



# Evolution of sedimentary environments and geography of the Gavkhouni Playa during the Late Quaternary

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## Abstract

Gavkhouni Playa, as lowland of the Zayandehrud River catchment area, is located in an inter-mountain basin in Central Iran. A total of 16 sedimentary cores were taken from the inner and outer parts of the basin, and surrounding areas to investigate depositional systems of the Gavkhouni Playa during the late Quaternary. Sedimentary facies were identified based on sedimentary texture, type of evaporite minerals, presence of organic materials, color changes, and other microscopic characteristics, and sampling was performed based on changes in types of sediment and sedimentary facies. A total of 80 sediment samples were selected for granulation analysis by two methods of wet sieving for coarse-grained particles and Laser Particle Sizer Analysette for smaller than sand (silt and clay) particles. Sedimentology parameters were measured by the Sedilizer software, and the results were statistically analyzed by the SPSS software. The major types of sediments in the Gavkhouni Playa sub-surface, mud and sedimentary environments included aeolian, fluvial, deltaic, lacustrine, and playa environments. According to <sup>14</sup>C-AMS isotope dating analysis, the sedimentation rate for 40 ka period, is about 0.4 and 0.25 mm in western and eastern parts per year, respectively. Paleogeography of the Gavkhouni Playa and its extent have been reconstructed for the last 40 ka BP. The results showed that the Gavkhouni Basin extended to the western part of sand dunes during the late Pleistocene. During the early-middle Holocene, coastline regression and the Zayandehrud Delta progression toward the playa occurred in the northern part of the area. During this time, aeolian sands spread to the Gavkhouni Playa. In the Late Holocene, arid conditions caused a decrease in water level and coastline regression along with the domination of the playa environment in the Gavkhouni margin. But, there were still ephemeral lake conditions in the center of the Playa. Gavkhouni Playa experienced an increase in the level and progression of the coastline towards land about 3000 years ago. The presence of arid conditions about 1000 years ago (cal. BP) changed the Gavkhouni lands into a playa environment, and this situation was dominant in the area almost to the present day.

**Keywords** Paleoclimate · Paleogeography · Sedimentology · Late Pleistocene · Holocene · Gavkhouni Playa

## Introduction

Identification of climate changes is important for understanding paleoenvironmental characteristics (Hamzeh and Farahi Ghasr-Aboonahr 2020). Sedimentary evidence of closed basins can be one of the most important methods for identifying climatic periods and changes in sedimentary environments (Kwak et al. 2016). Changes in the shorelines and water levels in inland lakes can be reconstructed using the indicators, such as sedimentology (changes in the sedimentary nature), stratigraphy (lithology and granulometry), geochemical, mineralogy, paleoecological (diatoms, ostracoda, and shells), and archeology data, and changes in the sedimentation rate (Damnati et al. 2016). Sub-surface sediments of the playa are important indices of local

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climates (Brisset et al. 2018), and they provide valuable and important high-resolution sedimentary and geochemical archives to investigate paleoclimate and important hydrological changes in the basin (Abdi et al. 2018). Changes in the sedimentation are reflected in the physical and chemical properties of the sediments that can be used to identify sedimentary processes and sedimentary paleoenvironments (Kirillin and Shatwell 2016). Climate change and monitoring its mechanism, especially during the Quaternary have been extensively studied in the literature. One way to investigate such changes is by reconstructing surface shapes in sedimentary environments. Adaptation to climate change on a regional scale often depends on the understanding of geomorphological responses to these changes (Harrison et al. 2019). Geologists have focused their attention on the history and evolution of the earth's morphology for a long time, and this kind of knowledge is obtained using the evidence recorded in the earth's historical memory. Meanwhile, a high rate of sedimentation protects the existing archives and allows for high resolution investigation (Hamzeh and Farahi Ghasr-Aboonaser 2020). Therefore, studying the history of sedimentation in saline lakes is one of the important methods in understanding hydrological conditions and paleoclimate in the arid and semi-arid areas (Last and Ginn 2005). There are several lakes in the arid and semi-arid lands of Iran due to its special climatic characteristics and relatively low annual precipitation, which are very important in terms of paleoenvironment, geology, climate, geography, and ecology (Brisset et al. 2018). During the last decade, in Iran, studies on climate and Paleoenvironment include Urmia lake (Bottema 1986; Kelts and Shahrabi 1986; Djamali et al. 2008), Neor lake (Sharifi et al. 2015), Zaeribar lake (Van Zeist and Wright 1963; Stevens et al. 2001; Wasylikowa et al. 2006), Mirabad lake (Stevens et al. 2006), Almalou lake (Djamali et al. 2009), Maharlou lake (Fayazi et al. 2007; Brisset et al. 2018), Parishan lake (Noorollahi et al. 2011), Meyghan lake (Abdi et al. 2018), Shadegan wetland (Bogemans et al. 2016, 2017), Concerning Gavkhouni Playa, Taghavi et al. (2014) analyzed climate change in the northern part of the Playa according to chemical sedimentary (major and minor elements). They identified several dry and wet periods in low depth cores. Ghahroodi Tali and Khedri Gharibvand (2017) study morphological approach in the playa management strategy. Tabaei et al (2019) studied environmental changes in the early Holocene in northern Gavkhouni and southern Isfahan through palynology. Identifying climate change during the Quaternary is essential for understanding the importance of the natural environment characteristics, as well as a better understanding of the current climate (Abbas et al. 2016). Paleo-geomorphological studies and identifying the history of the past changes in this wetland can help

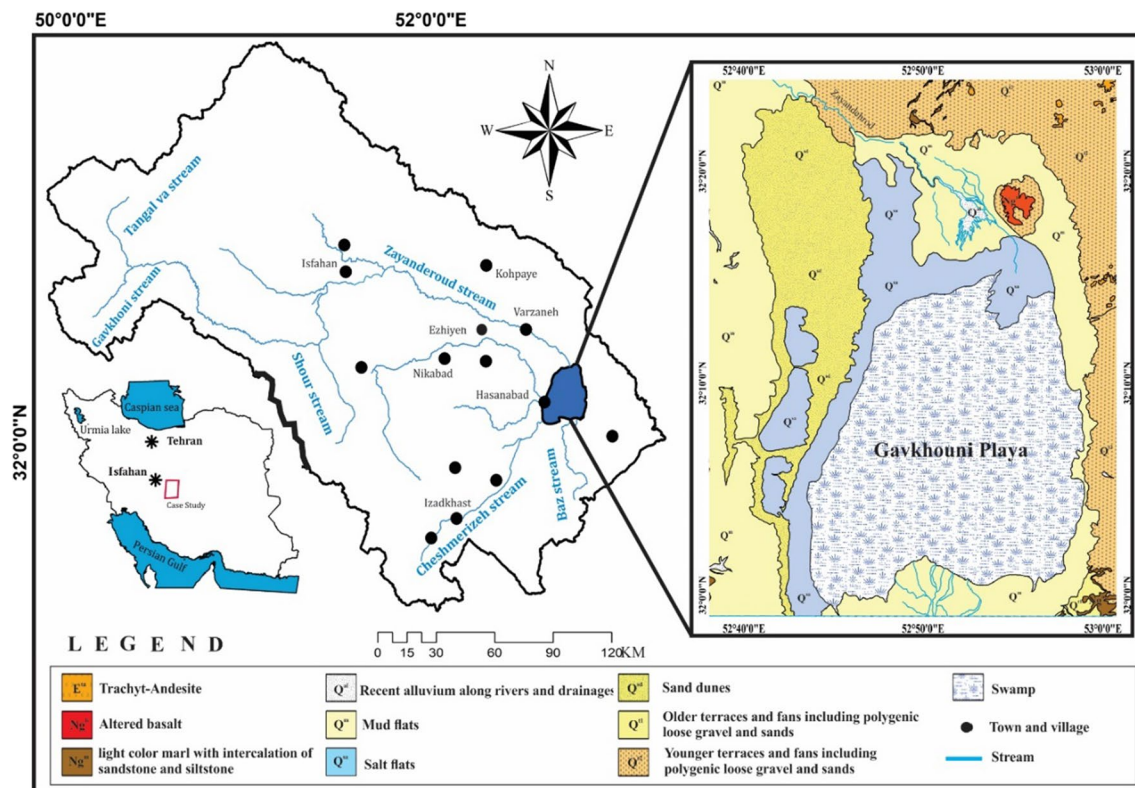
understand which factors contributed to wetland drought and water level changes in the past. Those change patterns, then, can be used to analyze present conditions and future variations of other parts of the country, which are identical to Gavkhouni Playa. Although the previous studies conducted in Iran have generally clarified climate change, paleoenvironment, and geomorphology, further studies are required to obtain a clear picture of this situation in central and other parts of the country. Although, meteorological data are the most accurate data for this type of study, and in terms of time, they have been able to only identify the climate for the past 60 years. Hence, it is necessary to study paleoclimate and geomorphology that will lead to the production of long-term data. On the other hand, the data obtained from such studies are among the most fundamental inputs for modeling paleoclimate and reconstructing and discovering the cause of climate change. In this study, we attempted to reconstruct climatic conditions and geomorphology of the Gavkhouni Playa during the Late Pleistocene and Holocene through the sedimentological and paleoenvironmental investigations.

