Vegetation history and human-environment interactions through the late Holocene in Konar Sandal, Kerman, SE Iran

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Table of Contents

1 Abstract........................................................................................................................................1

2 Introduction...................................................................................................................................1

3 Site description ................................................................................................................................3
   3.1 Physical settings .......................................................................................................................3
   3.2 Climate .......................................................................................................................................5
   3.3 Vegetation ...................................................................................................................................6
   3.4 Archaeological and bio-archaeological settings ......................................................................8

4 Materials and methods ..................................................................................................................10
   4.1 Radiocarbon dating ..................................................................................................................10
   4.2 Pollen extraction and counting .................................................................................................10
   4.3 Sedimentological and geochemical analyses .........................................................................11
   4.4 Data analysis and visualization ...............................................................................................11

5 Results and interpretation .............................................................................................................11
   5.1 Radiocarbon dating and lithology .........................................................................................11
   5.2 Palynology ...............................................................................................................................11
     5.2.1 LPAZ-A (250-210 cm, 4-3.8 ka) .....................................................................................15
     5.2.2 LPAZ-B (210-170 cm, 3.8-3.4 ka) .................................................................................16
     5.2.3 LPAZ-C (170-130 cm, 3.4-2.8 ka) ...............................................................................16
     5.2.4 LPAZ-D (130-14 cm, 2.8-0.6 ka) ..................................................................................16
   5.3 Sedimentology and geochemistry ............................................................................................17
     5.3.1 Zone-1 (250-180 cm, 4-3.5 ka) .....................................................................................18
     5.3.2 Zone-2 (180-135 cm, 3.5-2.8 ka) ..................................................................................18
5.3.3 Zone-3 (135-75 cm, 2.8-1.8 ka) .................................................................18
5.3.4 Zone-4 (75-14 cm, 1.8-0.6 ka) .................................................................20

6 Discussion ........................................................................................................20
   6.1 Evolution of regional vegetation and landscape over 4000 years ..............20
   6.2 Local and regional hydroclimatic changes ..............................................21
   6.3 Human-environment interactions .........................................................23

7 Conclusions .....................................................................................................26

8 Acknowledgements ..........................................................................................27

9 References .......................................................................................................27
1 Abstract

The Jiroft valley, in southeastern Iran, was an important agricultural centre since the Early Bronze Age (3rd millennium BCE). The valley is characterized by harsh environmental settings: hot climate with poor rainfall. However, more optimal conditions may have prevailed earlier that supported ancient settlements. A 250-cm sediment core was retrieved from a peat-land at Konar Sandal, a major archaeological find attributed to Jiroft culture. The palynological data from this core was combined with geochemical and sedimentological proxies aimed at establishing the human-environment interactions in the area. The study focus was directed at vegetation history and landscape evolution, hydroclimatic changes and past human activities, that started just after the projected collapse of the Jiroft (4 ka) and extended all the way from the late Bronze Age to the Mongol invasion (0.6 ka). The results indicate that the valley was dominated by Saharo-Sindian open pseudo-savannah vegetation for the last 4000 years. However, due to anthropogenic clearance and intensified agro-pastoral activities, and also climatic factors, the land cover shifted from open xeric scrubland forests to more open, degraded landscapes. The principal human practice in these early settlements was cereal cultivation. But it is likely that during the more arid periods, communities retreated and abandoned agriculture, facilitating successional processes. Such droughts occurred in 4-3.8 ka and 3.4-2.8 ka and were supported by palynological data, C/N and Fe₂O₃ content. Peat formation was characteristic to the wetland during these arid periods. These droughts corresponded to drought phases detected in other studies, and were attributed to changes in Siberian Anticyclones. Dynamics of Artemisia and desert shrubs indicate milder climate around 3.8-3.4 ka and 2.8-0.6 ka. In the latter episode, during the rule of Persian Empire (ca. 550 BCE-650 CE) and Islamic epoch, the highest vegetation degradation state and most intensive human activities were observed. Some inconspicuous human practices, such as date cultivation, may have occurred on site as an adaptation to extreme environmental conditions.

Keywords: Agro-pastoralism, Climate Change, Geochemistry, Konar Sandal, Palynology, Vegetation history

2 Introduction

Southeastern Iran is situated in the unique settings of major cultural, climatic and phytogeographical transition zones. During the 3rd millennium BCE, Early Bronze Age (EBA) urban centers rose and flourished in Kerman and neighboring provinces in southeastern Iran. Some of the most important settlements were based in Konar Sandal, Shahr-i Sokhta, Tepe Yahya, Bampur, Shahdad and Tal-i Iblis (Dyson et al., 1990; Madjidzadeh & Pittman, 2008; Lawler, 2011).These centers were vital for trade, agriculture and cultural exchange.

Konar Sandal, the home of Jiroft culture, most likely served a connection or trading post between the Mesopotamian and Indus Valley societies (Steinkeller, 1982; Vidale & Frenez, 2015). Trade
relations between Mesopotamia were recorded in cuneiform writings (Steinkeller, 1982). Famous Jiroft-style steatite vessels were also discovered in the Sumerian cities, proving the existence of such inter-cultural relationships (Steinkeller, 1982). Likewise, a seal with Indus style iconographic components was discovered in Konar Sandal, further validating the importance of the settlement as a Bronze Age trade center (Vidale & Frenez, 2015). The archaeological surveys by the Franco-Iranian expeditions established that Jiroft, during the Bronze Age, was a socio-economically advanced agrarian society that developed distinct artistic styles and even novel writing systems (Majidzadeh, 2003; Majidzadeh & Pittman, 2008; Desset, 2014), although some of these claims are debated.

Nevertheless, in late 3rd millennium BC, Konar Sandal together with the other EBA settlements in the region steadily declined and were practically forgotten (Majidzadeh & Pittman, 2008; Lawler, 2011). The reasons proposed to explain the rise and collapse of these societies are subjected to many speculations and hypotheses. One of the hypotheses is that such civilization dynamics are attributable to climatic changes that favored, and later wrecked the agriculture in the area as a result of poor rainfall and consequential desertification (Fouache et al., 2005; Majidzadeh & Pittman, 2008; Lawler, 2011).

The idea of linking environmental, especially climatic changes and cultural dynamics is not novel. It is based on the logic that climate is one of the most essential determinants for good agriculture in pre-historic times. For example, in Middle East, the 4.2 ka event that ushered the sharp decline in precipitation is believed to have affected the earlier Akkadian Empire (Weiss et al., 1993) and the Old Kingdom of Ancient Egypt (Booth et al., 2005). Further to the east, the Indus Valley Civilization (Staubwasser, 2003) and multiple Bronze Age cultures in China (Gao et al., 2007) were also affected. My literature review indicated that studies on cultural-environmental connections in southern parts of Iran mostly clustered around the Zagros Mountains and lakes located alongside the Caspian Sea in the north (Djamali et al., 2009a,b; Jones et al., 2015; Djamali et al., 2016; Ramezani et al., 2016; Shumilovskikh et al., 2016; Talebi et al., 2016). In southeastern Iran, possibilities on such cultural-environmental interactions during the EBA were proposed in Shahr-i Sokhta (Salvatori & Tosi, 2005). However, in general, there are very few studies that have been conducted in southeastern Iran on cultural-environmental connections.

The key investigations in Konar Sandal have focused on archaeological findings (Madjidzadeh & Pittman, 2008), bioarchaeology (Mashkour et al., 2013) and geomorphology (Fouache et al., 2005, Fouache et al., 2008). However, harsh environmental conditions, notably desertification combined with complex phytogeographic conditions implies that data from palaeo-environmental studies are important to understand cultural dynamics in the region. Hence, lack of multi-proxy palaeo-environment data from the region hampers our understanding of the role of environment on ephemeral communities and their interactions. The vegetation and especially the vegetation history are highly understudied in Iran due to lack of experts (Akhani et al., 2013); the research on vegetation history is also burdened by the rarity of suitable wetlands to study in
dry areas of the country. As a result, fundamental questions remain unanswered such as how did historic societies cope with aridity? What did they cultivate? What kind of natural vegetation was exploited?

