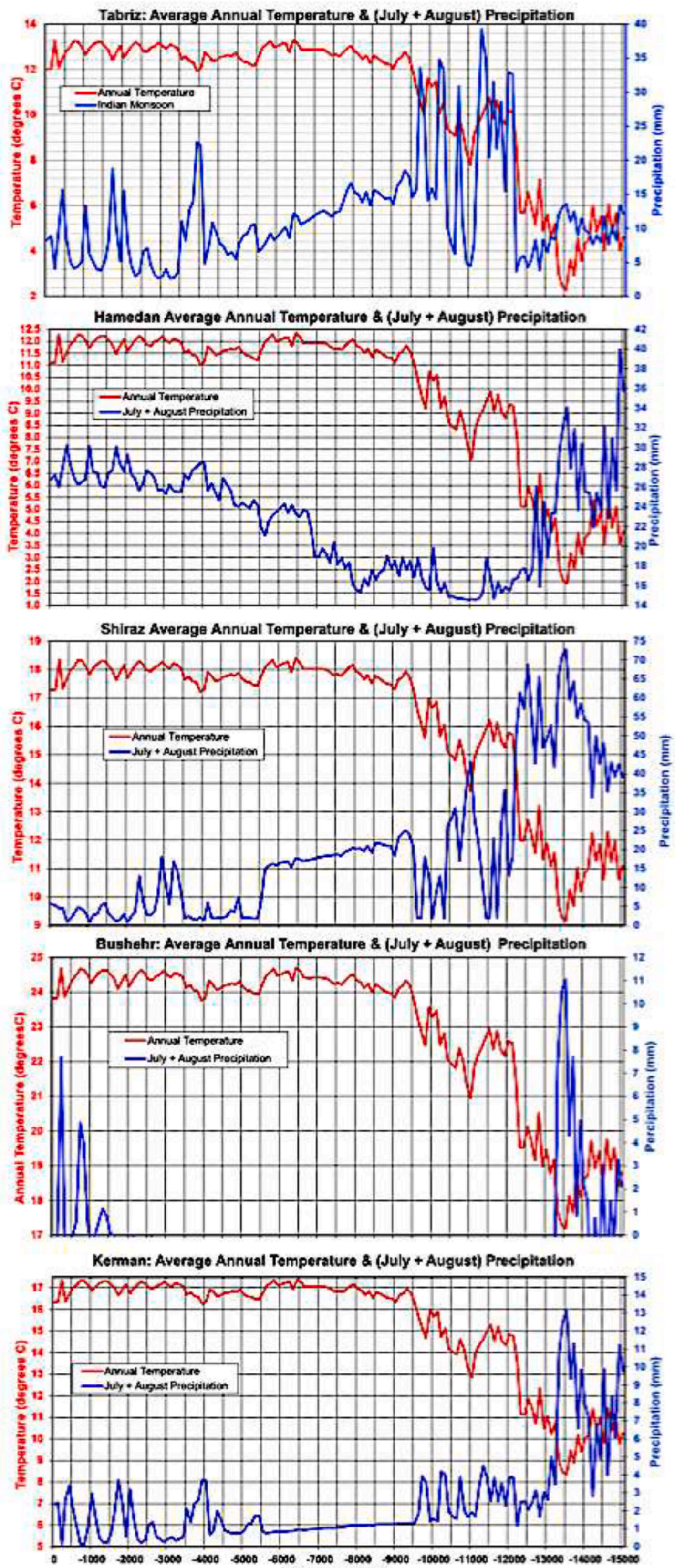


Fig. 13. MCM models of five locations in Iran arranged from Kerman in the south (at the bottom) to Tabriz in the north (top).