## Study area

Gavkhouni Playa, with an area of about 550 km<sup>2</sup> is located 130 km southeast of Isfahan, between the longitude of 32° 00' north and 32° 23' and latitude of 52° 43' and 52° 49' east. Gavkhouni Playa is located in a mountainous area in Central Iran and its altitude is about 1474 m above sea level. Gavkhouni Playa is one of the basins separating the Urmia-Dokhtar Tectonic Zone from Central Iran, located parallel to the Zagros' overthrust. Its structural system is graben to half-graben, resulting from orogeny and volcanic eruptions during the late Cretaceous and early Eocene. Its main source of feeding is the Zayandehrud River, some seasonal rivers and streams that lead to the playa directly (Pakzad and Fayazi 2007) (Fig. 1). The average over a period of 20 years in 8 meteorological stations around Gavkhoni Playa for humidity is 30.15%, rainfall is 0.25 mm per year, temperature is about 17 °C and wind speed is 3.5 m/s.

## Materials and methods

The western part of Gavkhouni Playa is limited to the sand dunes of Varzaneh city and the margin of the playa is limited to mud and mud-salt flats. The main body of Gavkhouni Playa is covered with thick layers salt deposits. These salts have a high sedimentation rate and during a decade it reaches a thickness of more than 2 m and is affected by dissolution in wet seasons. Due to the fact that in the current



**Fig. 1** Location of the Gavkhouni Playa, Zayandehrud River catchment area, and geological units around the playa (Geological Survey of Iran 2017)

**Table 1** Location and some characteristics of the extracted cores (error rate of elevation from sea level  $\pm 3$  m)

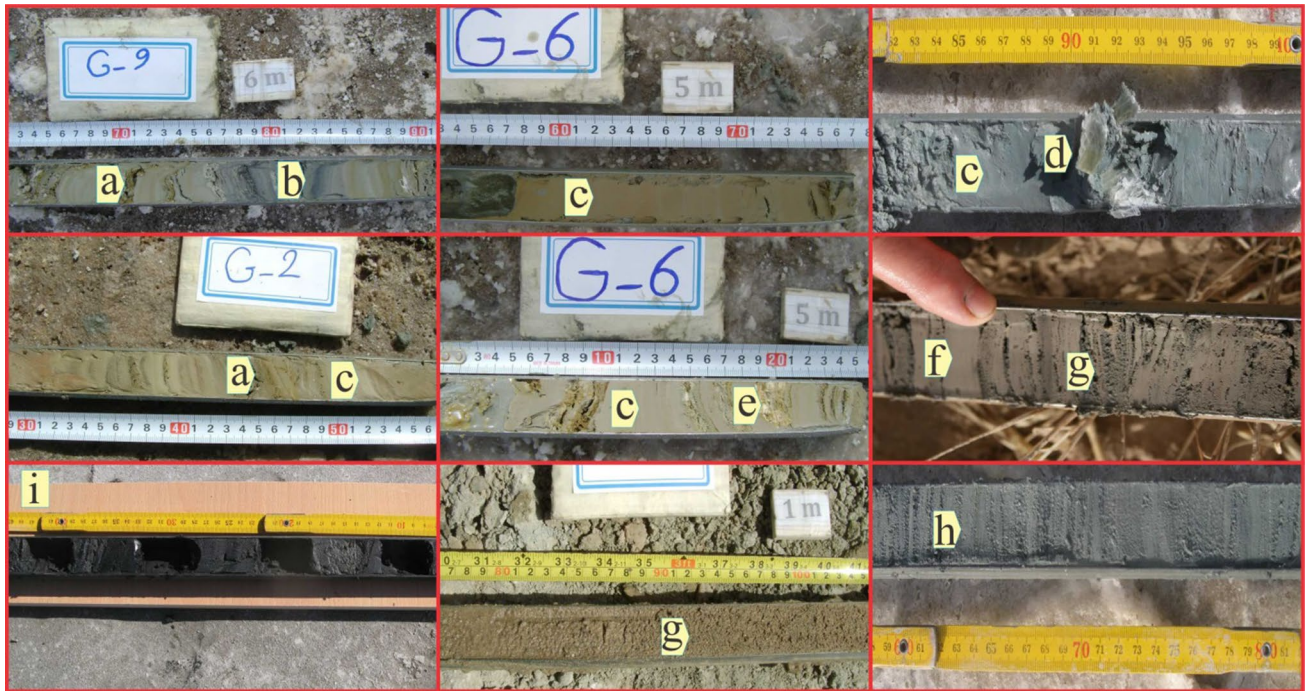
Core name	Longitude	Latitude	Altitude (m)	Depth (cm)	Number of samples
G-1	664,192	3,552,448	1475	530	13
G-2	667,592	3,553,190	1468	602	21
G-3	671,254	3,555,191	1468	150	6
G-4	672,480	3,556,275	1466	820	21
G-5	675,824	3,557,741	1469	190	4
G-6	675,827	3,557,584	1469	1058	20
G-7	679,643	3,558,978	1473	170	8
G-8	667,911	3,581,780	1475	478	2
G-9	679,776	3,555,799	1466	1006	14
G-10	684,368	3,559,091	1465	362	0
G-11	655,008	3,563,795	1480	1022	17
G-12	679,815	3,572,926	1468	80	4
G-13	679,804	3,572,839	1467	1130	35
G-14	664,895	3,544,801	1472	550	16
G-15	645,532	3,581,518	1490	490	8
G-16	613,850	3,578,103	1565	20	1

situation, most of the playa is dry and sampling was done in the dry season, so it was possible to take samples from the central parts. The thick salt layer was cracked using iron pipes and the cores were taken from the underlying layers. Of course, the cores taken from the mud flats had no salt layer. A total of 16 sediment cores were taken from the inner parts of the playa and surrounding areas during the field operations to investigate sedimentology and determine sub-surface units (Table 1; Figs. 2, 9). Handy Auger was used to taking an intact core with a mean depth of about 7 m. As one of the limitations of using the Auger, the created wells were blocked during drilling in the sand sediments, which were resolved by changing the location of the Auger.

The exact location of the cores was recorded by the GPS (global positioning system), and the cores were described in sub-surface in terms of sedimentology, sedimentary structures, microfacies, and identification of primary sedimentary environments in the field. Samples were taken according to the changes in the color, texture, and sedimentary type. The time frame of each sample was not important. Environments and sub-environments were identified by integrating



**Fig. 2** **a** View of the salt pans and salt polygons of the Gavkhouni Playa sub-surface in the northeastern part and **b** drilling in the sub-surface sediments of the Gavkhouni Playa



**Fig. 3** Facies available in the core samples taken from the Gavkhouni Playa. **a** Lamina brown clay, **b** gray to black organic materials of deltaic or lake environments, **c** soft mud facies in cream and sometimes brown colors related to the playa environment, **d** large secondary crystalline gypsum formed under the influence of sulfate-rich

solutions, **e** salt lamina at different depths, **f** clay in different colors at different depths in the coarse-grained sediments related to the river environment, **g** dry brown sand facies (aeolian sands), **h** alternation in the sand and silty, or mud lamina related to the lake environments, and **i** sample of the prepared cores

sedimentary information and analysis of sedimentary facies (Fig. 3). Spatial distribution of different sedimentary environments and translocation and transformation of them into each other were reconstructed based on the data obtained from two different approaches, and finally, their stratigraphic column and sedimentary type were drawn (e.g., Li et al.

1996; Valero-Garcés et al. 1998; Benison and Goldstein 2001) (Fig. 4).

