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Research Article

An Ancient Wetland in the Presently Arid Region of Southern Jordan: A Sedimentological and Paleoenvironmental study

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Abstract: Geological, geochemical and geochronological approaches were implemented to investigate the geological characteristics and thepaleoenvironment of the Pleistocene deposits of Hamra Faddan area in southern Jordan. These sediments Faddan were attributed to the Lisan Marl Formation. The current study investigated the possessing characteristics of these sediments marked at 48-79m above sea level were different depositional environments have been recognized. Furthermore, the highest stand recorded for Lake Lisan was at 130m below sea level. Therefore, these deposits could not be considered as a part of the Lisan Marl Formation. The Late Pleistocene sediments of Hamra Faddan area comprise mainly carbonate-rich fine grained sands and carbonate-rich silty sand, with thicknesses ranging from 0.7m to 2.6m. The major mineral composition of these sediments includes calcite, quartz, kaolinite, halite, gypsum, dolomite, anorthoclase and merlinoite. Integration of chronological information with the new results of geochemical, sedimentological and microfossils studies, the paleoenvironment of Hamra Faddan sediments is interpreted in terms of shallow in-stream wetland with low energy and a dry warm climate, with an increase in temperature through the Last Glacial Maximum (LGM), followed by another episode through the Younger Dryas (YD) periods in which a shallow-low-energy wetland existed with a dry warm climate and an increase of temperature.

Keywords: Jordan, last glacial maximum, lisan marl formation, optically stimulated luminescence, pleistocene lakes, younger dryas

INTRODUCTION

Paleolake studies are of great significance for reconstructing past continental climatic records and lake-level chronologies, a link between regional hydrological records and the timing of global events can be generated accordingly. Such process can be an important aspect when considering the mechanisms of shifting climates over the world and demonstrate their sign on continental climates (Bartov *et al*., 2003).

Conducted paleoclimatic studies in the Levant have resulted in inconsistent interpretations about late Quaternary climate changes (Fig. 1). Nature and level of Quaternary climatic changes are still controversial even though different climatic changes recorded on different scales. It is documented that wetter periods prevailed during inter-glacial in large areas of the Middle East whereas glacial were dry (McLaren, 2004).

The last part of the last glaciation 50-12 ka (ka: thousands of years) was characterized by fast climatic change, cold conditions, vegetation and faunal shifts (Finlayson and Carrion, 2007). As a consequence, various studies concerned with paleoclimate and the reconstruction of paleoclimatic regimes were conducted in the Levant in general and in Jordan in specific (Bar-Matthews *et al*., 1997).

Moumani (1996) recognized a shallow, freshwater lake covering 4 km^2 at Al-Hasa aged to 182-82 ka by using data of 3 Optically Stimulated Luminescence (OSL) dates. Abboud (1999) studied climatic regimes and environmental conditions for WadiMuqat Basin situated in NE Jordan during late Quaternary and generated two climatic models in six zones. Yasin (2000) investigated Mudawwara area southern Jordan in terms of sedimentological, stratigraphical, archeological and paleontological aspects and documented the presence of a large paleolake and human habitation. Bartov *et al*. (2002) described the sequence of events of lake level variations in the Jordan valley during the period of 55 to 15 ka by applying stratigraphic principles with radiocarbon and U-series dating.

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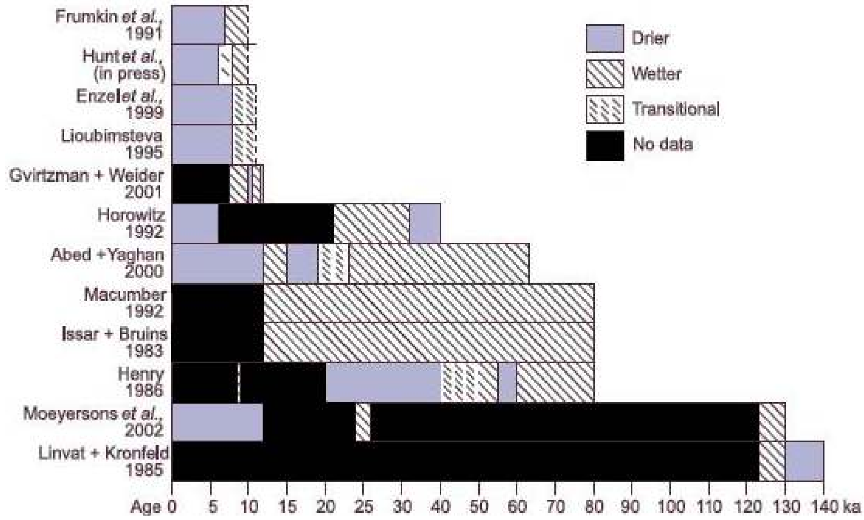

Fig. 1: Published works on wetter and drier periods in the levant over the last 140.000 years (McLaren, 2004)