To firmly establish such complex links, it is necessary to carry out detailed palaeo-environmental studies involving multiple proxies at local scale, paying specific focus on vegetation history. Hence, the main goal of study is a detailed palynological analysis in a sediment core retrieved from a peat deposit near the excavation site in Konar Sandal (Fig. 1) that will be further supported by geochemical and sedimentological proxies to reconstruct the past vegetation dynamics, but also hydroclimatic changes. By focusing on vegetation, this study provides a novel perspective into whole culture-environment interactions debate. This study investigates if the changes observed in the vegetation are due to natural (e.g. climatic, hydrological, fire) forcings or human activities. The specific aims of the study are to establish:

(i) How did regional vegetation and landscape evolve in this region during the late Holocene?
(ii) What were the local and regional hydroclimatic changes and how could these be connected to vegetation dynamics, history and human practices?
(iii) What human practices (i.e. burning, cultivation and/or pastoralism) were present on the site and how those activities correspond to the natural environment? How did the environment facilitate or limit these practices; and how did people alter their environment?

3 Site description

3.1 Physical settings

Konar Sandal is an archaeological site situated approximately 25 km south of the city of Jiroft, in Kerman province, SE Iran (Fig. 1). The site is best known for the remains of settlement which was in the EBA home to the Jiroft culture (Majidzadeh & Pittman, 2008). Konar Sandal is situated in a fluvial plain in the Halil Rud (rud is river in Persian) basin. The archeological site is roughly at 570 m a.s.l. and ca. 1 km to the east of the Halil Rud. The Jiroft valley descends from two mountain ranges, the Kerman massif to the north-west, and the Barez Mountains in the east. The Barez Mountains rise to an elevation of 3740 m. The valley formed in a subsiding tectonic basin controlled by two complex fault systems bordering it in the east and west; these systems seem to have been active since the Mio-Pliocene (Fouache et al., 2005).

Halil Rud originates in Kerman Mountains flowing in south-eastern direction for ca. 400 km before draining into Lake Jazmurian, which is an endorheic lake. Fouache et al. (2005) suggested that during the Early Bronze and Iron Ages the river’s original position was to the west of its present day location. The river waters are fed by rain and melting snow of the Barez and Kerman mountains. Due to variable input of freshwater at the source, the hydrological regime of the Halil
Rud is characterized by intermittent and discontinuous flows, displaying high inter-annual variability. The variability may manifest itself through flooding events (Fouache et al., 2005). Construction of dams in the upper parts of the river has been interfering with flooding patterns, resulting in irregular flow on the downstream side (Mashkour et al., 2013).

The floodplain in the Jiroft valley is 2-5 km in width, containing many island-like structures of old fluvial terraces. The two major archaeological sites of Konar Sandal (Konar Sandal North [KSN] and Konar Sandal South [KSS]) are located on two of these terraces, which are 1-2 m higher than the modern floodplains. The 1992 flood event had almost covered the entire valley but these high terraces remained above the flood waters (Fouache et al., 2005).

*Figure 1.* Key physical, archaeological and phytogeographical features in the Jiroft valley. The coring site is in a peat deposit close to the archeological sites KSN and KSS.
The groundwater table in the alluvial plain is close to the surface. It creates artesian wells and serves as an important water resource for agriculture. Spring water chemistry changes from being freshwater near Jiroft, to more saline near Konar Sandal. Therefore, the groundwater is non-potable around Konar Sandal, mainly due to the high percentage of gypsum and other evaporates (Fouache et al., 2005).

3.2 Climate

According to the Iranian bioclimatic classification, the Jiroft plain is a Tropical desert defined by overall low annual precipitation (Djamali et al., 2011). Alternatively, Jiroft’s climate can be attributed to a subtropical desert based on Köppen-Geiger classification (Kottek et al., 2006). The region is influenced by two climatic forcings: Mediterranean and Asian monsoon systems that have varying impact on it. The dominant climate is of Mediterranean type, with a short wet season during winter and almost no precipitation during the hot summer (Blumler, 2005). The precipitation is driven by the North Atlantic Oscillation and winter rainfall is determined by changes in westerlies that drive the Mediterranean cyclones towards central Asia (Fallah et al., 2015). However, due to its close latitudinal proximity to the Intertropical Convergence Zone (ITCZ), SE Iran is on the terminal NW boundary of the Indian Summer Monsoons (ISM) (Meher-Homji, 1984).

During the mid-Holocene, southeastern parts of Iran are believed to have undergone a dramatic shift, from a humid Indian Ocean monsoonal climate to semi-arid Mediterranean conditions (Fleitmann et al., 2003, Fallah et al., 2015). The ITCZ peaked at its northward position 10 ka delivering intensive summer precipitation over the region. Around 8 ka the ITCZ started shifting southwards, leading to a decline in monsoon intensity, followed by a final retreat of the monsoons 6-7 ka in southeastern Iran (Fleitmann et al., 2003). The gradual transition to Mediterranean climate was confirmed by climate modeling, where by around 6 ka Iran witnessed intensified winter precipitation (little change in summer precipitation implied a complete retreat of monsoons) (Fallah et al., 2015). As a result of such transition, as well as the northward shift of the West Asian Subtropical Westerly Jet, Iran also experienced extreme droughts, such as the 4.2 ka event (Fallah et al., 2015). The dramatic climatic transition resulted in substantial aridification in the Middle East (Djamali et al., 2010; Fallah et al., 2015).

It is to be noted that modern-day monsoon driven precipitation has been reported in meteorological records from the extreme SE parts of the country, but it is not widespread. Rodwell & Hoskins (1996; 2001), explained such long-distance monsoon-influence in southern parts of Iran, referring them to as ‘monsoon-dessert mechanism’. The ISM westward depression enhances the climatic influence of subtropical anticyclones that govern the Iranian climate. The strong anti-cyclones block both, the westerlies and the Mediterranean cyclones, from reaching the Iranian Plateau. These atmospheric changes result in a shorter spell of late spring rainfall, overall less annual precipitation and acceleration of the regional aridification (Djamali et al., 2010).
Meteorological records were collected from meteorological station located approximately 10 km south of Jiroft and were provided by the Iranian Meteorological Organization (*Fig. 2*). The average annual temperature in the area is around 26.3 °C, fluctuating on a monthly average basis between 13.5 and 37.1 °C in January and July respectively. The highest temperature recorded was 48.6 °C. The coldest and hottest monthly temperatures correspond to the winter and summer months; annual precipitation is 194 mm. Wet season, with monthly precipitation exceeding 30 mm, occurs from December to March. The dry season occurs from April to October, with monthly precipitation levels not exceeding 10 mm. The wettest month is February (46.6 mm), while the driest month is July (1 mm).

*Figure 2.* Present-day climatic conditions; diagram is showing monthly temperature and precipitation changes on annual basis in Jiroft. The dashed red horizontal lines stand for maximum ($T_{\text{max}}$) and minimum ($T_{\text{min}}$) temperature averages; the solid red line in the middle is for mean monthly temperature ($T_{\text{mean}}$) changes.

**3.3 Vegetation**

From land use perspective, vast areas in the Jiroft valley have been converted to date palm, orange or cereal (wheat, barley) plantations, visible in satellite images. Mashkour et al. (2013) also reported similar observations, emphasizing that Jiroft is an important center for agriculture in modern southeastern Iran. The extreme-heat, occasionally reaching almost 50 °C, is ideal for cultivating dates and citrus fruits (Mashkour et al., 2013). The local wetland vegetation is characterized by aquatic plants dominated by *Cyperaceae*.

Based on natural vegetation transect surveys conducted by Léonard (1991), Jiroft lies on the boundary of two significant phytogeographical domains in North Africa and Eurasia (*Fig. 1 & 3*). In the northern side of the plain, originating in the Kerman Mountains, the vegetation belongs to the Irano-Turanian floristic region. Further to the south, extending up to Lake Jazmurian, the vegetation is defined by the Saharo-Sindian flora (Zohary, 1973; Léonard, 1991; 1993).
Figure 3. Vegetation map based on Frey & Kürschner (1989), simplified by Djamali et al. (2011). The exact position of the early Holocene ITCZ is, however, uncertain.
In Kerman Mountains, the Irano-Turanian landscape is represented by Amygalus scoparia and Acer monspessulanum subsp. persicum. At 1150 m a.s.l., the Irano-Turanian vegetation is completely replaced by the Saharo-Sindian flora (Fig. 1). The latter is described as a pseudo-savannah type dominated by Prospis koelziana var. koelziana and Ziziphus spina-christi (Léonard, 1991). Similarly, Frey & Kürschner (1989) attributed the region to a Prosopis-Ziziphus zone (Fig. 3). Djamali et al. (2011) indicated that xeromorphic vegetation occupying this region is adapted to withstand extreme temperatures.