Samples were placed inside the Analysette 3 sieve shaker (Made by Fritsch Co. Germany) to determine the size of sedimentary particles, and different sizes of grains were separated by the wet sieving method for 30 min on average. After drying, samples were weighted

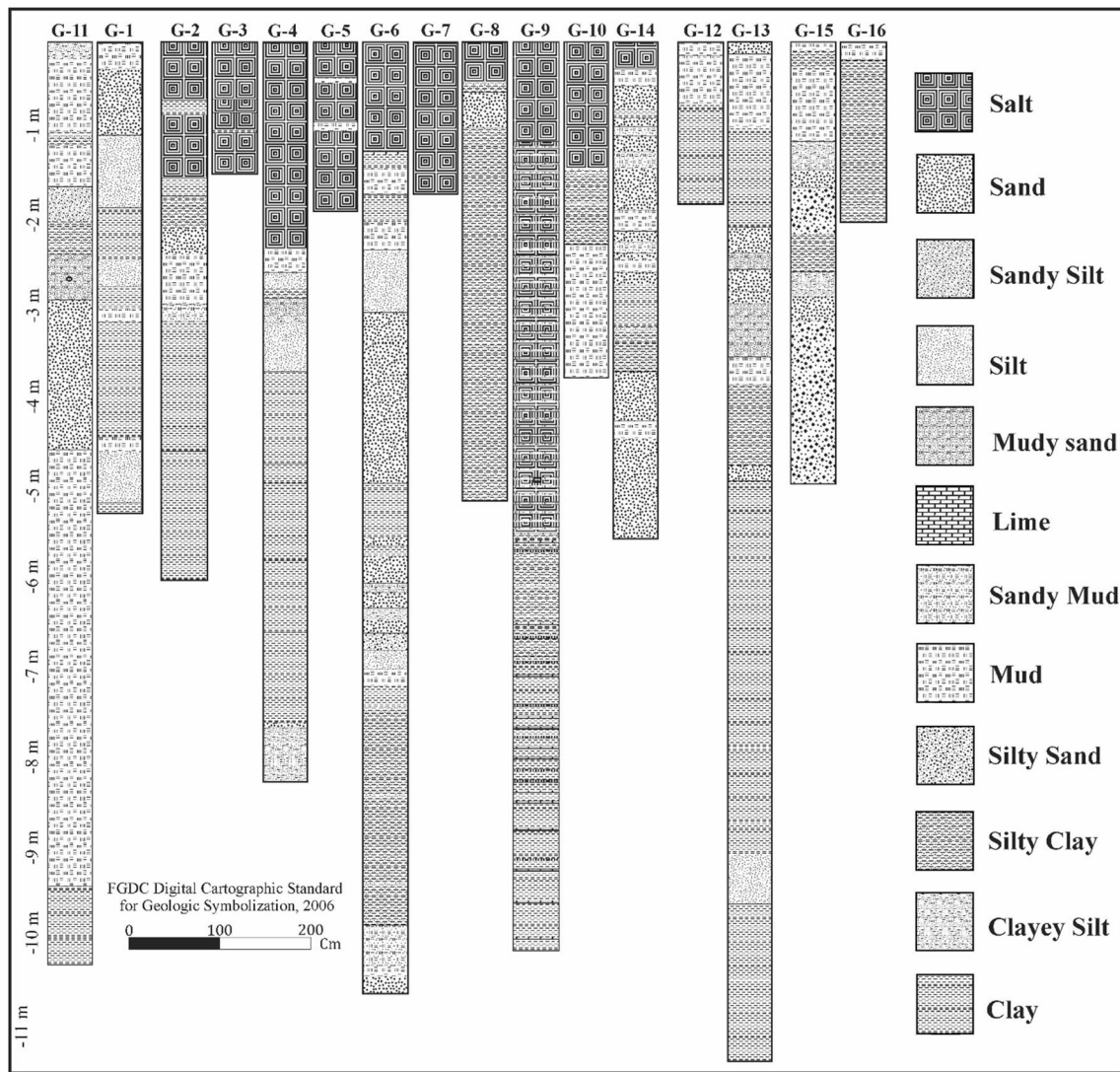


Fig. 4 Sedimentary type of the core samples taken from the Gavkhouni Playa

Table 2 Radiocarbon age and calibrated age data

Core	Sample depth (cm)	Laboratory code	Age <sup>14</sup> C (year BP)	Calibrated age (year cal BP)			Date material	Sedimentation rate (mm/year)
				Min age	Mean age	Max age		
G-6	185	TÜBİTAK-0733	3764 ± 27	4080	4158	4236	Organic material	0.44
G-6	1035	TÜBİTAK-0735	21,727 ± 78	25,815	25,970	26,124	Organic material	0.39
G-9	680	TÜBİTAK-0734	22,737 ± 83	26,757	27,067	27,377	Organic material	0.25

and particles smaller than 63 μm were analyzed by the Laser Particle Sizer Analysette 22. Also, statistical parameters, such as mean, kurtosis, standard deviation, sorting, and skewness of sediments were calculated using

the Sedilizer software. In this study, radiocarbon dating <sup>14</sup>C-AMS (accelerator mass spectrometry) was performed using organic materials and bulk samples (Table 2). The sample age was calibrated by the OxCal software (Bronk

Ramesy and Lee 2013) with a 2-sigma error range and a reliability coefficient of more than 95%. These samples included organic materials mainly present in silt and clay. Due to the calcareous background of the Cenozoic period in western playa, there is a possibility of error in the bulk samples (Heyvaert and Baeteman 2007), but only the results of dating the three sedimentary samples of bulk organic materials were sufficient due to semi-arid climatic conditions, limited vegetation growth, and poor conditions of organic materials. Dating analysis was performed at the Marmara Research Center, Earth and Marine Sciences Research Institute in Turkey.

## Results and discussion

### Analysis of facies and interpretation of sedimentary environments

Sedimentary facies reflect the physical and chemical conditions of sedimentary environments. Totally, 8 sedimentary facies were identified based on sedimentary texture, type of evaporite minerals, presence of organic materials, color changes, and other microscopic characteristics. Sediments with the plant residues and evaporite sediments (gypsum and salt) were often observed as intermittent (Figs. 3, 4). According to sedimentology and sedimentary facies, 5 sedimentary environments including aeolian, river, deltaic, lake, and playa environments were identified as well as two types of dominant aeolian and aqueous processes. Facies available in sediment cores of the Gavkhouni Playa are briefly described in the following.

#### Salt Facies (Ha)

This facies often found on surface sediments and in sub-surface sediments in dry periods including salt crystals with a thickness of a few centimeters to more than 2 m that can be seen in some cores (G-4). The thickness of this facies changes rapidly in different seasons of the year due to the amount of precipitation or persistence of drought in the playa. The surface of this facies can be seen in the form of polygons (often pentagonal) depending on thickness of salt in different sizes. This facies shows a playa environment, widespread in middle and southern parts of the playa, and it does not exist or, if any, it is very thin and brittle in northern parts and at the mouth of the Zayandehrud River (Fig. 3e).

#### Clay facies (Cl)

This facies can be seen in various colors, such as light gray, light brown, dark brown, and black in the stratigraphic column of the cores. Oxidation spots, organic materials of black

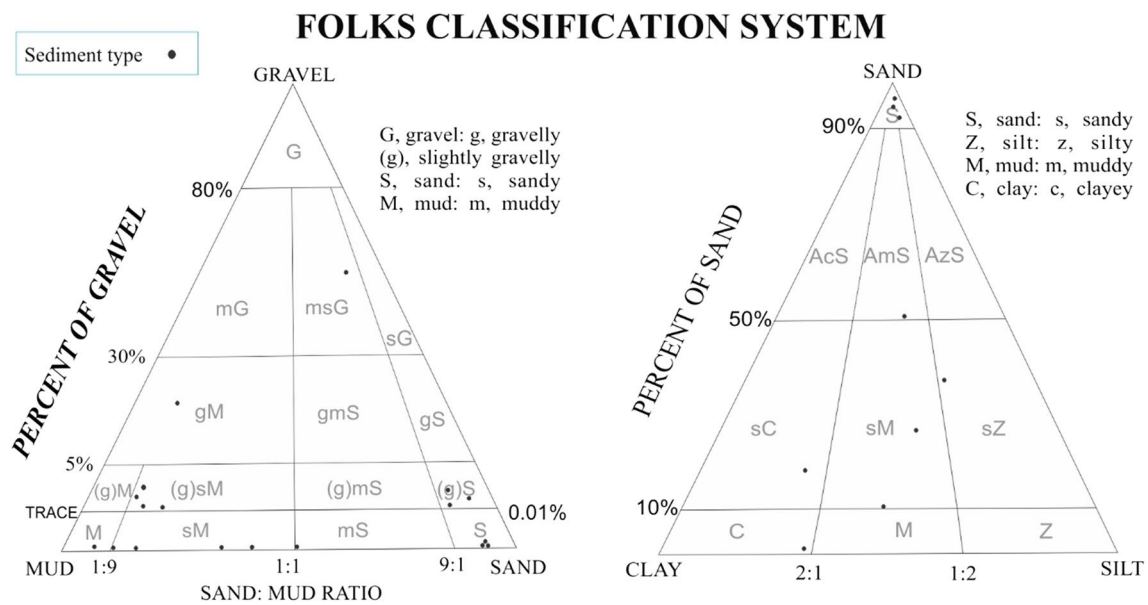
spots, plant residues, and plant roots are associated with this facies in some cases. It is sometimes observed in the form of small lenses in the sand facies. The dark color in sediments and significant amount of organic materials indicating the lake environment (Reading 1996). In the northern part of the playa, consecutive frequency of this facies with plant residues along with gray sand facies indicates the creation of deltaic environment conditions. The presence of sediments with lamina indicates a change in the regime, energy, and displacement of the Zayandehrud River canal, frequently seen in northern cores of the playa (G-13). Also, the brown color of this facies is due to the proximity of the sediments, weathering, and the presence of iron oxide (Fig. 3a, c, f) representing the arid period sediments with low precipitation (Playa) (Li et al. 1996). The brown color was observed at different depths containing large crystalline gypsum. In some places, the size of these crystals reaches more than 5 cm. Formation and growth of these gypsum crystals are secondary to contact with  $\text{SO}_4$ -rich sediments, which is relatively saline due to the evaporation of groundwater and its movement towards the earth's surface (Eugster and Hardie 1978) (Fig. 3d). This facies is often related to the sedimentary environment of the floodplain and is limited to the lake and playa environments.