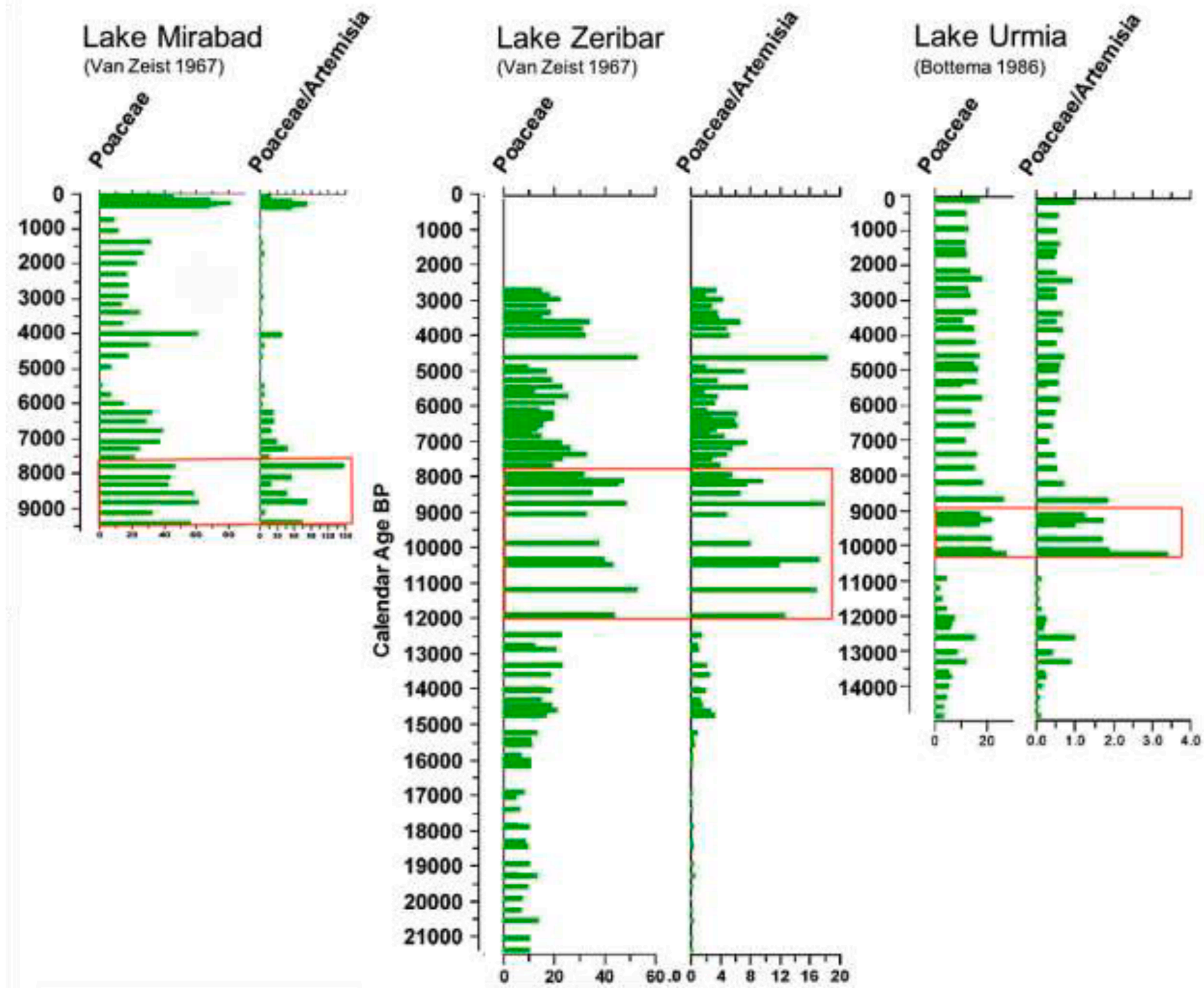


Fig. 14. The grass pollen percentages and ration of grass pollen to sagebrush pollen from the three major pollen records from western Iran. Grass pollen is an indicator of wetter climates, and an increase in the ratio of grass pollen to sagebrush would indicate wetter climates as well. Grass does particularly well during episodes of summer rainfall.

sediment to be deposited close to rural arable land.

Field studies undertaken in the Fahraj Plain combined observational descriptions and measurement of the morphology of the nebkha to reveal relationships between them and the vegetation that appears to aid in their formation. The nebkha in the Fahraj plain may include some of the highest in the world measuring more than 25 m in height. Based upon the studies of our colleagues, we suggest that research on nebkha formation has begun to provide distinct clues about environmental changes in the Fahraj region; however, expanded and more detailed studies are needed to determine the exact role that climate change and vegetation response play in the formation of the nebkha. Distribution of nebkha dunes shows that changes in vegetation type plays a crucial role in the formation of a nebkha. In particular, the shrub, *Tamarix*, is vital in the establishment, formation and growth of nebkhas. Prosopis have taproots that go deep into the water table…they will survive longer than the tamarix, which are more shallowly rooted. But the Prosopis growth form is less conducive to slowing the wind down to form dunes. However, it also appears that where *Prosopis* (which has a deeper root system) has colonized and replaced *Tamarix*, the nebkhas are being degraded and destroyed. It is apparent that although *Prosopis* can reduce wind speed when used as wind breaks, its growth form is not as an efficient sand trap as *Tamarix*, and is therefore is not as useful for protecting land from wind erosion. As a result, it may actually intensify the desertification of the Fahraj plain.

Well drilling, water mining, will also result in the death of the tamarix. But this is being exacerbated by the unreliable nature of the Indian Ocean monsoons too. Both mesquite and tamarix rely on the monsoonal rains, and it is clear that they did during the late Pleistocene and the Holocene as well, However, when the monsoon becomes unreliable they begin dying as well. Therefore, dunal vegetation is being assaulted both by water mining and unstable climate. And as they die, it is a very good possibility that the dunes will become increasingly unstable, and aeolian erosion will increase.

Additional field work and research examining a range of nebkha morphologies with different vegetation species and densities is required to validate and further refine these findings.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Jr. Although both sediment and pollen samples were processed in the early 1980s, the data were never published. Because they are a valuable contribution to the palaeoecological record of northeastern Africa and compliment the published data of Dr. C. V. Haynes and his colleagues, and because of the recent death of Dr. Peter J. Mehringer, we thought that it would be a fitting time to present these findings.

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