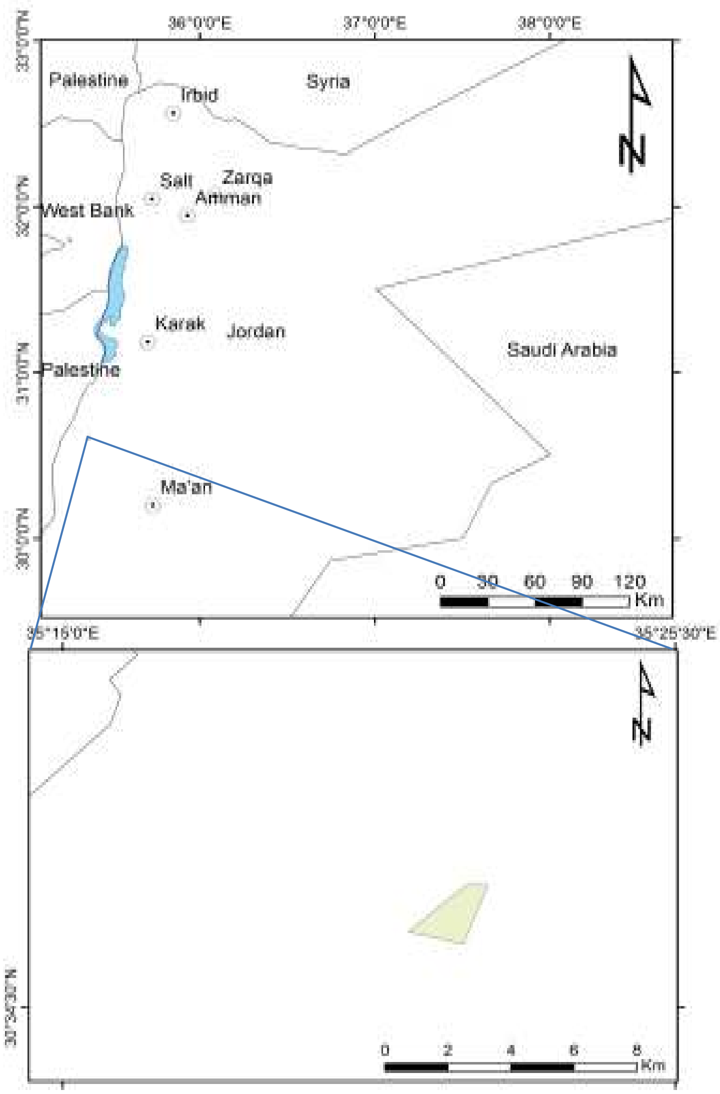

Fig. 2: Location map of Hamra Faddan study area

Moumani *et al*. (2003) analyzed sedimentary features and fossils at WadiHasa in Jurf Ed Darawish southern Jordan, coupled with optical luminescence chronology; they documented interchanging wet and dry since the last interglacial. Davies (2005) studied a 31m sediment core from Qa' el-Jafr in southern Jordan, she documented important records concerning Quaternary paleoenvironments. Abed *et al*. (2008) reported the presence of a fresh water lake in al Azraq located in eastern Jordan corresponding to 330 ka (Marine Isotope Stage (MIS) 9).

Petit-Maire *et al*. (2010) documented the existence of a lake in Mudawwara southern Jordan during Oxygen Isotope Stages (OIS) 7a-6e, 5e and 5c-a by analyzing Lacustrine coquina. Winer (2010) studied marls, microfossils and root voids in WadiHasa southern Jordan by applying stratigraphic relationships and geochronological methods; this study revealed numerous in-stream wetland deposits.

More recent work was done by Mischke *et al*. (2012) and documented the presence of many sites of Pleistocene lake sediments in the hyper-arid region of southern Jordan by examining ostracod shells from 49 pond and stream sites in Jordan and adjacent areas which in turn suggests that climate regimes were wetter during the Pleistocene.

In Hamra Faddan area, Barker and others in 1997, 1998, 1999 and 2000 attempted to understand the Quaternary geological history (McLaren, 2004). Hunt *et al*. (2004) analyzed plant macrofossils and *molluscs* samples from Hamra Faddan to report that climate was more humid during the Early Holocene. Recently, Rech *et al*. (2013) documented the occurrence of Quaternary lacustrine deposits in the Jordan Valley.

This study investigates the geological, geochemical and geochronological characteristics of Hamra Faddan areain an attempt to interpret the paleoenvironmental conditions that were prevailing during the Pleistocene.

Study area: Hamra Faddan is situated in Wadi Araba in southwestern Jordan at the eastern side of the Aqaba-Dead Sea Transform (DST) Fault System (Hunt *et al*., 2007). The study area extends along an area of about 8km^2 with low topographic variation (Fig. 2). A view of the study area is shown in Fig. 3.

The DST Fault is the major fault affecting Jordan and the surroundings. According to Rabb'a (1994), major faults and lineaments within the study area are oriented in various directions; while, four trends dominate:

- Wadi Araba-Dead Sea Fault which trends in an NNE-SSW direction covered with alluvial and eolian sediments along most of its extent.
- Tertiary and Quaternary Dana Fault extending in a western direction.
- Late Proterozoic to Quaternary Salawan Fault which extends in a western direction parallel the Dana fault.
- Malqa Fault extends in a western direction.

Geological setting: Quaternary sediments in the study area are represented by saline Lisan Marl Formation (Fig. 4). This formation comprises three parts: The lower part of white to grey marl with gypsum veins and crystals, the middle part which consists mainly of green marl and clay with gypsum veins and the upper part that comprises white to grey marl and clay (Rabb'a, 1994).

The Late Pleistocene to recent sediments comprise poorly sorted rounded to sub-rounded Pleistocene Fluviatile Conglomerate Formation of the Late Pleistocene age (Rabb'a, 1994). The Lisan Marl Formation is overlain by Holocene to recent sediments; alluvium, aeolian sand, alluvial fans and alluvial gravels.

