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Evidence of past environmental conditions during the evolution of a calcretised Wadi System in Southern Jordan using stable isotopes

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ABSTRACT

A stratigraphically and temporally ordered sequence of channel calcretes preserved along the Wadi Dana, Southern Jordan, records the Quaternary evolution of the formation and infilling of rock-cut channels and their subsequent incision in a tectonically subsiding basin. It is currently unknown under what palaeoenvironmental conditions these non-pedogenic calcretes formed. Stable isotope analyses have been used to investigate whether any past topographical, hydrological, vegetational, diagenetic, and/or temporal signatures can be identified from the channel calcretes. The results of this research indicate that channel calcrete development is influenced by altitudinal variation (affecting vegetation and hydrology) within the landscape as well as location within individual wadi channels (which has an affect on diagenetic processes). The lack of calcretisation of a terrace that is between +1 and 1.5 m above the modern wadi floor supports the idea that the environment is currently too arid for calcrete to develop. Thus the presence of older Wadi Dana channel duricrusts suggests wetter conditions when they formed. The $\delta^{18}O$ data of the calcrete implies cooler conditions than today, as there is little evidence of a strong evaporative effect. Any temporal control is limited and mainly a function of stratigraphic position with some numeric dating.

1. Introduction

Detailed information on arid zone channel calcretes, which is important for understanding environmental changes in drylands, is scant. This is especially the case in areas such as southern Jordan, where our understanding of climate changes is extremely limited. These issues are addressed by studying discontinuous remnants of a series of palaeofluvial low gradient channels and straths preserved along river thalwegs in the Wadi Dana, Southern Jordan (Fig. 1a). Cobble- and boulder-rich alluvium that has accumulated in these confined rock-cut channels has become cemented by $CaCO_3$ derived largely from river and groundwaters (McLaren, 2004). The calcretised channels have subsequently been abandoned and preserved through downcutting in a tectonically subsiding basin and the remaining calcretised raised rock-cut channels have been preserved as fragments of their original form (Fig. 1b). Because of the arid nature of the environment in Wadi Dana, the groundwater calcretes here have not been exposed to any pedogenic (beta) calcrete modification (McLaren, 2004). Working in Gujarat, western India, Malik and Khadkikar (1996) have also found that in rapidly subsiding basins, groundwater calcretes can be preserved in their original form, escaping any pedogenic alteration. In addition, Spötl and Wright (1992) have argued that diagenesis in alluvial conglomerates need not be associated with pedogenesis. Yet, "very little information is available concerning the range of isotopic values in groundwater calcretes" (Wright and Tucker, 1991, p.10) and that is still the case to-date (e.g. Eren, 2011). The geochemical deposits in Wadi Dana provide an opportunity to analyse the stable isotopes of such groundwater calcretes.

The upper course of the Wadi Dana begins at a height of approximately 1100 m above mean sea level and it has cut a deep ravine through the Edom Mountains (Fig. 1c) until it extends out onto a broad level basin where a number of tributaries meet to form the Wadi Faynan at about 100–200 m above mean sea level (McLaren et al., 2004). Fill and strath terraces have developed when the sediment supply is equal to, or greater than the transport capacity, whereas incision has occurred when the sediment supply is lower than this capacity. Carcaillet et al. (2009), Hancock and Anderson (2002) and Cordova et al. (2005) contend that in mountainous areas, terrace formation has been associated with changes in sediment supply and/or water discharge produced by climatic fluctuations. Dutta et al. (2011) have also argued that staircases of fluvial terraces in the Himalayan front are the result of climatic fluctuations in the late Quaternary. Further, in the hyper-arid Taklamakan Desert, Yang et al. (2002) used channel terraces of the Keriya River as indicators of increased runoff associated with potential increases in regional precipitation in the late Quaternary. In Wadi Dana, significant changes in the level of the Dead Sea (which in the late Quaternary is largely climatically related e.g. Waldmann et al., 2009) have affected