#### Silty clay facies (CIS)

There was a silty clay facies in the column of the cores taken from the Gavkhouni Playa with a significant thickness. This facies can be seen at different depths with different colors and properties. Black, dark gray, light gray, gray, dark to light green, dark to light brown, and other intermediate colors can be seen. Depending on the type of sedimentary environment, it has salt crystals, gypsum, oxide spots, organic material spots, and plant residues. The sedimentary environment of this facies varies according to the different lateral properties showing the lake and playa environments (Fig. 3c).

#### Clayey silt facies (SiC)

This facies was found in some taken core samples (often in marginal cores). Repetition and thickness of this facies are very limited. It is often light gray in color and rarely found in brownish-gray and does not exceed 20 cm in thickness. It is mainly composed of calcite mud. This facies also indicates the lake environment, and in some cases, it is related to the crevasse splay environment of the rivers leading to the lake (meander) (Fig. 3b). Also, in the northern cores of the Gavkhouni Playa (G-13), this facies shows a deltaic environment by reducing the amount of clay and increasing the silt almost as pure silt along with clay lamina and silty clay.



**Fig. 5** Sedimentary types of the Gavkhouni sub-surface according to Folks' Standard Triangles (1974)

### Mud facies (Mu)

Mud facies is almost thick as observed in the sedimentary column of the taken core samples. This can be seen at different depths with different colors and properties. The colors are black, gray, dark to light green, and light to dark brown. Depending on the type of sedimentary environment, it has oxidant spots, organic material spots, salt and gypsum crystals, and plant roots. The brown mud, which is highly dense and considerably sticky, extends to the cores taken from the western margin of the playa at a depth of 4 m, and drilling is very difficult (G-11) due to high dehydration, compaction, adhesion, and density. This facies represents the sediments related to mud zone and floodplain and is an index of major arid periods when the sediments have been out of the water for a long time (Fig. 5). In general, the sedimentary environment of mud facies is different according to the varying lateral properties, but it often indicates the sediments of river floodplains and is limited to the playa margin environment (often in northern cores of the playa) (Fig. 5).

### Muddy sand and sandy mud facies (MS)

There was a limited thickness of muddy sand and sandy mud facies in the column of the taken core samples. This facies can be seen at different depths with different colors and properties. It is often seen in the dark to light green and light brown. Depending on the type of sedimentary environment, it has oxidant spots, organic material spots, and secondary gypsum crystals. The sedimentary environment of this facies varies according to different lateral properties.

However, it often indicates Croatia environments (floodplain) in the river environment and entry of the rivers in the lake environment (Fig. 3h).

### Sand facies (Sa)

This facies consists of the fine-grained to coarse-grained sands which are light gray in color, containing organic materials in some places. In some areas and depths, a very small thickness of sandy and muddy facies can be seen. In some cases, mud facies is seen as small lenses in the middle of the sand facies. This facies has been often formed in the delta of the rivers entering the lake and is located on the margin of the lake indicating the lake environment (Lak and Gharib 2004). In southern and southwestern cores (G-1, G-2, G-11, G-14, and G-15), the presence of the fine-grained and dry brown sand indicates activity and dominance of aeolian processes to the west of the playa under the influence of sandy dunes in the west wing of the Gavkhouni Playa (Fig. 3g). Gavkhouni sub-surface aeolian sands have been deposited under the influence of both aqueous and aeolian processes. Studying the effects of the activity of these two factors on the sediments of the area showed the existence of paleoclimatic conditions. Given the stratigraphic column of the cores taken from the Gavkhouni Playa, the arid periods associated with the sedimentation of aeolian deposits in the lake sub-surface and surrounding areas which are often 1–3 m deep (depending on the location of the core). The amount of aeolian sand deposition was found to be higher in thickness and consistency in the G-1, G-2, G-11, G-14 and G-15 cores periodically have the lake and sometimes alluvial sediments

(floodplain sediments). The presence of light brown sand facies and brown mud facies is evidence of the existence of shallow aqueous environments with alternating periods of drought and wind (Fig. 3g).

### Gravelly facies (G)

This facies is often seen at the mouth of incoming rivers in pure or mixed forms with other sediments, resulting from the transfer of coarse-grained sediments by the river flows and entering the lake environment. This facies represents the upper environment of the Zayandehrud River Delta, which is often gray with a brown mud background (Fig. 3i).

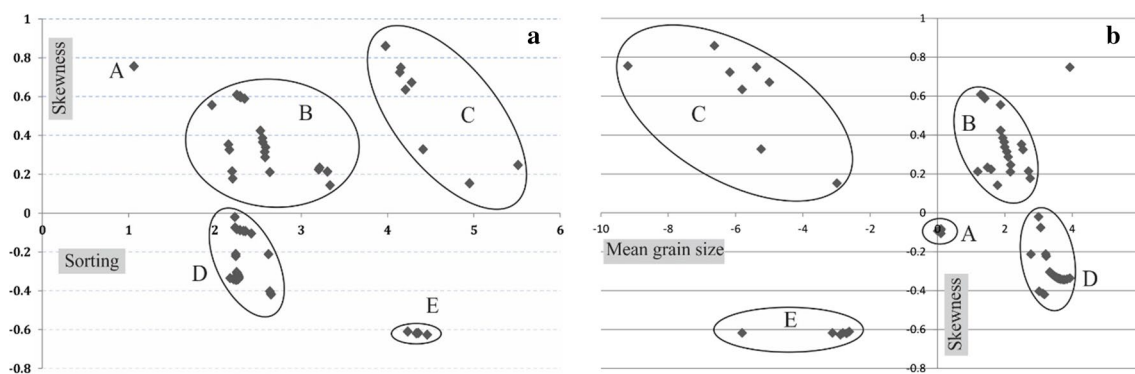
### Sedimentology

Identifying types of sedimentary environments and various facies are possible by analyzing grain size, which provides us with valuable information about the transfer, sedimentation, energy of the sedimentary environment, characteristics of source rock, weathering processes, and type of flow (Folk 1974). According to the results of granulation analysis, the type of sediments was determined based on the Folk's Standard Triangles (1974) (Fig. 5). Sediment size is among the indices showing conditions of the sedimentary environment and flow energy. Statistical parameters (sorting, skewness, kurtosis, and mean particle size) were controlled in terms of changes in the energy by the factors of erosion, transfer, and deposition rate. Regarding the percentage of the particles in the Gavkhouni sub-surface sediments (up to a depth of about 11.5 m), sedimentary types were determined as mud, silt, clay, silty sand, muddy sandy gravel, slightly gravelly sandy mud, slightly gravelly mud, gravelly mud, gravelly muddy sand, and sandy gravel according to frequency (Fig. 5).