Methods of investigation: Five localities (Fig. 5) were selected and studied in relation to sediment distribution and types using a shovel to clear the weathered surface and then fresh samples were collected.

Quaternary sediments of the study area are mostly semi-consolidated with total thicknesses ranging between 0.7 and 2.6 m; depending on topography and

Fig. 3: a: Northern view , b: Southern view of Hamra Faddan study area

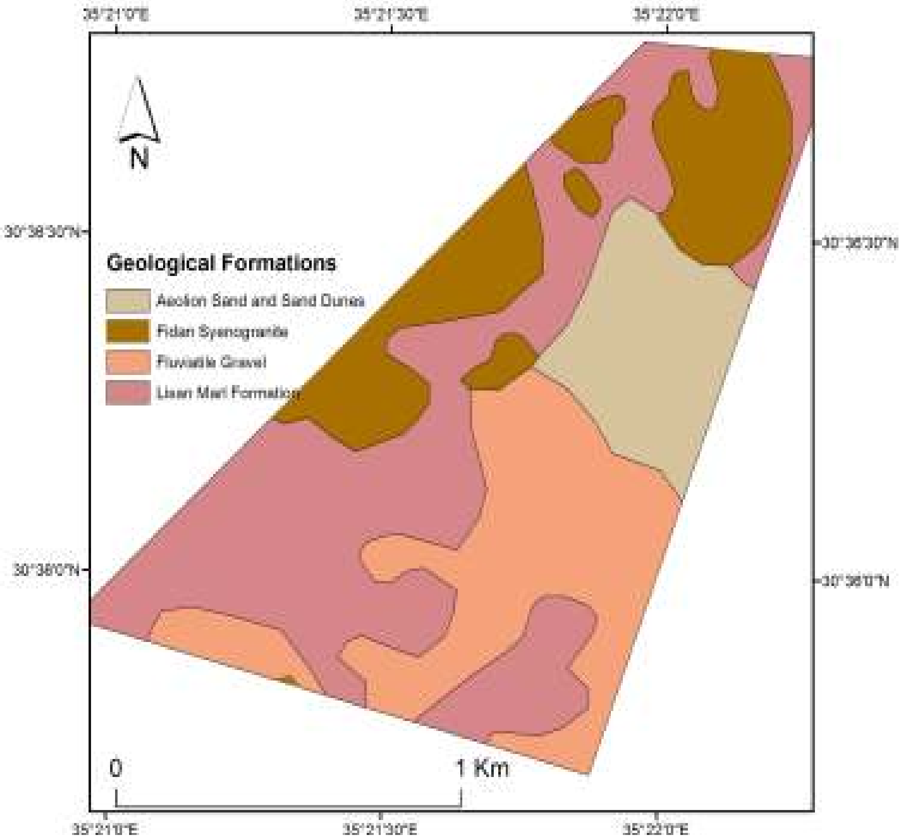

Fig. 4: Geological formations in Hamra Faddan area (Rabb'a, 1994)

Fig. 5: Hamra Faddan study sites

the location of the site. The studied sedimentary samples consist mainly of fine-grained materials; a fraction of fines (silt and clay), fine-grained sand and limestone.

Thirty sediment samples from five localities, covering the study area and representing the extension of the Quaternary deposits, were taken at an interval of 20-40 cm depending on changes in sediment types, color or any notable characteristic.

Analytical methods included X-Ray Diffraction (XRD) of powdered samples which was used to determine the bulk mineralogy of the sediment samples at the laboratories of Al Al-Bayt University by using a Philips X'Pert MPD (model PW 3010) diffractometer.

Table 1: Samples and analyses conducted

Site	Number of samples analyzed	Analytical Method
1	3	Grain size distribution
	4	L.O.I
	12	Microfossils Analysis
2	4	Grain size distribution
	3	L.O.I
4	3	Grain size distribution
	3	L.O.I
5	2	L.O.I
All sites	10	XRD

Table 2: Values of the Coefficient of Curvature (Cc) and the Coefficient of Uniformity (Cu).

Site		Cc value	Cu value
Site 1	Top	0.57	7.20
	Middle	1.25	10.90
	Base	1.12	10.12
Site 2	Top	1.92-1.73	8.33-9.20
	Middle	0.78	1.55
	Base	1.00	2.50
Site 3	Top	1.69	10.60
	Middle	1.83	17.39
	Base	1.20	15.00
Site 5	Top	1.93	10.00
	Base	0.69	9.780