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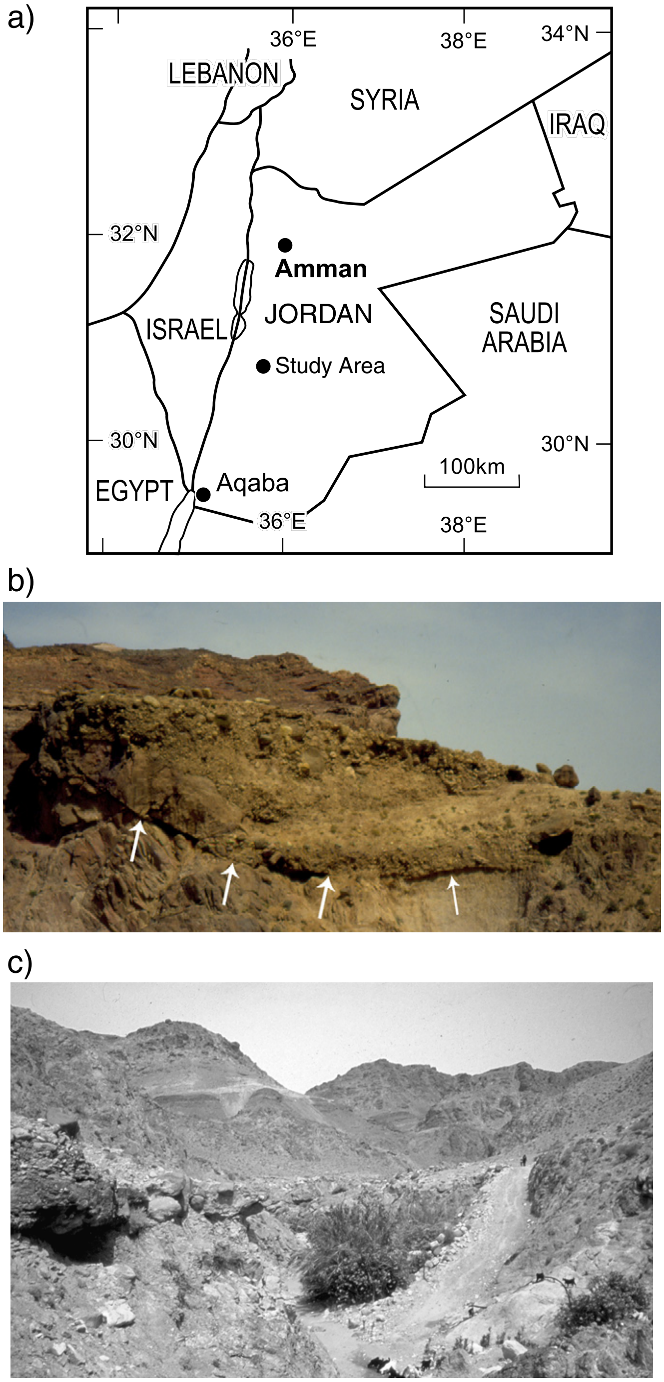

Fig. 1. a: Location of the study area. b: Channel calcrete preserved within a rock-cut channel; n.b. the white arrows indicate the junction between the base of the channel calcrete and the bedrock. c: View of Wadi Dana in the Edom Mountains with channel calcretes (e.g. near left of the image) and boulder trains on the hillslopes above the modern channel.

the base level of the Wadi Dana, which ultimately flows into the Dead Sea Basin. In addition, as the area borders the tectonically active Dead Sea Transform Fault System, trying to distinguish between climatic and tectonic controls on geomorphological processes in the Wadi Faynan area is difficult (McLaren et al., 2004, 2008). In the Holocene, landscape forming processes and evidence of climate change are further complicated by the impacts of significant human activity in the study area (Hunt et al., 2004; McLaren et al., 2004; Barker et al., 2008).

It has long been recognised that fluvial deposits provide important palaeoenvironmental records (e.g. Maddy, 1997; Maddy et al., 2008) and this is particularly the case if they are calcretised. Cemented deposits have a better chance of long-term preservation than loose sands and gravels within landscapes. Further supporting evidence of past environmental conditions may be discovered through studying the micromorphology of the cements (e.g. Nash and McLaren, 2003; McLaren, 2004) as well as the calcrete's stable isotope composition (e.g. Khadkikar et al., 1998).

Calcretes are important components of semi-arid depositional systems and according to Wright and Tucker (1991) are characteristic of regions experiencing a mean annual rainfall of about 500 mm yr^{-1}. Both Yang (2001) and Abdul-Salem (1966) argues that calcareous crusts can develop under an annual precipitation as low as 100–350 mm but when the rainfall falls below 100 mm yr^{-1} the crusts cease to exist. However, it is not just the actual amount of rainfall but the relationship between annual rainfall and evaporation. The current rainfall in the study area is about 50 mm yr^{-1} (McLaren et al., 2004) and the annual potential evaporation far exceeds the absolute amount of rainfall (Al-Qawabah et al., 2003; EMWATER, 2005). Although a net moisture deficit is necessary for calcrete formation, the current conditions are such that there is not enough available moisture for calcretes in Wadi Dana to develop. Indeed, a +1 to 1.5 m alluvial terrace in the Wadi Dana that has been dated to between 100 and 400 years BP only shows signs of incipient cementation (McLaren, 2004).