Notably, entire Jiroft valley has been exposed to unprecedented degradation resulting from livestock (especially goats and camels) trampling and overgrazing (Mashkour et al., 2013). Such disturbance has facilitated the environment for spiny-shrub species, including Rhazia stricta, accompanied by Calotropis procera subsp. hamiltonii, Ochradenus baccatus, Ziziphus spina-christi and Convulvulus acanthocladus. Along with these shrubs, some herbaceous plants, Forsskaolea tenacissima, Cheilanthes pteridiodes, Asphodelus tenuifolius and Ziziphus spina-christi and Convulvulus acanthocladus. Along with these shrubs, some herbaceous plants, Forsskaolea tenacissima, Cheilanthes pteridiodes, Asphodelus tenuifolius and Calligonum comosum (Léonard, 1991).

At lower elevations (600 m a.s.l.), at the point closest to Konar Sandal (approx. 5 km; see Fig. 1) the vegetation is dominated by spiny-shrubs: Rhazia stricta, Prospis koelziana var. koelziana, Lycium depressum ssp. augustifolium, Ephedra foliata and Calligonum comosum (Léonard, 1991).

Further to the south (500 m a.s.l.), near the city of Kahnooj, the Halil Rud riverbanks retain riparian vegetation characterized by Tamarix and Salix. Beyond this point, the landscape achieves the highest levels of degradation resulting from livestock trampling and overgrazing. The same shrubby vegetation of Prospis koelziana var. koelziana, Ziziphus spina-christi and Calligonum spp. attains a lower stage of development, occupying less surface area. In addition to these species, there is a pronounced appearance of Poaceae grassland along with Schismus arabicus, Stipagrostis hirtigluma, Rostraria pumila and Stipa capensis, covering approximately 60% of the ground cover (Léonard, 1991).

3.4 Archaeological and bio-archaeological settings

The Earl Bronze Age artifacts were accidentally discovered during floods in the Halil Rud that exposed ceremonial graves and beautiful artifacts. The mass grave plundering of these historical cemeteries drew unprecedented international attention to the site. The excavations have revealed the remains of an EBA settlement attributed to the Jiroft culture (Madjidzadeh & Pittman, 2008). Most of the on-site artifacts recovered by archaeologists and confiscated by the Iranian government were steatite vessels, often inlaid with semi-precious stones. Along with ceramics, inscribed bricks and tables were discovered with a distinctive writing system belonging to a variation of Linear Elamite (Madjidzadeh & Pittman, 2008). Desset (2014) confirmed, that the
following form of Linear Elamite and ‘Geometric’ handwriting systems evolved in Jiroft and was different from other historical handwriting systems (e.g. cuneiform and Indus) in second half of 3rd millennium BCE. The unique handcrafts and writing suggested that Jiroft evolved independently, arguably, as a civilization of its own (Madjidzadeh & Pittman, 2008). In addition to the artifacts, ruins of domestic and architecture quarters were found during the excavations. Discovery of platforms with copper slag, tools and ingots implies that metallurgical activities were common (Madjidzadeh & Pittman, 2008). Two citadel-like mud-brick mounds, Konar Sandal North and Konar Sandal South, located 1.4 km apart, are the most remarkable constructions in the area standing on the terraces of the Halil Rud.

Mashkour et al. (2013) conducted analysis of charcoals, fossil seeds and animal bones to investigate the bio-archaeological context of Konar Sandal during the Bronze Age. The analysis of charred wood revealed the dominance of two biotopes. The first one was riparian forest that thrived in the Halil Rud basin, characterized by Tamarix, Salix and Dalbergia sissoo. The second biotope was attributed to sub-tropical Saharo-Sindian, open shrub- and woodland flora. Similar to the current floristic settings, the area was occupied by Acacia spp., Prosopis cineraria/koeleziana, Zizyphus cf spina-christi, Lycium spp., Salvadora persica and Chenopodiaceae during pre-historic times (Mashkour et al., 2013).

Charred plant remains together with ornamental motifs on steatite vessels reveal that date palm (Phoenix dactylifera) was the main cultivated fruit tree. Along with dates, grape vines (Vitis vinifera) and cereals, free-threshing wheat (Triticum aestivum/durum) and barley (Hordeum vulgare) were also prominent cultivars in Konar Sandal during the Bronze Age. The settlement was dependent on freshwater supply from the Halil Rud for agriculture. Main domestic animals comprised of sheep and goats, proven by the bone artifacts. Bovines, camels and horses may have also roamed in the area (Mashkour et al., 2013).

Fouache et al. (2005) and Madjidzadeh & Pittman (2008) suggested that the Halil Rud Valley was inhabited in the 3rd millennium BCE, and afterwards may have been abandoned due to climatic aridification, followed by salinization that burdened agriculture. Up until the 1st millennium BCE, the valley may have been inhabited by nomads (Madjidzadeh & Pittman, 2008). The Kerman province (including Jiroft) even today serves home to numbers of tribal nomads continuing an ancient lifestyle (Zanjāni & Nejātiān, 2014). Interestingly, some artifacts dated to later periods imply that Konar Sandal may have been an important district even during the Islamic era of the Persian Empire (Madjidzadeh & Pittman, 2008). Moḥammad b. Ebrāhim, in his chronicles written during the 17th century, referred to Jiroft during the Seljuk period (12th century CE) as a trading centre between the East and West. According to his records, the goods came from “China, Transoxiana, and Khitāy, from Hindustān and Khurāsān, from Zanzibār, Abyssinia, and Egypt, also from Greece, Armenia, Mesopotamia, and Azharbāyjan” (Houtsma, 1886). Likewise, Marco Polo in his travelogue (around 13th-14th century) praised the incredible agricultural production in Jiroft Valley listing rice and multiple grains, as well as dates
and a variety of fruits cultivated in the area (Colbert et al., 1997). The travelogues also indicated that the glory of Jiroft was slowly fading as it was facing conquests by the Tartars (Yule, 1903).

4 Materials and methods

The 250 cm sediment core was obtained from a peat deposit locally named as Daryache (Persian name for lake) near Jiroft (28°27'5.2"N 57°46'49.1"E). The peat-land is located between the raised mounds of Konar Sandal, KSN and KSS, ca. 1 km to the west from the Halil Rud. Coring was done in February, 2015 using Russian peat borer. The core was sectioned into 1-4 cm intervals and samples were stored in polythene bags prior use.

4.1 Radiocarbon dating

Eight samples were sent for AMS radiocarbon dating to the Poznan Radiocarbon Laboratory, Poland to establish the chronology (Table 1). The dated material was bulk sediments. An age-depth model was generated with the Clam modeling package, version 2.2 (Blaauw, 2010) using a smooth spline interpolation with spar = 0.35, 95% confidence range and 10 000 iterations (Fig. 4).

4.2 Pollen extraction and counting

Thirty-five samples were extracted for palynological analysis at intervals of 1-10 cm. Initially, 19 samples (10-20 cm spacing) were screened. An additional 16 samples were selected for in-depth analysis from the key depths of interest and uncertainty. The chemical treatment was conducted adopting classical chemical pollen extraction procedure standardized by Moore et al. (1991). Samples were weighed and a single Lycopodium spore tablet (batch nr. 1031) was added to each sample placed in 50-ml tubes in order to determine pollen and charcoal concentrations (Stockmarr, 1971). Laboratory pollen extraction consisted of one cold HCl (37%) treatment. This was followed by cold HF (58%) treatment, adding an additional cold HF treatment to secure removal of undesired materials. The samples were then treated with concentrated HCl (37%) again. In the case of the formation of secondary micro-crystals, one or two additional warm HCl treatments were performed, placing the tubes in a hot bath (at 90 °C) for 10 minutes. The samples were dehydrated overnight in acetic acid; then acetylated using a mixture of sulfuric acid and acetic anhydride (at ratio of 1 to 9 respectively) in a hot bath for 4 minutes. Finally, the samples were passed through filters with 160 and 10 μm mesh sieves. The extracted materials were stored in micro-tubes containing alcohol, which was replaced with glycerin when making microscopy slides.