By investigating the statistical parameters (Fig. 6), the sorting of the sedimentary samples is a factor showing how close the size of sedimentary particles is to each other. Sorting of the sediments in the Gavkhouni Playa sub-surface was

done by the standard deviation of sorting with a mean of 2.6, a maximum of 5.5, and a minimum of 1, which was in the sorting range of moderate to very bad. It is possible to determine the energy of the sedimentary environment as well as transfer processes of the sediments using skewness index. For example, sediments with a negative skewness indicate an energetic environment with coarse-grained particles. The mean skewness of the taken core samples was  $-0.02$ , with a maximum of 0.86 and a minimum of  $-0.62$ , often classified into very fine to very coarse-grained particles. Mean kurtosis was 0.99 for the taken core samples (high kurtosis) scattered over a very wide to high kurtosis range. There are many changes in the statistical parameters of sedimentology due to a combination of the performance of varying processes in different sedimentary environments (Snelder et al. 2011). This situation for the sediments of the Gavkhouni Playa sub-surface resulted from the activity of aqueous and aeolian processes in the aeolian sand, river, delta, and lake environments. Several factors including particle size, sedimentation mechanism, and flow characteristics affect the degree of sediment sorting. The absence of river flows with a fixed regime caused deposition of the sediments with bad sorting. In the Gavkhouni Playa, the river flows enter the central basin with different severity levels and durations from the Zagros heights. In the eastern parts of the playa, the degree of sorting increases and the amount of skewness is positive with the increase in the fine-grained particles due to great distance from the estuary of the river. The presence of sand dunes in the western parts of the Gavkhouni Playa has been very effective in sedimentological parameters.

The correlation between sorting and skewness is widely used to study the genesis and source of the sediments (Folk 1966) and deduce energy changes in the environment and source of particles in the lake environments (Jiang and Ding 2010). As shown in Fig. 6, there are about 80 granular samples in five graph ranges, indicating the mechanism and process of sedimentation and source of the sediments. The sample classified into A range with good sorting and



**Fig. 6** a Correlation between standard deviation of sorting and skewness and b correlation between mean particle size and skewness



positive skewness (fine-grained particles) is related to the aeolian sediments in the western margin of the Gavkhouni Playa at depths of about 1–3 m. Also, some of the samples classified into the B range can be of aeolian and lake sources suggesting both aeolian and aqueous processes are active in this range. However, it seems that this range has often been influenced by lake environments. The C range with a very weak sorting and skewness towards the fine-grained sediments is possibly related to the lake or deltaic environments in G-12 and G-13 cores. The sediments with bad to very bad sorting and skewness towards the coarse-grained particles are related to the upstream environments (including G-15, G-16, and G-8 cores) that can be seen in the ranges of D and E. (Fig. 6).

In other words, unit A represents the arid periods, which have been in the area for a short time due to the depth of the cores, and units B and C represent the humid periods and lake conditions, which have been often more than the arid periods in the area. Units D and E represent different climatic periods in the river environments that have changed according to the river regime. In general, the last global glaciation was characterized by the emergence of an instantaneous ratio of warm periods followed by gradual cooling. The cycle has been repeated several times during the Pleistocene that has led to the creation of a pattern called the “saw teeth” in paleoclimate diagrams (Bradley 2015; Lowe and Walker 2015).

### Morphoscopy

Each sedimentary environment has unique morphological effects on the surface of clastic sedimentary grains accumulated in that environment through its own transfer and deposition processes (Hamzeh et al. 2016a). Morphoscopic studies, in other words, investigation of the grain shape are directly related to the composition and size of the grain, type of movement, and transfer distance (Koykka 2011). Studying aeolian sediments lead to the identification of components in the sediments, source rock of clastic sediments, the environment of the sediments, and climate of the source area. Therefore, whatever aeolian particles are, they are mineral and rocky in nature, and it is natural for them to be genetically and materially related to their source materials (igneous, metamorphic, and sedimentary rocks). The sediments deposited in the aqueous environments are usually more rounded and have a smooth and polished surface, sometimes with V-shaped grooves on their surface compared to the aeolian sediments. However, sediments in the aeolian environments have good sorting and show pit-like grooves on their surface.

In some cases, these sediments have semi-rounded shapes on their surface (Fitzsimmons et al. 2007).

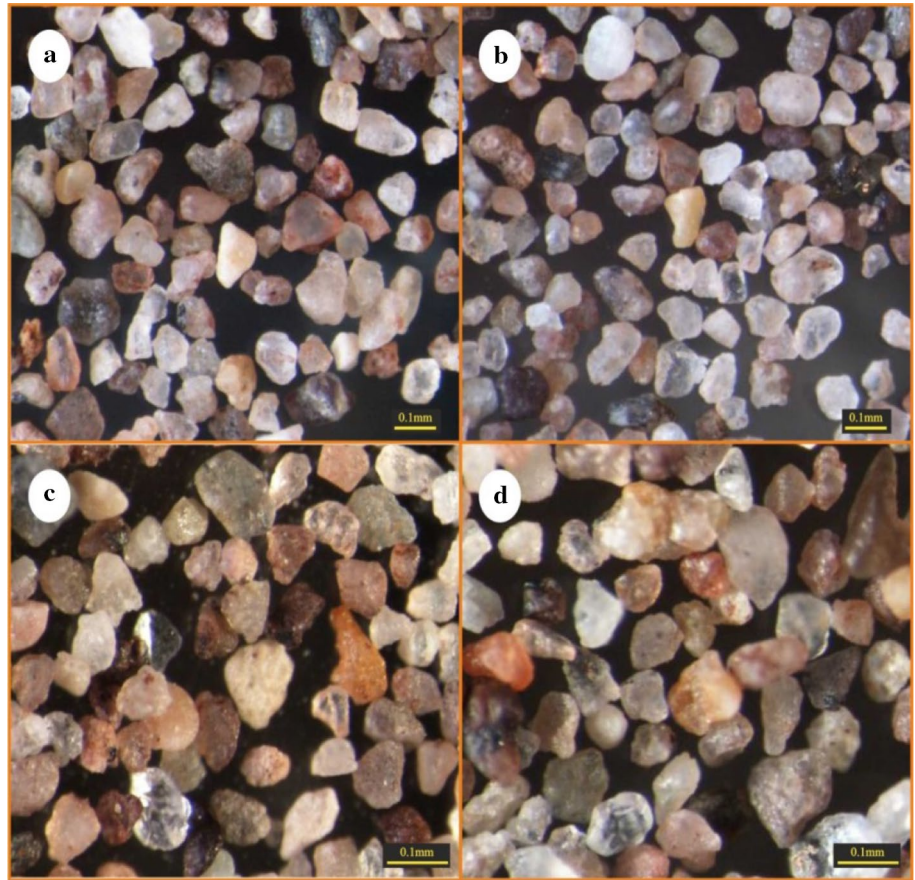
Aeolian deposits of the Gavkhouni Playa sub-surface are often (more than 95%) concentrated in 125 and 63  $\mu\text{m}$  fractions due to their fine-grained particles (fine-grained and very fine-grained sand). In the quartz aeolian deposits, igneous and feldspar rocks can be seen in 125  $\mu\text{m}$  fraction, and quartz, clastic carbonate, feldspar, and gypsum can be seen in 63  $\mu\text{m}$  fraction. The degree of sorting and rounding is much more in 125  $\mu\text{m}$  fraction and lies between mature to supermature due to the absence of clay in the texture. A fraction of 63  $\mu\text{m}$  is less rounded than 125  $\mu\text{m}$  fraction. According to the mineralogical maturity, both of them are among the fragments that will degrade soon due to the presence of feldspars and rocks; therefore, it can be said the sediments have low maturity indicating the sediments are close to the source. The opacity of quartz particles is the evidence of aeolian transfer (Fitzsimmons et al. 2007) (Fig. 7).

Morphoscopic investigations showed that the Gavkhouni Playa sands have an aeolian source. These sands are rounded with an opaque surface attributing to the collision of the sedimentary grains with each other during transfer. Morphoscopic investigations on the aeolian sand sediments in the studied cores showed the presence of aeolian sand particles along with red mud sediments, indicating simultaneous operation of the aeolian processes in the western marginal areas with the playa environment in the internal parts of the playa. In other words, when the Gavkhouni region has had the conditions of a playa, aeolian processes have also been active in the western parts. Therefore, the sequence of sediments in the mentioned periods is a combination of the aeolian and playa sediments. The frequency of the aeolian sand and playa mud sediments varies in different periods. The simultaneous presence of the particles with different roundness, opaque and transparent particles, as well as the presence of sediments with low mineralogical maturity in the samples taken from the aeolian sands in the cores suggest deposition of the sediments from several sources, different distances and processes in the past. Sources of the aeolian sediments in the Gavkhouni area include northern and north-eastern alluvial sediments, which are mostly in the form of igneous particles and alluvial sediments coming from the west and southwest and are mostly the sedimentary limestone as well as the Zayandehrud sediments, which are igneous and metamorphic sediments according to the frequency.