Khadkikar et al. (1998) studied calcretes in alluvial systems in Gujarat, west India and they identified three major sinks of carbonate in alluvial deposits: pedogenic calcrete, calcrete conglomerates and groundwater calcrete. Khadkikar et al. (1998) found that pedogenic calcretes are more typical in extra-channel areas. However, in Wadi Dana, extra-channel areas generally have steep slopes that are dominated by gravitational hillslope processes and runoff during flood events, so that even if incipient pedogenic calcretes did develop under wetter regimes they are likely to have been broken up, eroded and removed/washed away down slope during periods when slopes were relatively unstable. Calcrete conglomerates in Gujarat occurred as ribbons, sheets and lenses due to reworking of pedogenic and groundwater calcretes. Although eroded and reworked channel calcrete fragments exist in the current wadi channel, recemented calcrete conglomerates are uncommon, which again may suggest that conditions are now too arid for calcretisation. Khadkikar et al. (1998) argued that the groundwater calcretes originated from carbonate-saturated waters travelling preferentially along stratification planes, with river waters being a major source of carbonate. In Wadi Dana (McLaren, 2004), calcretisation has occurred because of the inorganic precipitation of $\mathrm{CaCO_3}$ cementing alluvium in rock-cut channels. In addition, groundwater in the channels comes up through bedrock fractures, leading to carbon dioxide degassing allowing precipitation of calcium carbonate.

Most calcrete profiles described in the literature are polygenetic with different sedimentary and diagenetic processes acting at various stages during their evolution (e.g. Tandon and Kumar, 1999; Dhir et al., 2004). This questions the usefulness of polygenetic calcretes as distinctive palaeoenvironmental indicators. In addition, Budd et al. (2002) have highlighted the numerous pitfalls in the use of pedogenic carbonates as a proxy for palaeoclimatic reconstruction. Monogenetic non-pedogenic calcretes such as those in Wadi Dana may be more useful in palaeoenvironmental reconstructions. Although much is now known about the behaviour of stable isotopes (δ^{18}O and δ^{13}C) in pedogenic calcretes (e.g. Quade et al., 1995; Royer et al., 2001; Wright, 2007, and references within), relatively little is known concerning what factors affect stable isotope ratios in alluvial channel calcretes (particularly those completely unaffected by soil forming processes). Despite this lack of understanding, Burns and Matter (1995) have clearly indicated that stable isotope ratios of cemented alluvial conglomerates have the potential to hold valuable information about near surface environmental conditions.

We assume that carbonates precipitated from groundwater/meteoric water will have oxygen isotope compositions that predominantly relate to the δ^{18}O of precipitation, however in the Wadi Dana we need also to consider the residence time of water in the channels as well as channel processes as both can lead to evaporation, which will affect the δ^{18}O water composition. Evolved groundwaters may contain concentrated δ^{18}O values but areas with high inputs of rainfall, may precipitate carbonates that have lighter δ^{18}O amounts (Jacobson et al., 1988). Carbon isotope ratios (δ^{13}C) of the calcrete derive mainly from HCO_3^- in groundwaters and are useful as tracers of environmentally determined processes. Bicarbonate is derived from interaction of groundwaters with rocks and soils in the catchment. In general, there are a number of processes that control the inorganic carbon isotope composition of the calcrete: the carbon isotope composition of the bicarbonate in the inflowing waters, which will be a function of the catchment rocks and maybe critically in this environment the plant/soil types and vegetation density (Amundson et al., 1988), CO_2 exchange between atmosphere and the water, and photosynthesis/respiration of aquatic plants in the channels. Cerling (1984) found in low productivity soils that total soil CO_2 is strongly affected by atmospheric CO_2. In comparison to pedogenic calcretes, Wright and Tucker (1991) argue that groundwater calcretes are likely to have heavier δ^{13}C values "unless light C is introduced from phreatophytic vegetation" (p. 10). Heavier δ^{13}C values may indicate dry conditions with reduced net respiration in the soil, C_4 or CAM photosynthesising plants or mixing with atmospheric CO_2 (Wright and Tucker, 1991).

To summarise, the calcretes described here formed in rock-cut channels developed along thin river thalwegs and are formed by monogenetic calcium carbonate cementation of alluvium indicative of fluvial regimes (McLaren, 2004). Only groundwater calcretes exist/persist in the environment and thus the Wadi Dana calcretes provide an ideal opportunity to study the isotopic signatures of primary groundwater calcretes and thus this research presents an opportunity to more fully comprehend the utility of channel calcretes in palaeoenvironmental studies.

Through studying the stable isotope compositions of the channel calcretes, we aim to assess the usefulness of these groundwater calcretes as palaeoenvironmental indicators through:

a. Investigating the effect of hydrology/topography on the modern fluvial waters and where they are sourced.
b. Analysing the channel calcretes that have formed in a stratigraphical, reliable temporal sequence to see if any patterns of changes over time can be identified.
c. Considering if there are any changes that could be related to the diagenetic environment within wadi channels, or associated with their location in the landscape.
d. Observing whether any climatic signature can be distinguished.