The pollen were identified and counted using 500× magnification light microscope. The numbers of Lycopodium and charcoal particles were also recorded. For each sample, the minimum of 300 upland-flora pollen was counted (on average 320 grains per sample). An exceptional case occurred in DAR-20, where counting proceeded only up to 128 upland pollen grains, due to
extremely low pollen concentrations. Pollen identification was based on pollen identification keys and atlases (Reille, 1992; Beug, 2004) and Iranian pollen reference collections established at the Institut Méditerranéen de Biodiversité et d’Ecologie, Aix-en-Provence, France.

4.3 Sedimentological and geochemical analyses

Lithology was recorded in field by visually assessing the sediments after the core was retrieved and photographed. Magnetic susceptibility (MS) was measured every 2 cm using Bartington MS2C core logging sensor. The grain size was measured every centimeter using Micromeritics SediGraph III Particle Size Analyzer. X-ray fluorescence (XRF) scanning was performed with hand-held XRF scanner to detect iron (III) oxide (Fe₂O₃) at irregular intervals of 4-10 cm. Each scanning event took around a minute.

4.4 Data analysis and visualization

Palynological, geochemical and sedimentological data analysis and visualization was performed in C2 software, version 1.7.2 (Juggins, 1991-2011). Total pollen sum (TPS) was established by including all identified pollen types (arboreal, upland herbs and aquatics). Meanwhile, two different versions of pollen sum (PS) was calculated; the first (PS-1) included arboreal and herbaceous pollen; the second (PS-2) comprised all arboreal and herbaceous pollen but excluding Amaranthaceae (formerly Chenopodiaceae).

Charcoal concentrations were calculated using the equation:

\[ C_t = \left( \frac{T_c}{L_c} \times \frac{L_s}{Wt_s} \right) \]

where \( C_t \) stands for charcoal concentration, \( T_c \) for charcoal count per sample, \( L_c \) for \textit{Lycopodium} count in the same sample, \( L_s \) is number of \textit{Lycopodium} spores per tablet, \( Wt_s \) is weight of sediment (Wang et al., 1999):

5 Results and interpretation

5.1 Radiocarbon dating

AMS \(^{14}\text{C}\) dating and calibration results are displayed in \textit{Figure 4} and \textit{Table 1}. Based on the age-depth model, the core ranged from 3951 cal yr BP at the bottom (DAR-250) to 636 cal yr BP at the top (DAR-14). In the deepest section dated at 245 cm, the \(^{14}\text{C}\) result is slightly offset (by less than a century) against the sequence of the remaining dated samples. This implies that gentle disturbance may have occurred in the sediment as a result of flooding. From 235 cm to 143 cm sedimentation rate in the peat-land is relatively high, but gently diminishing from the latter point onwards. The sedimentation rate appears uniform throughout the remaining core. The calibrated
dates from the age-depth model (Fig. 4) were applied for interpretation and discussion of the remaining results.

DAR pollen records start just after the projected collapse of Jiroft around (4 ka), covering the period since in the late Bronze Age, all the way through the Iron Age (started ca. 1400-1300 BCE), the Persian Empire (ca. 550 BCE-650 CE), Islamic invasion (651 CE) and Islamic period, and ending soon after the Mongol invasion (ca. 1219-1221 CE).

Figure 4. Age-depth model of Daryache (Konar Sandal, SE Iran) sediment core with respect to the lithological description. The black line indicates median calibrated ages BP, the grey shadow indicates the minimum and maximum values at a 95% confidence interval.

Table 1. Summary for AMS dating and calibration results on eight Daryache core peat samples.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Depth (cm)</th>
<th>Lab no.</th>
<th>Age $^{14}$C (yr BP)</th>
<th>Calibrated age (cal yr BP)</th>
<th>Material dated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dar-35</td>
<td>34-35</td>
<td>Poz-85097</td>
<td>1125 ± 30</td>
<td>1037</td>
<td>Bulk sediments</td>
</tr>
<tr>
<td>Dar-64</td>
<td>63-64</td>
<td>Poz-83152</td>
<td>1700 ± 35</td>
<td>1579</td>
<td>Bulk sediments</td>
</tr>
<tr>
<td>Dar-95</td>
<td>94-95</td>
<td>Poz-83153</td>
<td>2130 ± 30</td>
<td>2139</td>
<td>Bulk sediments</td>
</tr>
<tr>
<td>Dar-114</td>
<td>113-114</td>
<td>Poz-85099</td>
<td>2405 ± 30</td>
<td>2510</td>
<td>Bulk sediments</td>
</tr>
<tr>
<td>Dar-143</td>
<td>142-143</td>
<td>Poz-83154</td>
<td>3010 ± 30</td>
<td>3080</td>
<td>Bulk sediments</td>
</tr>
<tr>
<td>Dar-195</td>
<td>194-195</td>
<td>Poz-83155</td>
<td>3400 ± 35</td>
<td>3672</td>
<td>Bulk sediments</td>
</tr>
<tr>
<td>Dar-235</td>
<td>234-235</td>
<td>Poz-83156</td>
<td>3655 ± 35</td>
<td>3902</td>
<td>Bulk sediments</td>
</tr>
<tr>
<td>Dar-245</td>
<td>244-245</td>
<td>Poz-85100</td>
<td>3570 ± 30</td>
<td>3935</td>
<td>Bulk sediments</td>
</tr>
</tbody>
</table>
5.2 Palynology

The summary of pollen results is presented in simplified percentage pollen diagrams (Fig. 5&6). In total 70 pollen types were identified at 35 depths. These represent 25 taxa of arboreal plants (trees and shrubs), 38 herbaceous (upland herbs) and 7 semi-aquatic and aquatic plant taxa. Pollen zonation is based upon pollen dynamics that differ from adjacent zones. For the most part, local pollen representation zones (LPAZs) were established with the help of *Artemisia* and *Sparganium*-type pollen curves. In total, 4 major LPAZs were identified, two of which were divided into a few more sub-zones. Pollen preservation varied; poor preservation was prevalent in the deepest parts of the core (>240 cm). The sample at 20 cm depth was also exceptionally poor in pollen counts, but rich in charcoal. In many cases, pollen identification and counting was hampered due to the high organic matter content that could not be affectively removed during pollen extraction.

The most abundant pollen type was Amaranthaceae that made up between 19 and 92% of PS-1 per individual sample, with an average of 62% (Fig. 5). Due to its ubiquitous pervasiveness, a second pollen diagram was generated, where Amaranthaceae was excluded from PS-2 and was instead represented as a percentage of TPS (Fig. 6); the diagram in *Figure* 6 was the main figure used for interpretation of pollen results. In addition, Amaranthaceae was difficult to interpret due to its halophytic nature and ecologically diverse preferences for its growth that range from semi-arid to arid and well-drained to poorly drained edaphic conditions, and its high prevalence amongst the Iranian semi-desert plant communities (Freitag, 1977). The second most prevalent pollen types were *Artemisia*, *Poaceae* and *Prosopis*. In the vast majority of cases, the curve for *Artemisia* negatively corresponds to *Poaceae* (>30 μm). Djamali et al. (2009a) and Shumilovskikh et al. (2016) applied a *Poaceae*/*Artemisia* ratio, where the lower number corresponds to drier conditions, and *vice versa*. The observed relationship between *Artemisia* and *Poaceae* does not conflict with the other proxies, proving, that higher numbers of *Artemisia* may translate into a surge for arid conditions.

It is not surprising that aquatic plants were abundant (especially Cyperaceae and *Sparganium*-type) in this core because of its location. All aquatic plant pollen were, therefore, excluded from the pollen sum. The most prominent arboreal plant taxon was *Prosopis*. However, due to lack of palynological data and reliable identification records in pollen atlases, *Prosopis* was not identified to specific level (*P. farcta*, *P. koelziana*, or *P. cineraria*). However, based upon our personal observation of two *Prosopis* species of the IMBE reference collection (*P. farcta* and *P. cineraria*) and an earlier botanical survey by Léonard (1991), *P. cineraria* and *P. koelziana* are most likely species reported from this region.
Figure 5. Selected pollen taxa and groups in the DAR core. Pollen abundance is expressed as percentages. Insignificant pollen taxa were excluded from visualization. TPS was calculated including all pollen types identified; PS-1 was derived only from arboreal and herbaceous pollen types. Micro-charcoal particles (10<\textless N<160 \ \mu m) were expressed in millions of particles per 1 g of sediment. Pollen taxa not exceeding 1% in any individual sample are represented as circles. Exaggeration lines represent 5 time multiplication of original percentage value.