Non clay minerals in the mud fractions of <63 µm were identified by Scanning at 2Ø range: 2° - 60°. Grain size analysis of the samples was conducted at the laboratories of Al Al-Bayt University, using 8 different sieves with sizes of, 2, 850, 425, 250, 180, 150, 106 and 75µm, respectively to signify the particle size distribution. Sieve size of 75µm was the limit between the sand size and the fines according to the American Association of State Highway and Transportation officials (AASHTO) standard. Samples were dried at 110°c for one hour and then disaggregated and quartered in the lab in order not to destroy the original texture of the sample and then were put in a shaker for 15 min. The weight of the sample was measured before the sieving process and after 15 min of shaking. Every sieve was taken carefully out of the shaker and its contents were weighted to obtain the weight of each size and conduct the needed calculations. Values of the Coefficient of Curvature (Cc) and the Coefficient of Uniformity (Cu) (Table 1) were calculated using the following equation:

$$Cc = D60/D10, Cc = (D30)^2/(D10)(D60) \quad (1)$$

Loss on Ignition (L.O.I) analysis was conducted at the laboratories of Al Al-Bayt University using an empty quartz crucible for the determination of L.O.I value to estimate the percentage of organic carbon in the sample, where samples were dried at 110°C for two hours then taken out and cooled to room temperature using a Desiccator. After drying, 3g of each sample were taken and put in a dry crucible which gives weight1 (wt1). Samples with the containing crucibles were then put in a muffle furnace at 1100°C for two hours and then taken out and cooled to room temperature using a desiccator. After cooling, samples were reweighted which gives (wt2) in which:

$$L.O.I = [(wt.1-wt.2)/wt.\ of\ the\ sample]*100\ \% \quad (2)$$

L.O.I is mostly used for the determination of organic matter content in the sediments with respect to some proportionality factor.

Micropalaeontological analysis was conducted at the Institute of Geological Sciences, Freie Universitaet Berlin where sediment samples of 170-490 g were treated with 3% H_2O_2 for 48h and passed through 250 and 100mm sieves. Where there were abundant carbonate concretions or coarse-grained sediments, an additional 1000mm sieve was used. The remains were dried at 40°C. Ostracod, gastropod, bivalve shells and charophyte remains were picked under a low-power binocular microscope. The ostracod shells were mainly identified with reference to Meisch (2000) and a specimen collection at the Institute of Geological Sciences, Freie Universitaet Berlin.

RESULTS AND DISCUSSION

For the analytical investigation, a representative number of samples were chosen from each section in order to obtain sufficient results to fulfill the required objectives of the study. Table 1 shows each site with the number of samples chosen and the analyses conducted. Table 2 shows the results obtained for each site while Table 3 shows X-Ray Diffraction Analysis (X.R.D.) Results. The Microfossil results are shown in Fig. 6.

Sedimentology and depositional environments: Hamra Faddan lacustrine deposits were documented as Lisan Marl Formation (Rabb'a, 1994); the Late Pleistocene paleolake of the Dead Sea. Nevertheless,

Table 3: X-Ray Diffraction analysis (X.R.D.) results

Site	Calcite	Quartz	Anorthoclase	Kaolinite	Halite	Gypsum	Merlinoite	Dolomite	Polyhalite
Site1	xxx	Xxx	X	xx	x	----	----	----	----
Site2	xxx	Xxx	----	----	xx	----	----	----	xx
Site3	xxx	Xxx	----	xx	xxx	xxx	----	xx	----
Site4	xxx	Xxx	----	x	----	----	----	x	x
Site5	xxx	Xxx	----	xx	----	----	xx	x	----

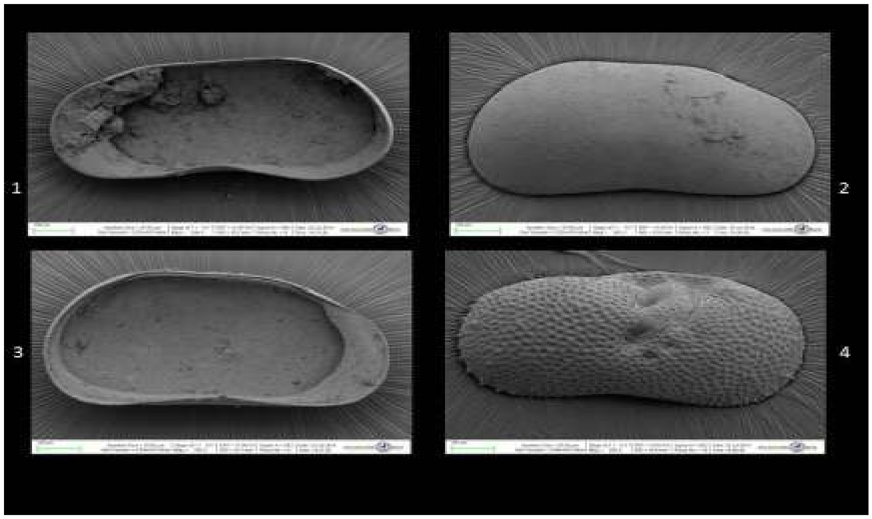

Fig. 6: Microfossils analysis for Site 1: 1-*Candona neglecta*, 2 and 3-*Pseudocandona* sp., 4-*Ilyocypris* sp.