2. Background: geologic and palaeoclimatic history

The Wadi Dana originates on Cretaceous and Tertiary sediments (predominantly limestones and marls), which cap the escarpment area around the village of Dana. Cenozoic basalts were extruded close to the study area around Dana village (Barjous, 1992). These rocks unconformably overlie a Lower Palaeozoic sequence of shallow marine through to terrestrial sandstones with thin shales, dolomites and copper ores. In turn, these rocks rest upon Late Proterozoic volcanic and intrusive rocks, which are exposed in the lower parts of the Faynan catchment (Bender, 1974; Rabb'a, 1994). Structurally, general uplift of the mountains was accompanied by intensive fault dissection on a regional scale, which created the graben of the Jordan-Dead Sea rift system during the Cenozoic (Singer, 2007).

During the Quaternary, as a response to orbitally induced insolation changes over the tropics (Braconnot et al., 2008), there were significant movements of wind belts associated with the ITCZ. Northward movements can result in shifts in the levels of humidity in the study area, which largely took place during past interglacials bringing wetter conditions (Waldmann et al., 2010). Although much evidence for environmental change exists in Israel, there is still a dearth of information for Jordan itself. Robinson et al. (2006) provide a very useful summary of the evidence for climatic changes for the late Quaternary, over the period from 25 ka to 5 ka in the Levant (including Jordan) and also present some General Circulation Models (GCMs) for the LGM but little evidence of environmental changes exists going further back in time; what is known is largely summarised below.

In terms of evidence for Quaternary palaeoenvironments in Jordan, Turner and Makhlouf (2005) investigated a 652 ± 47 ka aged and 15 m thick friable sandstone horizon with roots, pedogenic calcrete and gypcrete in the southern area of the Azrak Basin, Jordan. They concluded that the sandstone correlates with a proposed warmer and wetter MIS 17. Abed et al. (2008) dated two cardium horizons in the Eastern Desert of Jordan by U/Th at 330 ka (MIS 9) and argued that the deposits represent a freshwater/brackish lake. They suggest that the source of the humidity is most probably more intense Mediterranean cyclones associated with warmer than present interglacial conditions. However, the possibility of a summer monsoon extending up from the south was not excluded. Frumkin et al. (2008) have studied calcite speleothems, indicating wetter conditions, in a lava tube from eastern Jordan and dated them using uranium series techniques to MIS 7 from ~250 to 240 ka and from ~230 to 220 ka and the stage 5–4 transition between ~80 and 70 ka. A cardium lake in the far south around Mudawwara, Jordan on the border with Saudi Arabia has been dated by Petit-Maire et al. (2002) between 170 and 88 ka (MIS 7–5). Thus, in general, all these ages support wetter and warmer interglacial conditions.

A large body of evidence for climate change in the late Pleistocene of Jordan comes from Lake Lisan (the precursor to the Dead Sea). Waldmann et al. (2009) studied the stratigraphy and sediments of Lake Samra (Dead Sea) dated between 135 and 75 ka. Their research found that lowstands are correlated with warm arid intervals in the northern hemisphere while minor lake rises were probably related to colder episodes during the last interglacial (MIS5b and 5d). Bartov et al. (2002) determined the water level of Lake Lisan from 55 to 15 ka using sequence stratigraphy, radiocarbon and U-series dating. Between 55 and 30 ka small fluctuations around 280–290 m below mean sea level, separated at 48–43 ka by a drop to at least 340 m. The lake began to rise sharply reaching its maximum elevation of about 164 m below mean sea level between 26 and 23 ka, then fell again, reaching 300 m below mean sea level at ~15 ka. During the Holocene it stabilised at ca. 400 m below mean sea level (Bartov et al., 2002).

Migowski et al. (2006) have studied the Holocene Dead Sea sedimentary record and have identified two major wet phases at 10–8.6 cal kyr BP and ~5.6–3.5 cal kyr BP. They also found evidence for multiple abrupt arid events during the Holocene that fitted in with significant breaks in the cultural evolution of the Near East at 8.6, 8.2, 4.2, 3.5 cal kyr BP. Currently, a dry subtropical high pressure belt of air dominates the study area, which results in virtually no summer rainfall and high temperatures (Bender, 1975). During winter, cooler moist air comes eastward across the Mediterranean Sea, which acts as a dominant source of rainfall. Annual average rainfall in the study area is around 50 mm yr^{-1} rising to about 200 mm yr^{-1} on the escarpment east of the Faynan catchment.