Figure 6. Similar to Fig. 5, but arboreal and herbaceous pollen is represented as PS-2, where Amaranthaceae is represented as in percentages of TPS.
The interpretation of pollen assemblages was based upon ecological characteristics of individual pollen types. Wetland hydrological dynamics was interpreted by the prevalence of aquatic plants (Cyperaceae, Lythraceae, Sparganium-type). Small Poaceae pollen (<30 μm) are believed to be produced mostly by Phragmites, which are local producers (Djamali et al., 2016). The upland plants, predominantly desert shrubs (Calligonum and Ephedraceae) and herbs (Artemisia) were central to establishing the regional climate. Pollen from cultivars (Cerealia-type) were investigated in relation to potential agricultural activities in the past. Depending upon pollen assemblages, prevalence of micro-charcoals (>10 μm) in the intervals were used to interpret fire, attributing their presence to either anthropogenic burning practices for agro-pastoral activities or naturally occurring forest fires. The extremely high micro-charcoal content can also be indicative of local fire events, possibly inside the wetland.

5.2.1 LPAZ-A (250-210 cm, 4.3-8 ka)

This zone is characterized by moderate frequencies of desert shrubs (Calligonum and Ephedraceae), that may be indicative of aridity, aeolian activity and sand dune formation (Zohary, 1973). The distinctive peaks of Artemisia accompanied by simultaneous decline in Poaceae (>30 μm) may further imply aridity (Djamali et al., 2009a, Shumilovskikh et al., 2016). At the same time, riparian trees (Salix and Tamarix) are present. The charcoal levels are rather low in this zone.

Within the same zone, it is possible to distinguish two sub-zones with slightly different floristic characteristics. The pollen composition in LPAZ-A1 (250-235 cm, 4 ka), is featured by peaks of Prosopis; Asteroideae and Cichorioideae that suggest either aridification and wetland desiccation or extreme soil degradation (Woldring and Bottema, 2003; Zohary, 1973). The wetland vegetation is characterized by the dominance of Cyperaceae over Sparganium/Typha. Such aquatic plant assemblages support evidence of desiccation and peat formation (Djamali et al., 2009b). There is little pollen of any cultivars, but a single pollen grain of Myrtle (Myrtus communis) was distinctly identified, which is intriguing as this tree is a typical Mediterranean element, presence of which shows either its cultivation or significant population occurring naturally in the valley.

In LPAZ-A2 (235-210 cm, 4.3-8 ka) there is a sharp rise in Artemisia accompanied by continuous increase in the populations of desert shrubs. This section indicates first significant appearance of Cerealia-type pollen, indicating cereal cultivation. There is also an increase in Sparganium-type pollen, indicating rising water levels (Shumilovskikh et al., 2016). Similar to LPAZ-A1, the pollen assemblage in this sub-zone however, indicates that the region was encountering dry spells, but positive changes in the water levels of the peat-land also occurred.
5.2.2 LPAZ-B (210-170 cm, 3.8-3.4 ka)

Regional pollen assemblage show a decline in Ephedraceae, followed by dramatic drop in Artemisia, indicating amelioration of desertic conditions and moisture increase. There is a corresponding increase in riparian trees, i.e. Tamarix. A peak of Prosopis has also occurred. Locally, at the wetland level, at the beginning of the zone, high values of Sparganium-type pollen and small Poaceae pollen (<30 μm) indicate a rise of the water table. However, towards the end, Sparganium-type is replaced by Cyperaceae. Lythraceae demonstrates significant values suggesting important seasonal water table variations (Daniel Pavon, IMBE, Aix-en-Provence, 2017; personal communication). Human activities, i.e. cereal cultivation, are indicated by high values of Cerealia-type pollen and Centaurea (mostly C. solstitialis-type); the latter is a typical weed in cereal fields (Bottema & Woldring, 1990). Towards the end of this period, cultivation shifts to pastoralism. This is supported by the gradual increase in Plantaginaceae (mostly Plantago lanceolata-type) and high values of Polygonum aviculare-type which signal intensive anthropogenic disturbance, such as trampling by livestock and overgrazing (Djamali et al., 2009b, Leroy et al., 2013). Increase in charcoal concentrations occurs simultaneously coinciding with the Sparganium due to burning for agro-pastoral land. This zone may be characterized by milder regional climatic conditions than the ones in LPAZ-A, and very likely favoured the agro-pastoral communities.

5.2.3 LPAZ-C (170-130 cm, 3.4-2.8 ka)

The following zone, similarly to LPAZ-A, retains the desert shrubs; an ultimate increase in Artemisia occurs in this section, accompanied by a sharp decline in Poaceae (>30 μm). At the lower end of the zone, Prosopis is completely absent, and only retains low values towards the end of the zone. The populations of riparian trees are insignificant. Sparganium-type pollen demonstrates very low values, and is replaced by Cyperaceae in this section. The emergence of such pollen may signal regional aridification, but clearly marks the low water level in the peat-land. The frequency of Cerealia-type pollen is insignificant suggesting less human activities and intervention. A small peak in Plantaginaceae, however, may suggest that some ephemeral pastoralist communities may have been active at this site. A few pollen grains of Olea were detected but no reliable conclusion should be made about olive cultivation: these pollen grains could be transported over long distances (Woldring & Bottema, 2003) or be produced by wild olive trees in the Kerman Mountains (Djamali et al., 2009a, Zohary, 1973).

5.2.4 LPAZ-D (130-14 cm, 2.8-0.6 ka)

This zone is characterized by substantial decline in percentages of Artemisia. There is also a continuous presence of Cerealia-type pollen suggesting an almost permanent occupation by sessile agrarian communities. Based on variations in pollen of aquatic plants and some upland herbs, the zone can be further divided into two distinct subzones.
In LPAZ-D1 (130-40 cm, 2.8-1.1 ka) there is moderate presence of desert shrubs (Ephedraceae) co-occurring with Asteroidae and Cichorioideae. Riparian trees briefly emerge. The beginning of the sub-zone is marked by an increase in Sparganium-type pollen and Poaceae (<30 μm) (*Phragmites*). Towards the upper end of the sub-zone, there is an increase in Lythraceae and decrease of Sparganium-type pollen indicating lower wetland water tables. The zone has a very characteristic crash in Amaranthaceae (Fig. 6); meanwhile, Poaceae is at its highest abundance. Taking into account high values of Poaceae/Artemisia ratio, the following assemblage is representative of milder conditions. Plantaginaceae and *Rumex* hint at pastoralism. In addition, there are two less, but significant spikes of charcoal, followed by disappearance of shrubs. These fires are likely to have an anthropogenic origin hinted by active human communities present on site.

In LPAZ-D2 (40-14 cm, 1.1-0.6 ka) Cerealia-type pollen culminates together with *Centaurea*. Plantaginaceae indicate active pastoralism. *Artemisia* stays low, and there are no desert shrubs, except for short episode of *Calligonum*. Asteroidae and Cichorioideae pollen reach their highest abundances in this section, likely indicating extreme soil degradation (or desiccation of wetland).

There is also a sharp increase in charcoal concentrations. Such dramatic peak in charcoal levels may occur due to close proximity to the source of fire/combustion; or, corresponding to low pollen concentration such fire may indicate the burning inside of the wetland. The fire could have destroyed the natural aquatic flora which only started recovering towards the end of LPAZ-D2. This is possibly the beginning of land reclamation and the extreme exploitation of the wetland which could explain its desiccation. Whereas upland plants suggest the milder climatic condition, the human impact on both, wetland and the landscape, may be inevitable.

5.3 Sedimentology and geochemistry

Palynological results were supported by sedimentological and bulk geochemical proxies. The latter were grouped into separate zones (1-4) based on the different trends in these sections (Fig 7). However, the palynological results were taken into account when interpreting these proxies, and determining the different zones. The results are presented in synthesized diagram (Fig. 7).