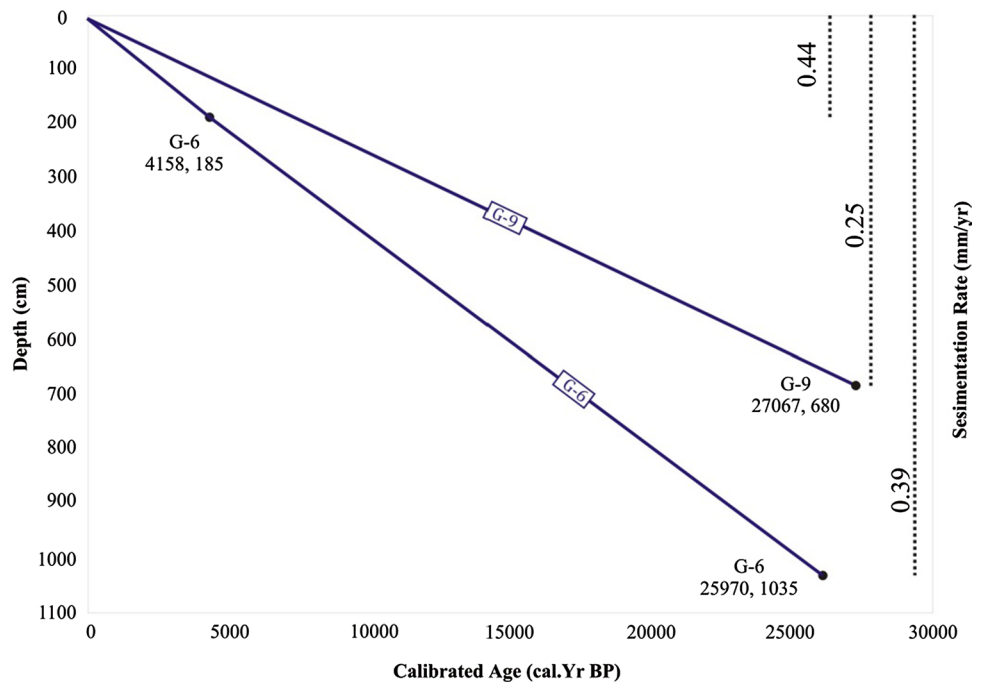
Also, the frequency percentage of the rocks and minerals in the aeolian sand varies from north to south so that, from the north to south, the mean frequency of the igneous and metamorphic particles, heavy minerals, and sand dunes decreases and in contrast, sedimentary particles show a



**Fig. 7** Microscopic image of sedimentary grains of the aeolian sediments in the sedimentary cores, **a** almost rounded igneous and quartz rocks (125  $\mu\text{m}$  fraction) (G-1 core sample 90–100), **b** almost semi-rounded to semi-angular igneous, quartz, and feldspar rocks (125  $\mu\text{m}$  fraction) (G-2 core sample 240–245), **c** semi-angular quartz, clastic limestone, feldspar, rocks, mica, and gypsum (63  $\mu\text{m}$  fraction) (G-1 core sample 90–100), and **d** semi-rounded clastic limestone, quartz, and feldspar rocks (63  $\mu\text{m}$  fraction) (G-2 core sample 240–245)



**Fig. 8** Age-depth model for the sediments of G-6 and G-9 cores



relative increase. The role of lithology in the catchment area and permanent river of Zayandehrud is more effective in the combined maturity, percentage of frequency, and material of the particles making up the sand deposits of this area, and other factors, such as paleoclimate and tectonics are less important (Pakzad 2003).

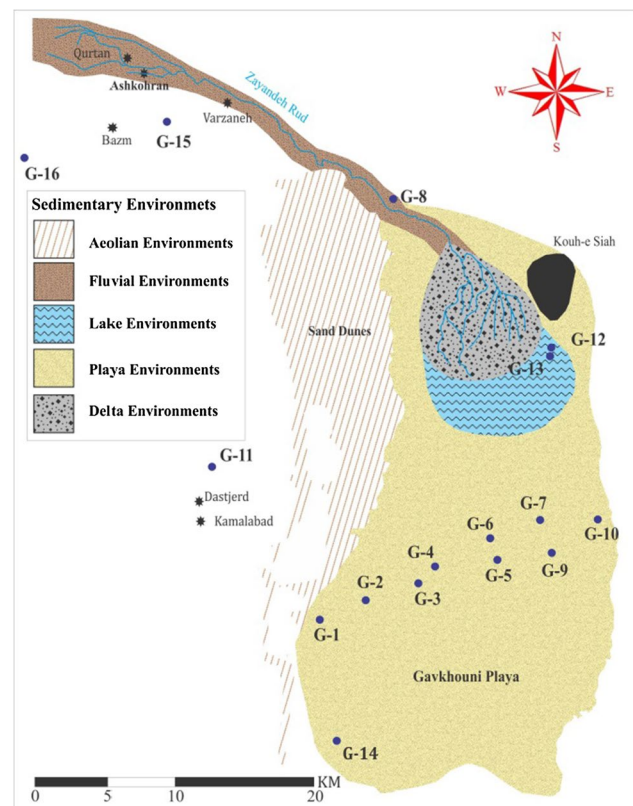
### Sedimentation rate in the Gavkhouni Playa

The mean sedimentation rate in the Gavkhouni Playa varies in different parts of the playa. In two dated cores, the mean rate was close to 0.35 mm per year. In the G-9 core, the mean rate was about 0.25 mm per year. However, given that the G-6 core is located in the western part of the playa and the volume of sediments entering the basin has been higher from the west, so mean rate of sedimentation is high in the western part. In the G-6 core, the mean sedimentation rate was 0.39 and 0.44 mm per year in deep and shallow parts, respectively (Fig. 8). This increase in the sedimentation rate in high sequences is probably related to the performance of highly deposited aeolian sediments. According to the results of dating, sediments of the taken core samples can on average cover a depth of 1058 cm for the western part of the playa, about 27,000 years, and a depth of 1006 cm, about 40,000 years, for the central part.

### Evolution of sedimentary paleoenvironments

The climate of the Iranian Plateau is mainly the Mediterranean and influenced by the Siberian high-pressure systems, Mediterranean cyclones (low-pressure system), and southwestern monsoon currents. In the past, climate change occurred in the Iranian Plateau with changes in the location and severity of these systems. Changes in these systems and their effects on Iran's diverse ecosystems have likely led to different responses in each ecosystem. So far, most of the information regarding the paleoclimate of Iran has been obtained from geological studies (Hamzeh et al. 2016a). It seems that the general pattern of the Pleistocene climatic change in western and northern Iran has been in the form of cold and arid periods (cold climate) and warm and humid periods (hot climate) (Kehl 2009). During the Pleistocene, north winds were likely to be common in the highlands of Central Iran. Giant kalouts of the Lut Desert (Dasht-e-Lut) are probably the evidence of these winds. Also, there is an evidence of geological erosion for the winds with greater severity than today in Central Iran during the Last Glacial Maximum (Hamzeh et al. 2016b). North winds (winter monsoon currents) were also likely to blow over the Persian Gulf during cold periods (Glennie and Singhvi 2002). Using these three available radiocarbon-dated samples, any attempt to

describe the paleogeographic evolution of the Gavkhouni Playa is constrained by the assumptions behind reconstructions used to interpolate between the dated samples concerning both time and space. The lack of data makes it difficult to determine the extent of environmental expansion, even generally. Given that, there is no precise information about these known factors, so the reconstruction presented below should be considered as an extensive design on a large evolutionary scale. As mentioned above, a reliable model of geomorphology and coastline changes is the prerequisite for paleogeographic reconstruction (Bogemans et al. 2017). It is important to identify the location and morphology of the river valleys and their drainage pattern (Heyvaert and Baeteman 2007) as rising water levels begin to flow through the valleys. Sufficient information about the timing of the environmental and level changes is another prerequisite for paleogeographic reconstruction. The time estimate is inferred from dating samples and the density of sediments is not included in the analysis. Changes in the sedimentary environments in the area, from north to south and from west to east have led to various forms. These forms have been gradually transformed into each other. In general, alluvial, deltaic, aeolian, playa, and lake deposits are observed from



**Fig. 9** Current conditions of sedimentary environments of the Gavkhouni Playa and surrounding lands (Based on geological map and field observations)

margin to center of the basin, respectively. Figure 9 shows the current conditions of sedimentary environments of the Gavkhouni Playa and surrounding lands. The existence of extensive floodplains can be seen along the Zayandehrud River and the not-so-large delta. The western part of the playa has been formed by high and wide sand dunes. The rest of the area including a large area of the Gavkhouni Basin is a playa environment covered with fine-grained sediments with a significant volume of evaporite minerals except for a small part of the playa forming the temporary lake environment.