3. Methods

This study concentrates upon seven calcretised fluvial channel deposits (Figs. 2 and 3) identified at maximum heights of +2 to 3 (Upper Dana Wadi), +5 to 7 (Faynan), +10 to 12 (Naqqazah), +15 (Dahlat), +22 to 25 (Mokeim), +30 (Fass Yad) and +125 to 130 (Quabbah) m above the modern wadi channel at their type sites. Field research involved logging, photographing and mapping the preserved remnants of the terraces along the middle and lower Wadi Dana valley as far west as the flat plain beyond the confluence of the Dana and the Wadi Ghuwayr. In total 85 representative samples were collected from 13 sections along the river for thin sectioning and

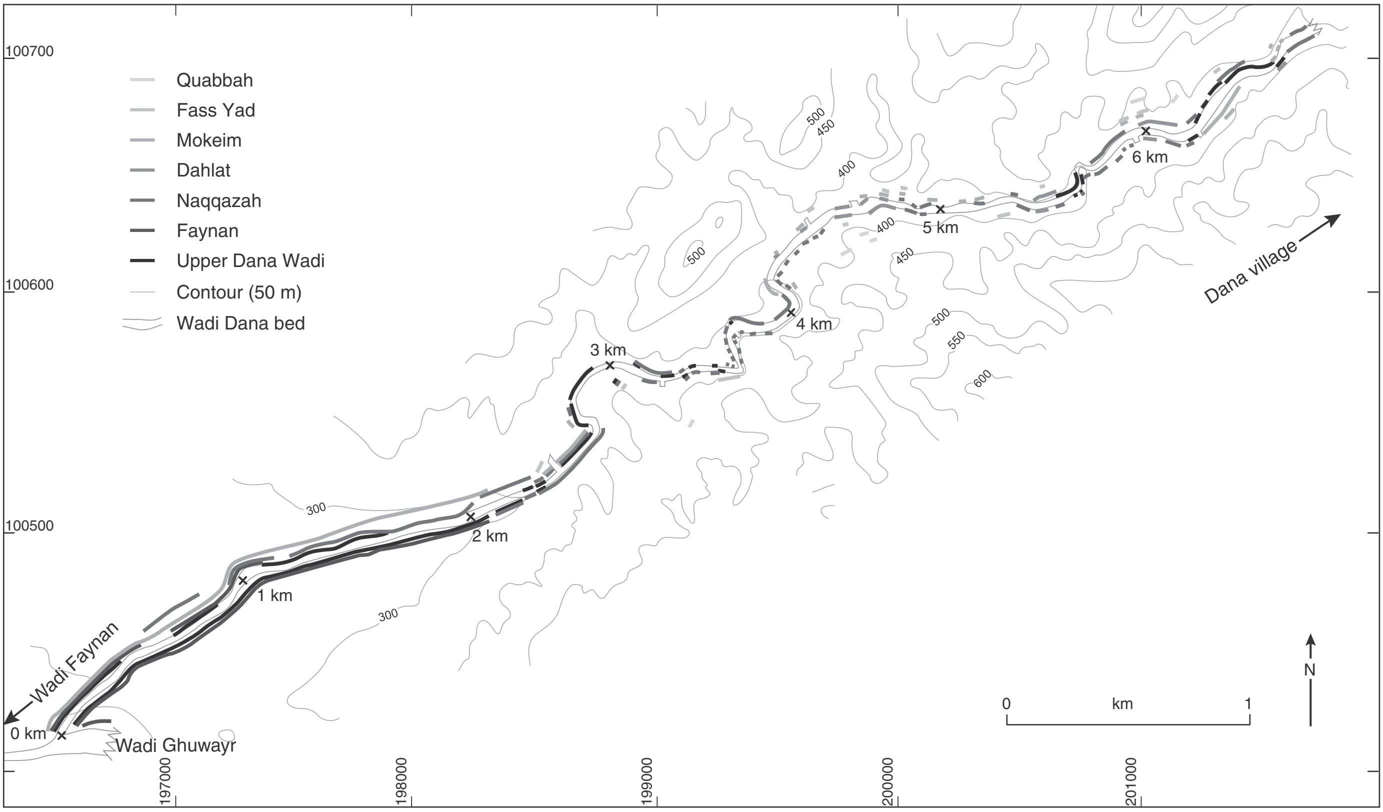

Fig. 2. Map showing the reach of Wadi Dana in the study area along with the distribution of the seven terrace locations.