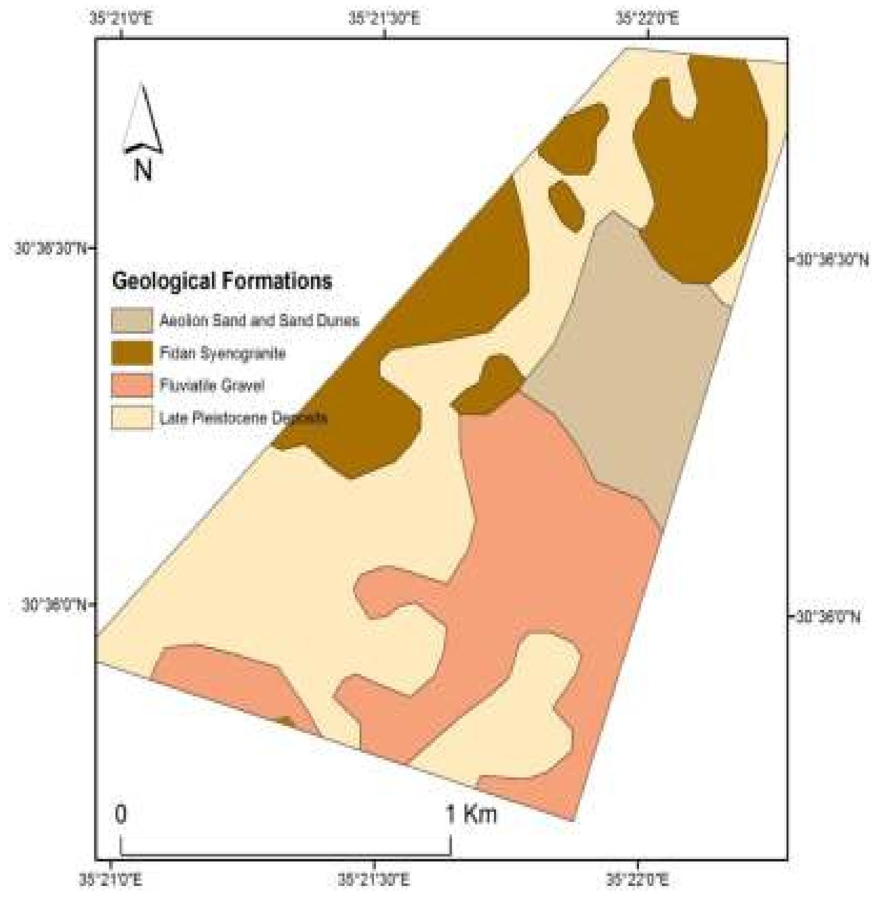

Fig. 7: Geological formations of HmaraFaddan area (modified after Rabb'a, 1994)

these deposits vary in height from sea level to ~80m above sea level (asl). The present altitude of the Dead Sea is about -400m and the highest recorded lake level is -130m (Landmann *et al*., 2002). Accordingly, these deposits couldn't have been deposited by the Lisan Lake and may have been wetland deposits indicating essential changes in local hydrological systems and can be classified as Late Pleistocene deposits (Fig. 7).

Site Number 1: In this carbonate-rich sands site, root casts are present from middle to top (Fig. 8), indicating that this site may have been deposited in a low energy