About 40–30 ka BP, the Gavkhouni area has been influenced by heavy precipitation, resulting in high sediment

loads coming from the west (Zayandehrud River). The great delta of the Zayandehrud has been formed in the current location of G-15 and G-16 cores where coarse-grained particles of gravel and sand have been deposited, currently exploited as a sand mine. High energy and volume of the water imported from the Izadkhasht River in the south of the Gavkhouni Playa have led to the development of the delta-related facies in the current location of G-5 core, and also alluvial facies in the current location of G-1 and G-2 cores. The results of dating in G-6 and G-9 cores indicated a high rate of sedimentation in most of the western cores confirming the hypothesis that the Gavkhouni Basin has been

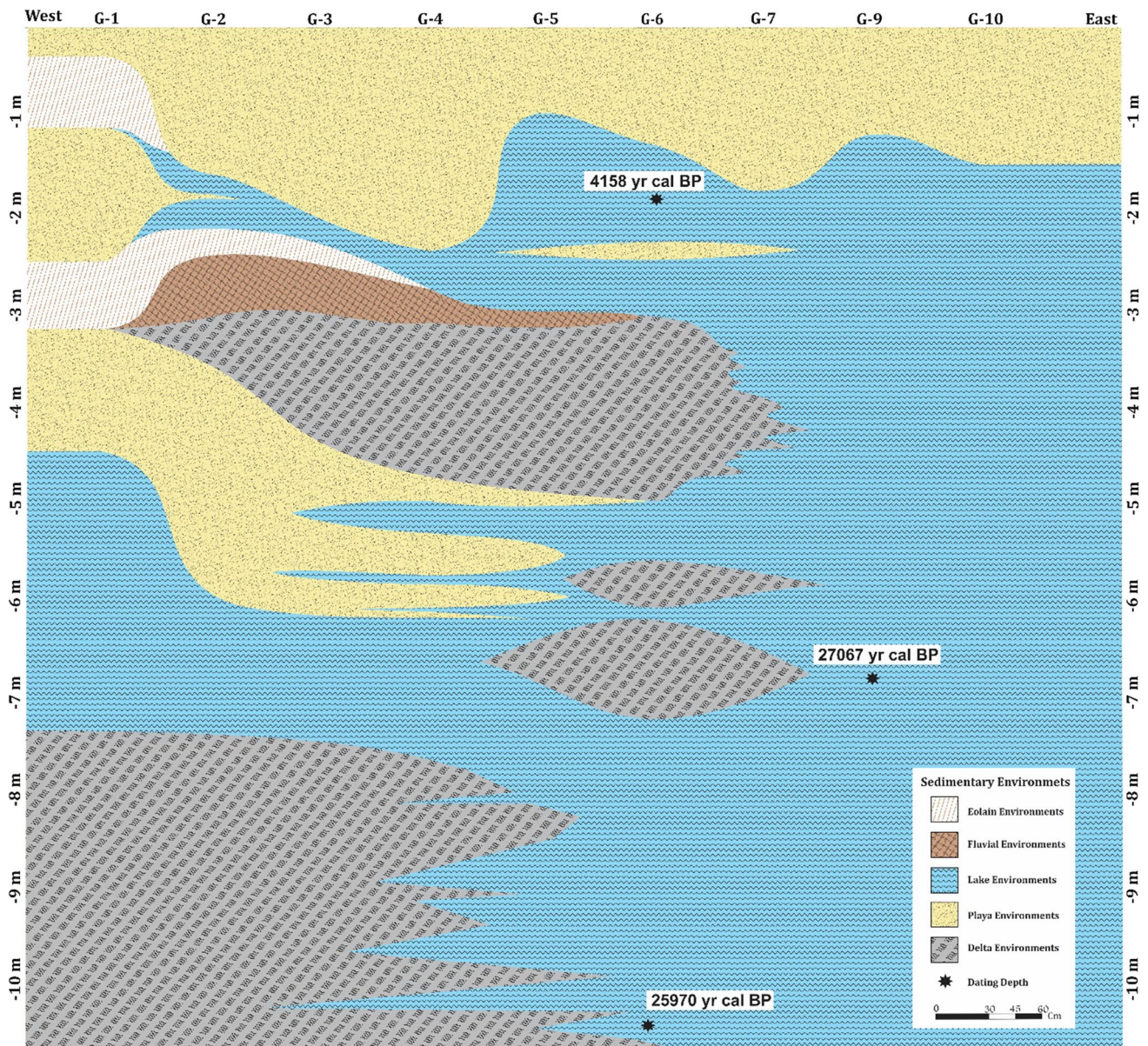


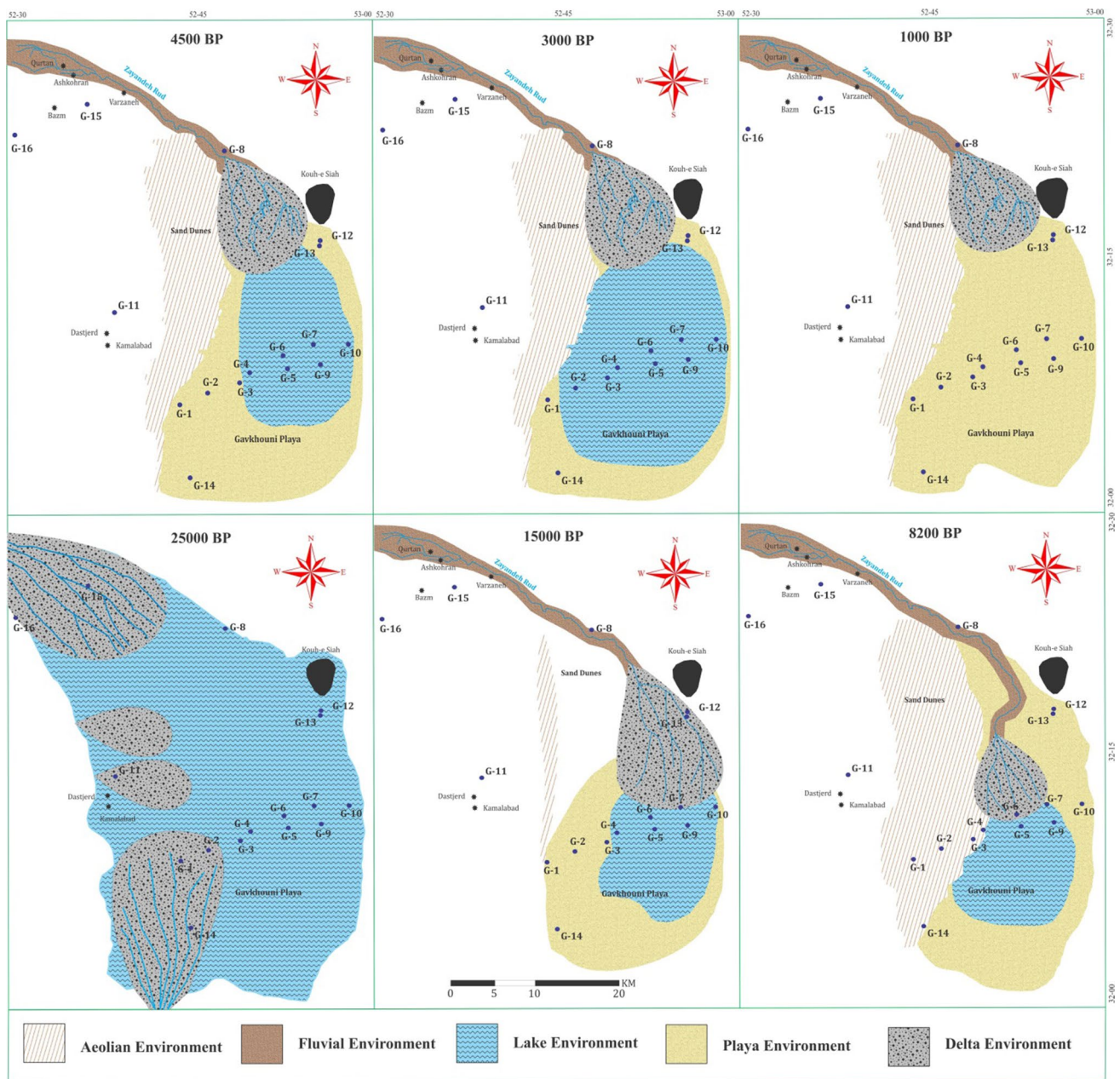
Fig. 10 Approximate adaptation profile of the sedimentary environments in the Gavkhouni Playa

filled from the west to the east. This situation continued until about 18 ka BP. During this period, the eastern parts of the basin included the lake sediments (Fig. 10). It took place from 18 ka BP to about 11.6 ka BP, with regression of the coastline and movement of the great delta of Zayandehrud to the north of the basin. The end of the delta stretched until the center of the playa (G-7) and sand dunes have been formed to the west of the basin.