The lithology is dominated by peat that was alternating between gyttja and amorphous peat. The gyttja is interpreted as sedimentary material that formed during waterlogging, in contrast, amorphous peat is characterized by high degradation levels that occurred after oxidation (i.e. due to a low water table; Myslinska, 2003). Ferric oxide analyses indicate aerial exposure of the peat under drier conditions, implying that the peat was subject to oxidative degradation (Nichols, 2009). Therefore, low levels of Fe₂O₃ indicate anoxic conditions, often due to waterlogging, thus often corresponding to transition from amorphous peat to gyttja in lithology. The carbon and nitrogen ratio (C/N) is used to trace the origin of organic matter. Meyers & Ishiwatari (1993) and Meyers (1997) suggest that C/N values between 4 and 10 indicate carbon of aquatic productivity,
while values above 20 indicate the terrestrial origin. Any values in between, usually between 12 and 18, are indicative of the mixture of both.

Large sized grains (sand) appear in sediments as a result of erosion, which in turn occurs either due to higher flow and flooding events, or aeolian transport happening due to desertification (Nichols, 2009). Similarly, MS is often used to detect erosion (either due to flooding or aeolian activity; Thompson & Morton 1979). In this study, MS was very difficult to interpret since it had little correspondence to the other proxies, especially Fe$_2$O$_3$which is naturally magnetic. In addition, grain size variation did not display similar trends as MS.

5.3.1 Zone-1 (250-180 cm, 4-3.5 ka)

In this zone, the lithology is dominated by gyttja, but transitions into amorphous peat at 200 cm depth. There is a declining trend of iron (III) oxide from ca. 8 % to 3 %. Fine-sized particles consisting of a mixture of silt and clay constitute on average 25% of sediments. The sand content remains mostly consistent, but slighter lower than the zone above. The MS values reach the highest value of 30 SI between 235 and 250 cm, and gradually decline towards the top of this zone. This is the only zone where MS corresponds to iron (III) oxide, backing the interpretation of rising water levels and waterlogging. Both, TOC and C/N show a steady increase, where aquatic productivity is gradually complemented by terrestrial carbon input (C/N values raise from ca. 8 to 19). The proxies in this zone suggest that the shallow peat-bog was transforming to a waterlogged wetland.

5.3.2 Zone-2 (180-135 cm, 3.5-2.8 ka)

The zone is characterized by very high sand content (ca. 85-95%), low magnetic susceptibility (ca. 5), low TOC and C/N (Fig. 7). Overall, iron oxide shows lower values compared to lower zone except a peak at 164-cm depth exactly corresponding to a peak in sand strongly suggesting an increased aeolian activity. The wetland was exposed to oxidation (degradation) and underwent acute desiccation. Overall, the productivity is very low in this zone. Oxidation perhaps facilitated degradation of organic matter and encouraged formation of amorphous peat that is prevalent in this zone. In this zone MS declines and remains almost steady to the top of the core (Fig. 7).

5.3.3 Zone-3 (135-75 cm, 2.8-1.8 ka)

In this zone, Fe$_2$O$_3$ demonstrates relatively high values but a reverse trend compared to the zone below, it shows a declining trend. Such a decline is supported by the formation of gyttja. Around 100-65 cm depth, undecomposed plant fragments occur, suggesting anoxic conditions that resulted in good preservation (Fig. 7). At the same time, both TOC and C/N ratios increase denoting to an increasing trend in organic productivity. Such an assemblage strongly suggests an increase in the water table.
Figure 7. Synthesized diagram displaying the multi-proxy results from sedimentology, geochemistry and palynology of the Daryache core. Zones (1-4) were established based on visual assessment of homogenous patterns displayed by all proxies, different from neighbouring zone in regard to depth. Exaggeration lines multiply palynological percentage values 5 times.
5.3.4 Zone-4 (75-14 cm, 1.8-0.6 ka)

The wetland encountered high water levels ca. 1.8-1.5 ka, which was followed by the cut-off from water input, leading to desiccation. There is a significant decline of sand content throughout the entire zone and ca. 40% of sediments are comprised of silt and clay that is generally indicative of declining aeolian activity, implying, that desiccation might arise due to human pressure. The desiccation is confirmed by the trend of iron (III) oxide shows oxidation (corresponding to increase in amorphous peat content) between 75 and 40 cm. At the same time, decreasing trend TOC and C/N could be associated to peaks of charcoal in LPAZ-D2 and disappearance of aquatic vegetation. The remaining part of the core, 40-14 cm, consists of unconsolidated dry material that has undecomposed plant matter, roots and gyttja; MS slightly increases from 5 to 10 SI (Fig. 7).

6 Discussion

6.1 Evolution of regional vegetation and landscape over 4000 years

The entire period extending from 4 ka to 0.6 ka in the Jiroft valley was marked by the explicit dominance of Saharo-Sindian vegetation. Continuous (although not uniform) presence of *Prosopis* confirmed that Saharo-Sindian flora dominated over the Irano-Turanian vegetation. Similarly, Léonard (1991; 1993) concluded that the region around Lake Jazmurian (to which the Jiroft valley belongs regionally), comprised of over >35% of endemic Saharo-Sindian species. These may have included different *Tamarix* and *Calligonum* species, but the fact cannot be confirmed in this study since neither pollen-type could be identified to the species level. Nevertheless, characteristic Irano-Turanian pollen appeared in the samples (e.g. *Juniperus*), but their overall counts were always very low. These pollen grains may have been produced locally, but most likely, they were transported from higher altitudes.

The landscape throughout the region during all the sampled period was an open pseudo-savannah dominated by xerophytic shrubs and trees (mostly *Prosopis*); however the land cover shifted from open xeric scrubland forests to even more open, degraded landscapes, loosing desert shrubs, Ephedraceae and *Calligonum* as significant landscape components ca. 2.5-2.1 ka. Instead there was an apparent spread of Poaceae grassland. Nonetheless, as observed by Léonard (1991), *Ziziphus spina-christi* was also a characteristic tree species in the area that has not been detected in DAR samples. Also, Frey & Kürschner (1989) indicated *Prosopis* spp. and *Ziziphus* spp. as some of the most distinctive trees in southeastern Iran and suggested devising a *Ziziphus*- *Prosopis* zone. Meanwhile, Wright et al. (1967), when studying pollen rain in Western Iran, noticed that *Ziziphus spina-christi* was a poor pollen producer and disperser. In addition, it was extremely underrepresented in the pollen rain of savannah environments regardless its high abundance. Moreover, representation of *Z. spina-christi* pollen suppressed by other pollen types produced by wind-pollinated plants, especially Amaranthaceae and *Artemisia*. Hence, this may explain why *Zyzyphus* was not detected during pollen analyses, also implying that it should have
been an important detail in the landscape of Jiroft. As mentioned, the pollen of Amaranthaceae and *Artemisia* are also often overrepresented; hence it is difficult to conclude what was the share of these plants in the regional vegetation cover when comparing to arboreal vegetation. Nonetheless, it is likely that herbaceous plants and scrubs were covering a substantially higher share of the landscape than trees or shrubs based on overall pollen representation and also pollen rain studies (Freitag, 1977; Wright et al., 1967).

Presence of riparian forests is more evident during the late Bronze Age, in 4-3.5 ka. However, *Tamarix* is a poor pollen producer (Freitag, 1977). Presence of *Tamarix* pollen primarily indicates that a *Tamarix* tree grew within the close proximity to the place from where the sediment core was retrieved. Due to its preference to root near water (which occurs most often, but is not definite), *Tamarix* may have grown on the banks of the studied wetland, thus depositing pollen within very close proximity to sediment core extraction site. Alternatively, Fouache et al. (2005) suggested that the river course was more to the west compared to its present day position during the Bronze and Iron Ages. Therefore, it could be that the river position, with its riparian forests, was closer to Daryache, and there was a greater probability of pollen being deposited to the wetland. Therefore, disappearance of *Tamarix* in the diagrams may not necessarily indicate droughts (i.e. drying out of either Daryache or the Halil Rud river bed, or overall aridity) or even exploitation of these trees by humans; the basic increase in distance between the pollen producing tree and Daryache reduces chances of detecting *Tamarix* pollen. Accordingly, there is no conclusion on whether riparian forests were a regular feature of the landscape in Jiroft.