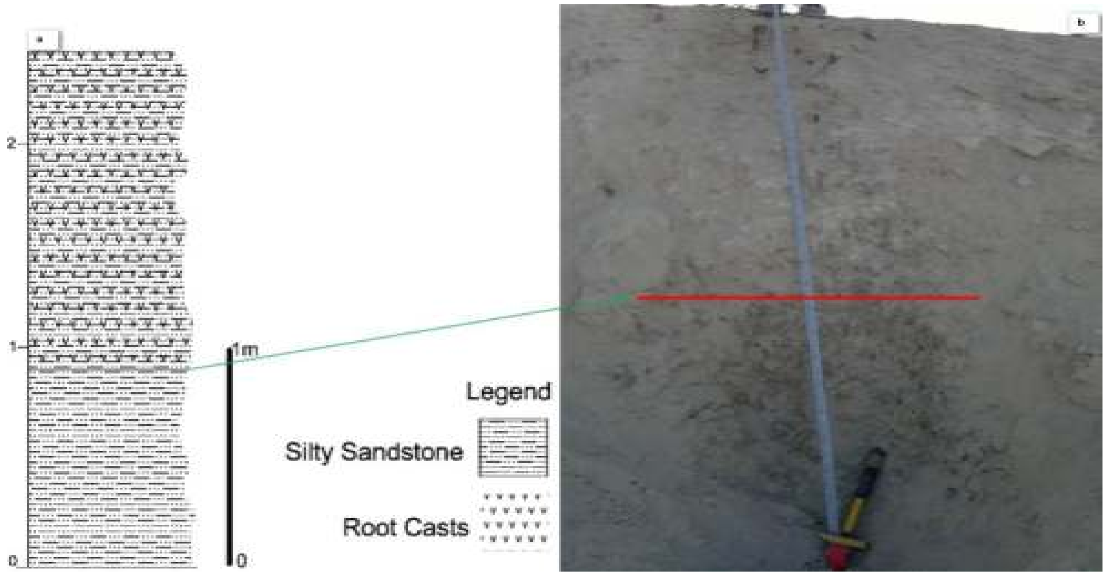

Fig. 8: a: Columnar section of Site 1, b: Photo showing the site

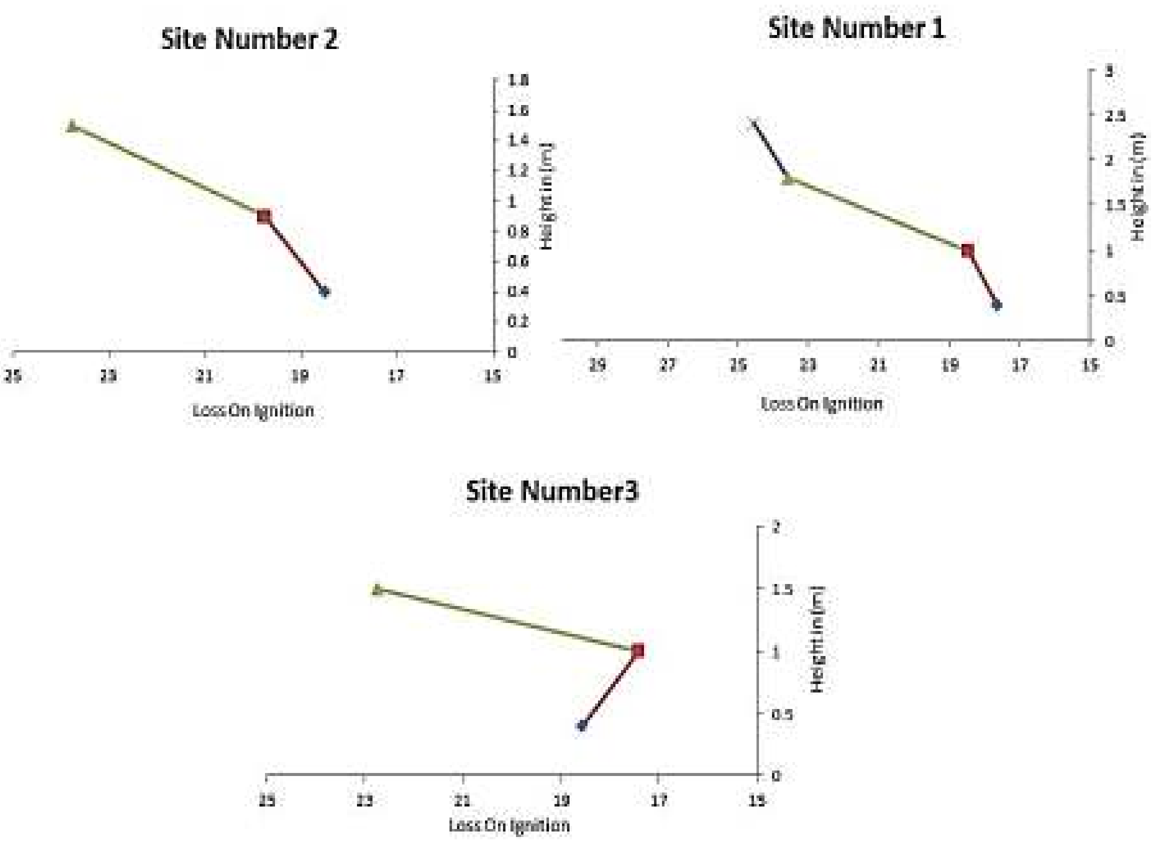

Fig. 9: Loss on Ignition results for sites 1, 2 and 3

environment accompanied with the presence of a vegetation cover. The grain size distribution indicates that the sediments are well graded as the values of C_c and C_u are in the range of $1<C_c<3$ and $C_u \geq 6$ (Table 2), which also is an indicator of a low energy environment that helped in the well grading of the grains. While L.O.I. values showed an increase upward (Fig. 9) indicating that the erosional intensity of the drainage basin was low or the presence of a variation in the bioactivity in the area.

The mineral composition of this site varied from bottom to top; at the base, quartz, calcite and

Fig. 10: a: Photo of site2, b: Columnar section of site 2

anorthoclase are the major components. In the middle, calcite, quartz and kaolinite are the major components, while at the top; calcite, halite and quartz are found to be the major components (Table 3).

Quartz occurs in most environments and it is a widespread mineral, calcite occurs in all types of occurrences and is the main mineral in limestone. Anorthoclase occurs from the erosion of the volcanic rocks and this is understandable by the presence of volcanic rocks in and around the studied area. Kaolinite is important because it occurs as a secondary mineral derived from the weathering of orthoclase and occurs in increasing temperatures. Halite also occurs in increasing temperature as an evaporate, it occurs in shallow marine environments, or in association with carbonates as seen in Site 1 in shallow marine environments when the water supply is decreasing and the carbonate deposition is terminated.

These indicators, when combined, may show that this site was deposited in a shallow water body with an increasing temperature environment.

Site number 2: Site 2 (Fig. 10) is thought to be the top of a stratigraphic sequence in the southern part of the study area; this carbonate-rich fine-grained sand site resulted in a grain size distribution (Table 2) indicating that the sediments are poorly sorted at the base and the middle of the section but well sorted at the top, according to the range of $1< C_c< 3$ and $C_u \geq 6$ for well-sorted sediments, which may indicate different intervals of low and high energy environments enabling this type of grading to occur. The L.O.I. values (Fig. 9) show an increase upward, which may indicate that the erosional intensity of the drainage basin was low or that there was a variation in the bioactivity in the area. The minerals found in this site are quartz, calcite and polyhalite at the base and quartz, calcite, polyhalite and halite at the top (Table 3). Polyhalite precipitates after calcite and halite and may be formed as marine evaporate deposits where the water has been concentrated and exposed to prolonged evaporation.

These indicators may show that this site was deposited in a shallow water body with an increasing temperature environment.