The evidence is consistent with the events reported in many parts of Asia, such as China's Loess Plateau (Liu and Ding 1998), East Central Asia (Li et al. 2018), the Arabian Sea (Schulz et al. 1998), Van Lake in Anatolia (Litt et al. 2014; Pickarski et al. 2015), as well as the North Loess of Alborz (Vlaminck 2018) and West of the Iranian Central Plateau (Mehterian et al. 2017). This correlation between various areas of Asia and Greenland shows a relationship between climate changes in different parts of the world. Therefore, sudden and severe climatic events have similar performance in different areas. In the absence of local-scale field research, perhaps the general state of the paleoclimate can be partially reconstructed using the information from other areas. The existence of general and progressive drought in various parts of Asia (Dennell 2017) and Iran (Urmia Lake (Djamali et al. 2008), the Iranian Plateau of Loess (Lauer et al. 2017), sequences of the old Loess land in the north of Alborz (Vlaminck 2018) and Qala-e Gerd Cave in Avaj, Qazvin province (Mehterian et al. 2017)) is the evidence of the correlated events in the last glacial cycle. With the onset of Holocene, an increase in the temperature up to 10 °C (Cuffey and Clow 1997) led to an increase in the extent of the aeolian deposits and spreading the playa environment on the margin of the lake. The presence of yellow aeolian sands at a depth of about 330 cm in the cores of the western part of the Gavkhouni Playa (G-1, G-2, G-3, and G-4) indicated activity of the aeolian process about 8.2 ka BP. This period accompanied by the spread of aeolian sands in the western marginal sub-surface of the Gavkhouni Playa probably coincides with the event took place 8.2 ka BP (late-middle Holocene) (Rapp 2019). This is probably due to the change in the angle of solar radiation, according to which orbital motions have led to the gradual weakening of monsoons, resulting in more arid conditions in the Middle East and Southeast Asia (Gupta et al. 2003; Fleitmann et al. 2007). The peak of this arid condition in the Gavkhouni area occurred around 8.2–8.5 ka BP, accompanied by intense aeolian activity and the spread of the aeolian sands in the west to the central parts of the Gavkhouni Playa sub-surface. Strong winds in the middle of Holocene led to the digging of a long and wide canal in northwest-southeast direction between alluvial sediments of the rivers in the north of the basin, which is now known as the Dasht-e-Jahanam (Jux

and Kempf 1983). No information is available on the height of the aeolian sands in this period, but the spread of sand masses in the west of the playa has certainly been greater than today. Due to the correlation between climatic events, the activity of the aeolian sands has been reported in the Hamoon sub-surface sediments, Jazmourian Plateau, and Neur Lake during 8.2 ka BP in the studies by Hamzeh et al. (2016a, b), Vaezi et al. (2019), and Sharifi et al. (2018), respectively. This could be due to the weakened Indian Ocean Summer Monsoons and arid conditions (Gupta et al. 2003). Dixit et al. (2014) attributed the short arid period in Southeast Asia to strengthen relationships between the North Atlantic climate and Summer Monsoons of the Indian Ocean. Expansion of playa facies at a depth of 1–2 m in the western and central cores indicated the existence of 200 years arid conditions about 4.2 ka BP in the area. This arid period shows a relatively good adaptation of the Northern Hemisphere (Staubwasser et al. 2003), as reported in parts of the North American continent, Middle East, and parts of Africa and Asia in a wide range (Booth et al. 2005; Parker et al. 2006). Hamzeh et al. (2016a, b) reported this arid period in Hamoon Lake with the progression of the aeolian sands in the lake. Also, it has been accompanied by an increase in the salinity and arrival of the aeolian sediments in the Jazmourian Wetland (Vaezi et al. 2018). This period probably coincided with the decline of Shahr-e-Sukhte civilization about 4.5 ka BP (Minniti and Seyed Sajjadi 2019) and the decline of the Jiroft civilization about 4.3 ka BP (Madjidzadeh and Pittman 2008; Mashkour et al. 2013). The presence of lake facies at a depth of fewer than 2 m during a time period of about 3.5 ka BP showed a good correlation with progression of the California's Mono Lake (Newton 1994) (Fig. 11). Also, Djamali et al. (2009) identified a layer of premature coal due to high human activity in Almalu Lake located in the southern wing of the Sahand Mountains indicating appropriate humidity conditions in the area. The existence of playa facies and yellow aeolian sands at a depth of less than 1 m in the cores of western margins (G-1) indicated the presence of arid conditions in the area (Li et al. 1996). This arid period is probably related to the arid period occurred about 1000 years ago (Hamzeh et al. 2016b) (Fig. 11), which is considered as the equivalent (not certainly) of the famine took place 1045 years ago, as mentioned in the history books of Sistan (Sistan and Baluchestan Province, Iran). In the current situation, the emergence of the playa conditions in the Gavkhouni area resulted in a decrease in the depth of the wetland and its transformation into a salt pan.





**Fig. 11** Reconstruction of sedimentary environments of the Gavkhouni Playa in different time periods (Geomorphological units are approximate)

## Conclusion

The following results were obtained by the studies on sedimentology and sedimentary facies in the Gavkhouni Playa:

Type of sub-surface sediments mostly included mud, silt, clay, silty sand, muddy sandy gravel, slightly gravelly sandy mud, slightly gravelly mud, gravelly mud, gravelly muddy sand, and sandy gravel. Investigating statistical parameters of sedimentology and sedimentary

facies showed that there are 5 sedimentary environments including aeolian, river, deltaic, lake, and playa. Facies of the aeolian environment are often brown and dry aeolian sands with good sorting, a positive rate of skewness (fine-grained particles) and medium grains. The river environment (floodplain) with mud and silty sediments is usually hard, without organic materials and has gypsum and brown in colour, with bad to very bad sorting and skewness towards the coarse-grained particles.

Lake facies are gray to light green (indicating regeneration process of the environment) in color and have fine-grained sediments with organic, soft and juicy materials along with thin lamina, layers of coarse-grained sediments, and also very bad sorting and skewness towards the fine-grained sediments. The deltaic environments with the high frequency of fine and coarse-grained sediments caused by many changes in the energy regime of the rivers leading to blue to dark gray color of the basin sometimes observed in brown layers with organic materials, very bad sorting, and skewness towards the fine-grained sediments. The high presence of evaporite minerals, such as salt and gypsum, dark brown sediments, and sediments with bad to very bad sorting and skewness towards the fine-grained particles are the characteristics of the playa environments. According to the results of dating, the rate of sedimentation in the Gavkhouni Playa was different in the varied parts. It was 0.44, 0.39, and 0.25 mm per year in the western, middle, and eastern shore parts, respectively. Regarding the low slope of the western part of the Gavkhouni Playa and more changes in the sedimentary environments, it can be said that the similar current conditions (without a thick layer of evaporite sediments) were dominant in the eastern part at least in 1000 ka BP.

Based on this study, about 30–18 ka BP, the Gavkhouni area has been influenced by heavy precipitation so that the amount of sediment load imported from the west (Zayandehrud River) was high. The great delta of Zayandehrud was formed and the coarse-grained particles were deposited in gravel and sand sizes. About 18–11.6 ka BP, along with the coastline regression, the great delta of Zayandehrud flowed into the north of the basin. The end of the delta stretched until the center of the playa, and sand dunes were formed to the west of the basin. With the onset of Holocene and increased temperature, it led to an increase in the size of the aeolian sand deposits and expansion of the playa environment until about 8.2 ka BP on the margin of the lake. About 8.2–4.2 ka BP, it was accompanied by a temporary progression of the Gavkhouni Lake, and 4.2 ka BP, it regressed again with a drought that occurred about 200 years ago. Progression of the lake facies took place about 3.5 ka BP, after which regression occurred and playa and aeolian facies were replaced by the lake facies. According to the type of the sediments in the Gavkhouni Playa sub-surface, it can be said that the conditions of the northern and eastern parts of the Gavkhouni Playa were similar to the current conditions for at least the last 3000 years and also the conditions of the western part were the same for at least the last 1000 years. An increase in the thickness of the layers of evaporite sediments, which are mainly salt, in

upper layers of the playa indicated that the Gavkhouni Playa has become drier than before in recent centuries.

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