6.2 Local and regional hydroclimatic changes

Djamali et al. (2011) in their study on Iranian bioclimatic classification attributed the pseudo-savannah biome to Tropic desertic bioclimate. The main characteristic feature of Iranian savannah like vegetation (that makes it also different from North African savannahs) is absence of C₄-grasslands (Cerling, 1999). The absence of such grasslands occurs due to the climatic factors, i.e. lack of summer precipitation. South-east Iranian savannah vegetation is adapted to withstand high soil salinity, extreme summer temperatures and they depend on groundwater instead of rain. Under such tough environmental conditions only xeromorphic species can flourish. Hence, it is not surprising that the Jiroft valley is dominated by *Ziziphus spina-christi*, *Prosopis* and C₄-chenopods (Amaranthaceae). Freitag (1977) also noted that Amaranthaceae is typical to semi-arid and saline environments, hence is very abundant in the Iranian desert. The dominant presence of both, Amaranthaceae and *Prosopis* in pollen diagrams (Fig. 5, 6 & 7) indicates that climate did not undergo major changes such as dramatic changes in precipitation. In fact, any evidence of summer precipitation during this period is absent. The lack of evidence for vegetation of transitional bioclimates is consistent with the idea of no ‘dramatic’ long term climatic changes. If such a change had occurred, pollen types of typical vegetation of *Tropical*
xeric or *Tropical hyperdesertic* bioclimates would have manifested themselves in the diagrams if the climate became significantly milder or more arid, respectively.

Nevertheless, evidence from pollen and the other geochemical proxies demonstrate several wet periods and droughts. While water in Halil Rud controls the sub-surface hydrology around Daryache, the river may be governed by climatic factors, such as the precipitation and/or temperature, in Kerman Mountains (Fouache et al., 2005). In addition, human activities may also influence peat-bog hydrology: vegetation clearance facilitates greater water input and erosion and input water may also be reduced by diverting the Halil Rud water for irrigation. However, it is highly unlikely that local climate, i.e. local variation in precipitation or temperature was a critical factor to influence hydrology in the peat-land.

The wetland encountered phases of low-water table (LPAZ-A, LPAZ-C) indicated by sedges (Cyperaceae); and the phases of high water table (LPAZ-B and LPAZ-D) when *Sparganium* rooted directly into the water. During late Bronze Age, 4-3.4 ka, the proxies in Zone-1 support the interpretation of pollen indicating transition from a shallow peat-bog (LPAZ-A) to a large, waterlogged wetland (LPAZ-B). The transition may be due to climatic change as amelioration of drought is supported by declining *Artemisia*. During very late Bronze Age and throughout the Iron Age (*ca.* 3.4-2.8 ka) there is a strong correspondence between LPAZ-C and Zone-2. The proxies strongly support the fact that the peat-land was shallow and formation of peat is supported by dominance of Cyperaceae and amorphous peat. The low water table is most likely to occur due to severe drought: *Artemisia* reach up to 70% representation in the pollen diagram, and increased abundance of desert shrubs inevitably support desertification and dune formation. Likewise, the increase in sand content may result from aeolian transport of sand. The aridity might be strong enough not to support growth of trees (Shumilovskikh et al., 2016), which may further explain the sudden disappearance not only of riparian forests (*Salix* and *Tamarix*), but also *Prosopis*.

The correspondence between Zone-3 and -4 and LPAZ-D is more complex. The period extends from the late Iron Age to Islamic periods, roughly between 2.8 to 0.6 ka. These periods were substantially re-settled and agro-pastoralism must have been widely practiced in the region. Significant disappearance of shrubs may be attributed to withdrawal of aridity since Zohary (1973) links these shrubs to desert type landscapes. On the other hand, shrubs may have been burnt to increase agro-pastoral land (this is supported by distribution of charcoal). These two scenarios do not contradict each other *per se*: people prefer milder environmental settings to cultivate, but in practice it may not be necessary. The low prevalence of *Artemisia* indicates that climate may have been a contributing factor to such demise of shrubs beyond human interference.

The water level rose *ca.* 2.8-1.7 ka, roughly corresponding to LPAZ-D1 and Zone-3. It is likely that rise in water level was driven by climate (as mentioned before, *Artemisia* is low). The final
part of the studied period, 1.7-0.6 ka, is characterized by an immense human impact on the wetland hydrology, resulting in declining water levels in Zone-4 and LPAZ-D2 (see further discussed in the next section). The numbers of *Artemisia* remain low; thus climate may have little contribution to such desiccation. Sharifi et al. (2015) also recorded that during this period, human impact may have interfered with proxies. The scholars detected an increase in dust input by aeolian activity characteristic in 1.9-0.6 ka, in form of higher input of fine silt and clay in sediment core. The increase in dust storms may have occurred as a result of aridification; but in this period they attributed them rather to human activities such as vegetation clearance than climate. Similar silt and clay input have occurred from *ca.* 1.8 ka (Zone-4) and was accompanied by the bare landscapes (LPAZ-D).

Interestingly, whereas *Artemisia* together with Amaranthaceae are very abundant in 4-2.8 ka, starting with the beginning of LPAZ-D1, *ca.* 2.8 ka they both decline and get significantly replaced by Poaceae. Overall grasses continue with very high percentages until the end of the core, 0.6 ka; but they thrive at a cost of chenopods only until around 1.4 ka. Shumilovskikh et al. (2016) witnessed similar dynamics of Poaceae, especially in relation to Amaranthaceae in the Gorgan Plain, NE Iran. Scholars identified *Artemisia*-steppe *ca.* 4-2.7 ka, where *Artemisia* and Amaranthaceae were the dominant components of the steppe vegetation. *Artemisia*-steppe was attributed to prolonged droughts. Similar findings concerning climate were also reported by Sharifi et al. (2015) between 4.5 and 2.8 ka in Lake Neor, NW Iran. The reason for such prolonged drought was attributed to the stronger Siberian High. Subsequently, Shumilovskikh et al. (2016) detected replacement of Amaranthaceae as a dominant component of the steppe by Poaceae, and it was named as *Artemisia*-grassland steppe that occurred *ca.* 2.7-0.7 ka. The development of *Artemisia*-grassland biomes was attributed to wetter climatic conditions.

These findings have significant correspondence to the findings of present study. The time period extending from 4-2.8 ka is mostly dominated by dry periods (LPAZ-A and LPAZ-C). This period has higher prevalence of *Artemisia* and woody species, and less aquatic plants (*Fig. 7*). During the same timescale, sedimentation rate declines (*Fig. 4*) perhaps due to fewer flooding events. Such frequent patterns of droughts may correspond to the drought period lasting until 2.8-2.7 ka identified by Sharifi et al. (2015) and Shumilovskikh et al. (2016); which was attributed to Siberian Highs. Whereas, the remaining episode of DAR core i.e. from 2.8-0.6 ka is characterised by higher sedimentation rate (*Fig. 4*). This perhaps could be due to increased flooding or water in Halil Rud. Such wet condition is also evident from demise in desert shrubs, *Artemisia*, and even Amaranthaceae, and also increase in Poaceae and overall sum of aquatic plants. This period corresponds to the episode of grassland spread in Gorgan Plain, as identified by Shumilovskikh et al. (2016).

### 6.3 Human-environment interactions

Although not explicit, signs of agro-pastoralism occur through the whole 4000 year period in the Jiroft valley. However, in LPAZ-A1 and LPAZ-C sections cereal cultivation is definitely absent.
This pattern coexists with dry conditions that prevailed from 4-3.8 ka and 3.5-2.8 ka as discussed earlier. Therefore, cereal cultivation was inevitably burdened by droughts. Historically agriculture, especially during the Bronze and Iron Ages, was one of the main factors for the sessile lifestyle and subsequent development of agrarian settlements. Therefore, climatic hostility may explain the development of nomadic pastoralist lifestyle that has deep historic roots in the region (Zanjāni & Nejātiān, 2014). It may be possible that nomads were active during these droughts in Jiroft. Few pollen types indicate pastoralism that existed during this period; but during these dry periods characterized in LPAZ-A and –C, Plantaginaceae and *Polygonum aviculare* occurred and are likely to be associated with intensive trampling and grazing by livestock (Djamali et al., 2009b, Leroy et al., 2013).