micromorphological analyses. A summary of the point count analyses and interpretations for each terrace height can be found in McLaren (2004), although information that is relevant to this research on cement size patterns are shown in Table 1. Detailed descriptions of the type-sites can be found in McLaren et al. (2004, 2008). Numerical ages using optically stimulated luminescence (OSL) dating and radiocarbon dating techniques are discussed (along with details of the methodologies used) in Hunt et al. (2004) and McLaren et al. (2004). Four water samples were collected for oxygen and hydrogen isotopes, these were from groundwater, a spot rainfall sample, as well as two samples from different water bodies in the Wadi Dana, one from flowing river water (exposed to some degree of evaporation) and the other from a clearly evaporating water body. The waters were collected in labelled containers and refrigerated before their return to the United Kingdom. The water samples were then kept in a cold store until analyses were conducted. The waters were equilibrated with CO_2 using an Isoprep 18 device for oxygen isotope analysis with mass spectrometry performed on a VG SIRA. For hydrogen isotope analysis, an on-line Cr reduction method was used with a EuroPyrOH-3110 system coupled to a Micromass Isoprime mass spectrometer. Isotopic ratios ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) are expressed in delta units, $\delta^{18}O$ and δD (‰, parts per mille), and defined in relation to the international standard, VSMOW (Vienna Standard Mean Ocean Water). Analytical precision is typically ± 0.08‰ for $\delta^{18}O$ and ± 1.0‰ for δD.

Carbonate isotope analyses were carried out on sub-samples from each terrace height (Fig. 3), in total twenty seven samples were analysed for carbon and oxygen isotopes. Hand specimens of calcrete were ground in agate and the equivalent of 10 mg of carbonate was reacted with anhydrous phosphoric acid *in vacuo* overnight at a constant 25 °C. The CO_2 liberated was separated from water vapour under vacuum and collected for analysis. Measurements were made on a VG Optima isotope ratio mass spectrometer. Overall analytical reproducibility for these

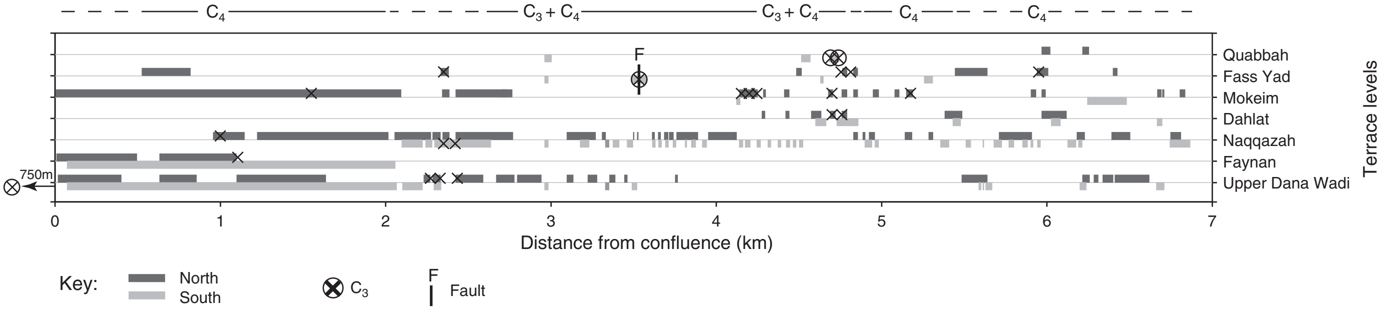

Fig. 3. Schematic longitudinal profile of the seven terrace Members in the study area (on both the north and south side of the wadi) field sample locations are marked with crosses. The x-axis shows the distance in km from the confluence of the Wadi Dana and the Wadi Ghuwayr. The interpreted patterns are discussed in the text and exceptions to these are circled and indicated in the key. The line at the top of the diagram represents the variations in the importance of C_3 v C_4 vegetation with distance from the confluence. (Please note that this figure does not show altitude differences between the terrace levels or with distance up wadi).

Table 1
The mean total percentages of micrite and sparite cements (minimum, mean and maximum values provided) sampled at different locations (top, centre and bottom) in the alluvial terraces preserved within distinct rock-cut channels.

Terrace	Faynan							Mokeim, Dahlat and Naqqazah							Fass Yad							Quabbah						
		Micrite			Sparite				Micrite			Sparite				Micrite			Sparite				Micrite			Sparite		
		% mean total							% mean total							% mean total							% mean total					
Position	*n*	Mean	Min	Max	Mean	Min	Max	*n*	Mean	Min	Max	Mean	Min	Max	*n*	Mean	Min	Max	Mean	Min	Max	*n*	Mean	Min	Max	Mean	Min	Max
top	10	43.5	30.2	49.3	1.6	0.0	6.1	11	36.5	21.6	47.2	1.5	0.0	4.3	6	65.8	26.9	100.0	8.2	0.0	21.9	2	0.0	0.0	0.0	66.2	65.4	67.0
centre	1	16.2	16.2	16.2	12.8	12.8	12.8	10	28.3	12.1	38.3	10.0	0.3	32.1	2	11.3	6.1	16.4	25.8	19.8	31.8	2	0.0	0.0	0.0	52.1	32.6	71.5
bottom	2	9.0	8.0	10.0	37.0	30.6	43.4	4	8.3	0.5	17.4	44.9	32.0	57.9	11	0.7	0.0	4.3	33.6	24.3	40.3	2	0.0	0.0	0.0	41.9	38.9	44.8