Site number 3: At an elevation of 48m above sea level, carbonate-rich fine sands can be found at site3 (Fig. 11) which is thought to be the base of the stratigraphic sequence mentioned above. This may indicate that this site was deposited in a low energy environment where the grain size distribution (Table 2) indicates that the sediments are well graded as the values of C_c and C_u are in the range of $1< C_c< 3$ and $C_u \geq 6$. L.O.I. values (Fig. 9) show two trends upward, in which to the middle there was a decrease in L.O.I and then an increase to the top, which may indicate that the erosional intensity of the drainage basin was fluctuating or that there was a variation in the bioactivity in the area. The major mineral components are calcite, gypsum, quartz and halite in the base of the section. In the middle, quartz, calcite halite, dolomite halite, gypsum and kaolinite are present and at the top, quartz, calcite and dolomite (Table 3). Gypsum occurs in shallow basins in arid regions and lagoons. Carbonates, in general, are formed in shallow waters as a result of evaporation, here dolomite is an example and it precipitates after gypsum. These indicators may show that this site was deposited in a shallow water body with an increasing temperature environment.

Site number 4: This site is found along an ancient stream cutting through the study area, composed of carbonates with L.O.I value decreasing upwards, which

Fig. 11: Site number 3: a: Photo of site 3, b: Columnar section of site 3

Table 4: OSL ages for Hamra Faddan samples (AL-Shdaifat, 2015)

Sample	Site	Depth [cm]	Water contents (%)	K (%)	U (ppm)	Th (ppm)	Ext. α (μGy/a)	Ext. β (μGy/a)
Sample 1	Hamra Faddan site 1	65	17	0.69	2.2	3.9	7	721
Sample 2	Hamra Faddan site 1	28	17	0.4	2	1.9	6	486
Sample 3	Hamra Faddan site 2	40	12	0.6	1.3	3.3	5	589
Sample 4	Hamra Faddan site 3	165	14	0.8	5.1	5.0	15	1159

Sample	Ext. γ (μGy/a)	Cosmic (μGy/a)	Total dose (μGy/a)	No. aliquots	OD (%)	De (Gy)	Age (Ka)
Sample 1	504	199	1432±43	16/16	21	29±2	21±2
Sample 2	344	232	1067±30	23/23	21	24±1	22±1
Sample 3	396	219	1208±31	21/22	33	14±1	12±1
Sample 4	870	171	2215±76	21/21	20	31±1	14±1

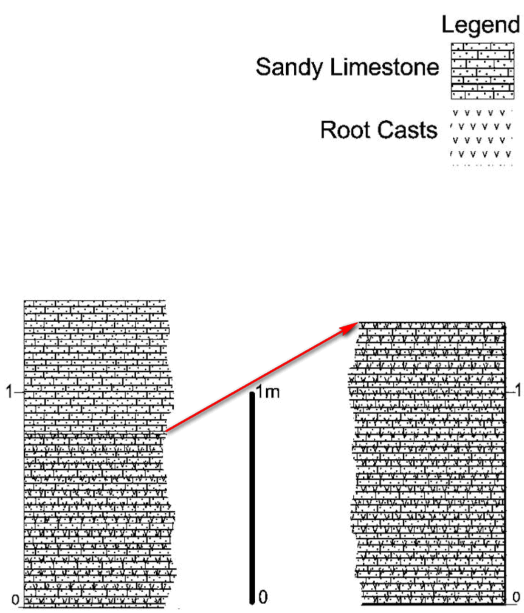

Fig. 12: Correlated columnar section of site5

may indicate that the erosional intensity of the drainage basin was high or that there was a variation in the bioactivity in the area. The fine grains may indicate a low energy environment while deposition of this site. The minerals found in this site are calcite, quartz, kaolinite, dolomite and polyhalite (Table 3). Dolomite

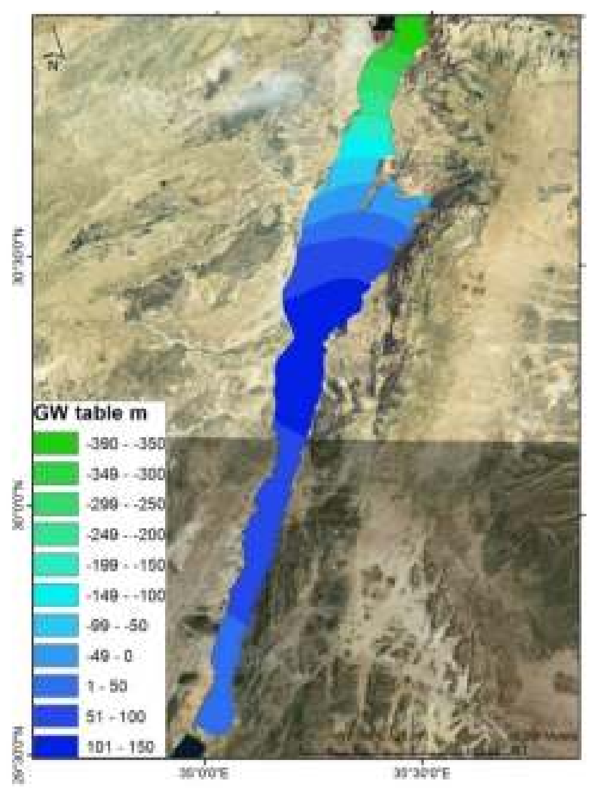

Fig.13: Groundwater table in Wadi Araba (Ministry of Water and Irrigation data, Jordan, 2012)

is formed in shallow waters as a result of evaporation. These factors may indicate that the depositional environment here was a low energy arid environment.