As discussed earlier, decline of woody species, trees and shrubs, may be attributed to climatic factors. However, it may also be the case that arboreal species were subject for human exploitation for fuel, wood or timber. Mashkour et al. (2013) report charred *Tamarix* remains found in Konar Sandal. Tengberg (unpublished) also confirmed that multiple shrub and riparian tree species were exploited by prehistoric communities for different purposes.

The decline in woody species, *ca.* 2.4 ka coincides with significant peaks of charcoal and intensive cereal cultivation. Burning is the common way to clear the landscape for agro-pastoral use. Therefore, burning, especially in LPAZ-D may explain the disappearance of desert shrubs. The beginning of LPAZ-D also coincides with episode of re-colonization of Konar Sandal and dating of artifacts, discussed by Mashkour et al. (2013). Distribution in charcoal particles therefore suggests that people played a key role in shaping and manipulating their surrounding environment. Prior to any systematic human disturbance in the area, Léonard, (1991) noted that the natural vegetation was characterized by xerophytic forest shrubs. Meanwhile, human disturbance, usually first start with burning, then proceeds with cultivation or livestock trampling and grazing. This transforms the landscapes into sparse, severely degraded scrublands, further explaining the near disappearance of woody species in the landscape.

Besides trees and shrubs, aquatic vegetation has also been subjected by the human exploitation and/or destruction. Such distinctive human impact on wetland hydrology and vegetation has been observed between *ca.* 1.7 and 0.6 ka which roughly corresponded to LPAZ-D2 and Zone-4. As mentioned in previous section, a decline in water table has been observed without corresponding evidence for droughts. A coincidence between decline in aquatic vegetation and a sharp peak in charcoals imply that such decline may have been resulted due to fire. Since, both, cultivation and pastoralism are disclosed during this period, such fire may also be set up by humans for acquisition of land. The decline in TOC may be resultant from human destruction of aquatic vegetation in the wetland by either burning and/or livestock grazing. Moreover, decreasing C/N ratio may indicate the increase of grazing and introduction of nitrogen into the wetland, coming from animal dung into the peatland surface.
*Cerealia* is the main crop detected in Jiroft valley, which is most likely wheat or barley (Mashkour et al., 2013). However, *Cerealia*-type pollen may be produced by wild grasses, as it was detected in west Asia (Djamali et al., 2009a). Nonetheless, Tengberg (2012) reported that cereals during the Bronze Age in the Indo-Iranian borderland were cultivated for both, human food and for livestock fodder. A single, but mysterious pollen grain of *Myrtus communis* was counted at the very bottom of the core. The plant is usually cultivated for rituals, spiritual and medicinal uses. Likewise, a few pollen of *Citrus* (citrus), *Juglans* (walnut), *Cucumis melo*-type (muskmelon) were identified, but their numbers were insignificant.

Date palm is the most important crop in the Jiroft valley (Mashkour et al., 2013). The crop requires hot and dry climate, but roots must be regularly watered; it is also incredibly resistant to saline soils. Konar Sandal, with its physical settings featured by the Halil Rud and artesian wells, and hot climate, served ideal site for date cultivation (Tengberg, 2012). Date pollen has never been found in any of the samples of this study, which, however, should not be surprising. Date palms are sexually differentiated, and male palms are very poor pollen producers. As a result, people have been cultivating mostly female trees and pollinating them manually (Tengberg, 2012). This process eliminates date palm pollen occurrence in the pollen rain. Nevertheless, in Konar Sandal, date palms were present since 3rd-millennium BCE. Clear ornaments of date palms are documented on Jiroft steatite vessels. Mashkour et al. (2013) also identified fossil charred date remains dated back to the Bronze Age. The date palms are continued to be extensively cultivated nowadays in the valley.

Besides aridity, increase in soil salinity has been the greatest problem for agriculture (and sessile lifestyle) throughout history (Boyko, 1966). Boyko (1966) noted that in Iran soil salinity often occurs due to rise of groundwater level which contributes to the dissolved gypsum level. Scholar also claimed that in records dating back 6000 BP, prehistoric communities adapted to this change by introducing drought-resistant livestock and aridity-adapted crops. Clearance of land and development of irrigation were other methods of escaping rise in soil salinity. Cultivation of date palm was one of the measures to adapt to this change in Konar Sandal. Cultivation of barley instead of wheat (both produce *Cerealia*-type pollen) is another means of adaptation to high soil salinity (Boyko, 1966). However, to what extent rise in soil salinity impacted agriculture in Konar Sandal is unknown. Nevertheless, Fouache et al. (2005) hypothesizes this as a reason that ushered the demise of Jiroft.

Djamali et al. (2009a) noted that increase in soil salinity as result of intensive agriculture and irrigation practices, can favor development of Amaranthaceae. However, based on the results of this study, it is difficult to establish any connection between halophytes (Amaranthaceae, *Tamarix*, *Prosopis*, etc.), soil salinity and its impact on cultivation. However, as discussed in previous section, ca.2.8 ka, Amaranthaceae is replaced by Poaceae. This could potentially indicate reduction in soil salinity that was necessary to increase cereal cultivation.
7 Conclusions

The blend of unique phytogeographical climatic and archaeological settings makes Jiroft valley a compelling site to study the environmental history and human-environment interactions. Results from palynological investigation, combined with geochemical and sedimentological proxies, have shown that Jiroft has encountered environmental changes due to both natural and anthropogenic forcings since the last 4000 years. During the late Holocene, the valley was characterized by Saharo-Sindian pseudo-savannah flora. However, the landscape has shifted from open xerophytic scrub forests to very open and degraded scrublands. A great part of such transition may be connected to human activities, i.e. burning and subsequent agro-pastoralism, that later resulted in soil degradation. Such evidence is strongly supported by charcoal concentrations and cereal pollen that correspond to diminishing woody shrubby vegetation (i.e. Calligonum-type and Ephedraceae). Hence human communities played an inevitable role in steering the landscape evolution. Nevertheless, environmental changes mainly prolonged droughts may have suppressed human activities (4-3.8 ka and 3.4-2.8 ka) permitting with a rise of desert shrubs.

The sub-surface hydrology in Daryache went through phases of high water table (3.8-3.5 ka and 2.8-0.6 ka) and low water table, with consequential peat formation (4-3.8 ka and 3.5-2.8 ka). These hydrological changes have high correspondence to climatic variation indicated by upland plant pollen dynamics, suggesting that climate may have had an influence on water table variations; although since the classical antiquity, and especially during Islamic period, there is a significant human interference with wetland hydrology. Such hydroclimatic dynamics also correspond to findings of other studies. The large scale drought between 4 and 2.8 ka is attributed to the Siberian High (anticyclones), although in the present study the drought was affected by wetter phase between 3.8-3.5 ka. Such a prolonged drought was supported by the high prevalence of desert shrubs, and dominance of Amaranthaceae and Artemisia. Meanwhile, the period between 2.8-0.6 ka has an overall trend in which Amaranthaceae is replaced by Poaceae, with lower prevalence of Artemisia, and distinctive deterioration in desertic vegetation.

Human activities, besides vegetation burning and clearance, could be narrowed down to episodic cereal-cultivation. Some of the indirect proxies, such as Plantaginaceae or Polygonum aviculare-type were used to support the evidence of pastoralism. The evidence for cultivation of any other crops was very sparse and limited to few pollen grains, making further discussion subject to speculation. Pollen belonging to date palm was not detected; however dates were expected to have been cultivated historically in the Halil Rud valley. Cultivation of cereals occurs predominantly during withdrawal of droughts, especially during the rule of the Persian Empire and Islamic periods, implying that climate had a significant impact on agriculture. Sessile-agricultural versus nomadic-pastoralist lifestyles are great subject for a debate on cultural activities in Kerman that may have been influenced by the changing environment.
The study is promising in adapting palynological analysis in the area that previously was poorly studied for vegetation dynamics; and tracing the impact of multiple physical and human activities e.g. hydrology, climate, agriculture, pastoralism, etc. Further study efforts, with a special focus on multi-proxy analyses are essential to contribute towards knowledge of human and environmental history in southeastern Iran. Meanwhile, research on the Halil Rud hydrology and also soil salinity would significantly contribute towards understanding the hydro-climate and historical agriculture in the Jiroft valley.

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9 References