samples is normally better than 0.2‰ for δ^{13}C and δ^{18}O. Isotope values (δ^{13}C, δ^{18}O) are reported as per mil (‰) deviations of the isotopic ratios (^{13}C/^{12}C, ^{18}O/^{16}O) calculated to the VPDB scale using a within-run laboratory standard calibrated against NBS standards.

4. Results: stable isotope geochemistry

4.1. Modern water isotope values

δ^{18}O and δD from ten rainfall stations from different locations in Jordan (from Bajjali and Abu-Jaber, 2001) as well as our four water samples collected for this study are given in Fig. 4a. The rainfall data show that there is depletion in δ^{18}O as altitude increases. For this study we (opportunistically) collected a spot rainfall sample from the top of the escarpment close to Dana village and the δ^{18}O and δD values are similar to the other high altitude data (Bajjali and Abu-Jaber, 2001), including those from Shawbak, approximately 15 km south of Dana. The other two samples collected in the study area come from surface waters and both lie on a local evaporation line (LEL) away from the global meteoric water line (GMWL). One sample is from slow-flowing water in the current wadi channel (δ^{18}O −0.59‰; δD −4.8‰), while the most enriched sample is from an evaporating remnant pond on the wadi floor and has the highest isotope ratios (δ^{18}O +4.89‰, δD +18.0‰).

4.2. Calcrete isotope values

The highest and oldest terrace member is Quabbah. Its age is uncertain but based upon its height above the modern wadi (+125 m), plus the knowledge that the lower +30 m terrace is likely to be about c.450,000 years old (see McLaren et al., 2004, 2008 and below) it is believed that this fluvial conglomerate is at least early Quaternary in age. This is the only terrace deposit that has undergone complete recrystallisation and only secondary spar cements remain (Table 1). Stable isotope ratios obtained for this Quabbah Member (Table 2, Figs. 3 and 4b) are depleted in both δ^{18}O and δ^{13}C (−6.1‰ to −6.4‰ and −6.4‰ to −6.5‰ respectively).

The +30 m Fass Yad Member is thought to be older than 109 ka (saturated OSL age) and perhaps as old as 450 ka due to an unrolled Acheulean handaxe found within the fluvial deposits (McLaren et al., 2008). One sample from this Member (Table 2—upper wadi sample; Figs. 3 and 4b) was collected from the eastern part of the study area in an upstream location (δ^{18}O −6.4‰, δ^{13}C −2.5‰). The calcrete was sampled close to the base of a shallow impermeable rock-cut channel where carbonate waters pond or flow laterally through the alluvial material (Wright and Tucker, 1991) and the deposit is dominated by primary spar cement that has crystallised slowly allowing large crystals to develop without the influence of evaporation (Fig. 5a; McLaren, 2004). Two Fass Yad samples (Table 2—mid-wadi samples; Figs. 3 and 4b) were collected downstream of the previous sample from the centre of the study area and thus received a greater quantity of channel flow during flood events. These calcretes were collected from the mid part of palaeo-channels and they contain a mix of micritic and sparry primary cements (Table 1 and Fig. 5b). The δ^{18}O values are −4.0‰ and −4.9‰ and the δ^{13}C values are −3.9‰ and −4.4‰. A further Fass Yad sample (Table 2—lower wadi; Figs. 3 and 4b) was collected from near the top of a wadi channel, in the most westerly location of all of the other Fass Yad Member deposits studied, also making it the lowest altitude site. The sample measured for stable isotopes contained 100% micrite (Table 1) and had a δ^{18}O value of −2.9‰ and δ^{13}C of −2.3‰. The final Fass Yad Member sample (Table 2—mid-wadi spring; Figs. 3 and 4b) came from the channel close to a palaeo-spring (Fig. 6a), which appears to be associated with a fault, the δ^{18}O is −4.3‰ and the δ^{13}C is one of the lowest of all the calcretes of −9.1‰.