Site number 5: The last site along the ancient stream is site5 (Fig. 12), where two localities were studied here at the two sides of the channel. One locality is composed of carbonates with fine sands and the other is composed of carbonates with fine sands and root casts. The fine sands may indicate a low energy depositional environment and the root casts indicate the presence of a vegetation cover in the site. The L.O.I values decrease upwards, which may indicate that the erosional intensity of the drainage basin was high or that there was a variation in the bioactivity in the area. The grain size distribution (Table 2) indicates that the sediments are well graded as the values of C_c and C_u are in the range of $1<C_c<3$ and $C_u \geq 6$. The minerals found in this site are calcite, merlinoite, quartz, kaolinite and dolomite (Table 3). Merlinoite is a part of the zeolite group and is formed in Saline, alkaline water environments.

These indicators may show that the depositional environment at this site was a saline low energy environment with increasing temperatures.

CONCLUSION

Time-stratigraphic units: Two time-stratigraphic units were identified in Hamra Faddan area using the Optically Stimulated Luminescence (OSL) dating as documented by Al-Shdaifat (2015) unpublished work (Table 4). Two samples were analyzed from the area where site 1 of this study is located representing the base and the top of the section. The sample from the base yielded and age of 22±1 thousand years while the sample from the top yielded an age of 21±2 thousand years. These two ages are correlated to the Last Glacial Maximum (LGM) which lasted from 23-18 ka (Roskin *et al*., 2011).

The LGM was quite dry (Roskin *et al*., 2011; Enzel *et al*., 2008), in which a cold dry period was recorded (Rosen and Rivera-Collazo, 2012). Also, an aridification drift in the Levant during Late Pleistocene and Holocene was documented by Iriarte *et al*. (2011).

MIS-1(11.6ka) warm stages correspond to lake level drops (Lisker *et al*., 2007), this indicates an environmental regime of increasing temperature at this period of the Pleistocene. The gypsum horizon that covers the Lisan sediments indicates a dry period that ended about 16,000 years ago (Abed, 1985).

At site 2 mentioned in this study; Al-Shdaifat (2015) analyzed one sample and obtained an OSL age of about 12±1 ka; this site is thought to be the top of a stratigraphic sequence. The base of this sequence was dated at Site 3 mentioned in this study in which the sample dated yielded an age of 14±1 ka. These ages are correlated to the Younger Dryas (YD) periods which lasted through 13-11.5 ka (Rosen and Rivera-Collazo, 2012). The YD period is identified by rapid cooler and drier conditions (Rosen and Rivera-Collazo, 2012; Carlson, 2010; Rossignol-Strick, 1995).

Paleoenvironment of Hamra Faddan during the late pleistocene: Climate varied considerably since the last glacial maximum (Staubwasser and Weiss, 2006). Quaternary paleoclimatic conditions in the southern and central parts of the Levant were strongly related to the monsoon activity which increased during periods of maximum northern hemisphere insolation; this had resulted in the formation of lakes and rivers in the present hyperarid regions (Vaks *et al*., 2010).

The late Pleistocene ended with a large salt deposition that can be distinguished from numerous boreholes along the Dead Sea shores. This salt deposition event is thought to be associated with the drying of late Pleistocene Lake Lisan (Frumkin *et al*., 2001). This indicates a dry period during the late Pleistocene in the area. Moumani *et al*. (2003) have also documented several wet and dry periods in Jordan since the last interglacial.

From the recorded paleoenvironmental records and the results of this study; the interpreted environment that dominated in Hamra Faddan area is thought to be a shallow marine low energy or standing wetland with a dry warm climate and increasing temperature during the LGM which corresponds to the dates from Site 1 and the formation of different minerals such as calcite, kaolinite, halite, dolomite and merlinoite. The presence of root casts and root voids indicate that these deposits may have been deposited in shallow water bodies with water depths not deeper than the average depth needed for rooting.

During the YD periods (12.9-11.7 ka) the area may have undergone an influence of a warm dry climate in which Sites 2 and 3 were deposited where a shallow low energy or standing wetland covered parts of the area with increasing temperatures allowing the formation of calcite, halite, polyhalite, gypsum and dolomite.

The microfossil results shown in Fig. 6 confirm that the climate of the Last Glacial Maximum (LGM) was wetter as is already suggested by high lake levels of the Dead Sea. The groundwater table was adequately high enough to support the formation of springs and small water bodies at site 1. *Ilyocypris* sp. prefers flowing waters but may occur in stagnant waters too. *Candonaneglecta* prefers colder conditions. The species may live in a wide range of habitats and freshwater to brackish water *Pseudocandona* sp. usually inhabits stagnant water such as ponds and lakes. The species are mostly occurring in freshwater but a few can live in considerably brackish water also. *Charophyte* stem incrustations were identified at Site one showing that charophyte algae were also present at the site and open surface water was present at least for a couple of months per year. The presence of poorly sorted sands and gravels in the study area shows that there may have been a desert wetland environment. Modern ground water table (Fig. 13) supports the idea of the formation of a wetland environment during periods of enhanced rain where the water table may have emerged with the surface forming several shallow water bodies.

At sites two and three it shows that the fine-grained silty sediments from this area were not formed in water bodies which lasted sufficiently long for population by carbonate-producing organisms.

A more detailed study regarding the microfossils is recommended in order to obtain more details about the environment that prevailed in the study area during the periods of the LGM and the Younger Dryas and a core sampling study for the sediments is recommended for the investigation of the wetland depths and subsurface extensions.

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