The next four terraces are considered together as they show a number of similarities. Of this group, the +22 (Mokeim), +15 (Dahlat) and +12 (Naqqazah) m terraces are thought to fall into the age range of

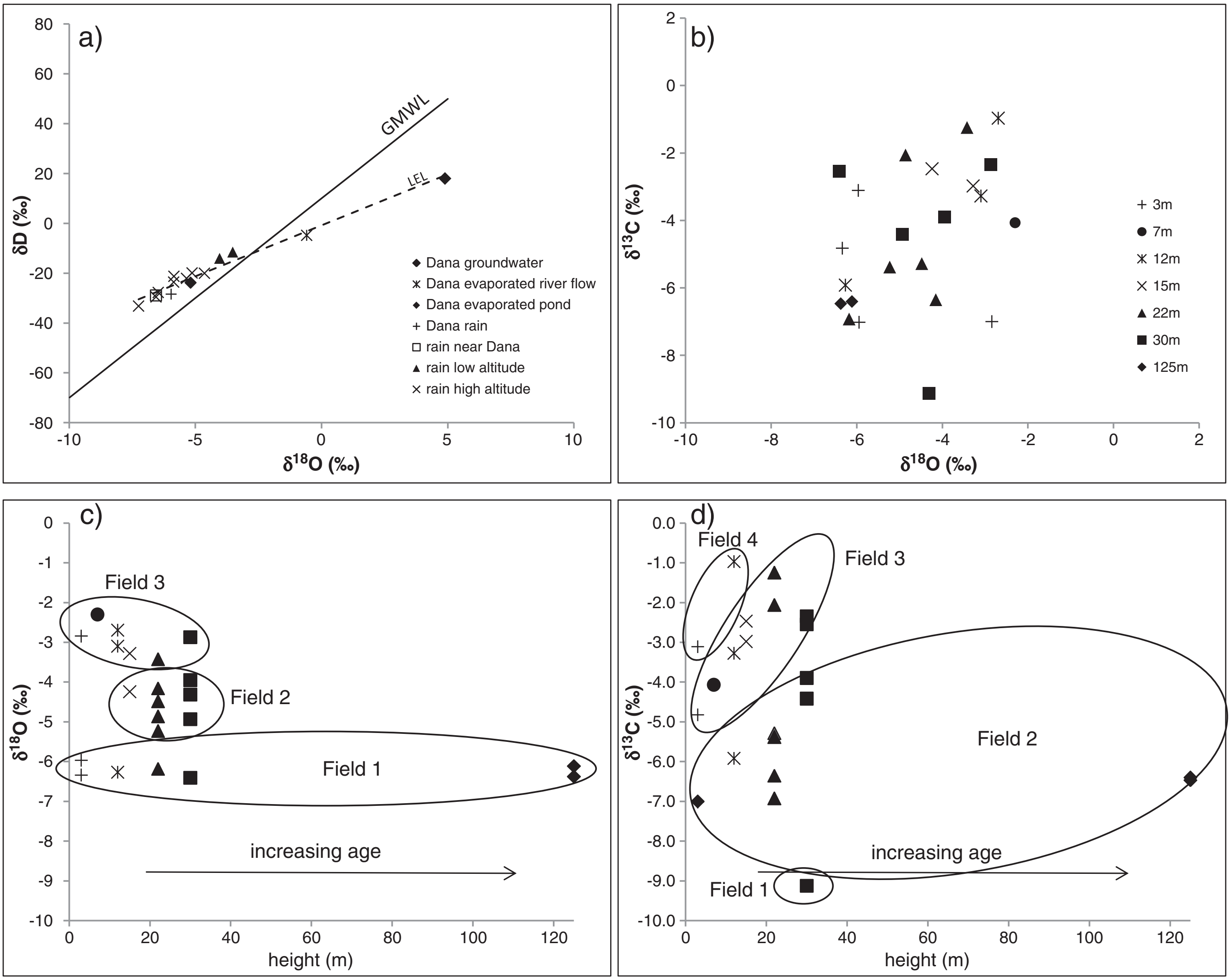

Fig. 4. a: (top left) $\delta^{18}O$ and δD diagram of rainfall from various sites in Jordan (from Bajjali and Abu-Jaber, 2001) plus rainfall, surface water and groundwater from the Wadi Dana catchment along with the global meteoric water line (GMWL). The local evaporation line (LEL) is also shown. b: (top right) Isotope values for all the fluvial calcretes sampled at different heights above the modern Wadi Dana, terrace names relating to the key are: $^{+}$3 m Upper Dana Wadi; $^{+}$7 m Faynan; $^{+}$12 m Naqqazah; $^{+}$15 m Dahlat; $^{+}$22 m Mokeim; $^{+}$30 m Fass Yad; and, $^{+}$125 m Quabbah. c: (bottom left) $\delta^{18}O$ values for all the fluvial calcretes sampled against increasing height from the modern wadi bed. Values are grouped as: Field 1, coarse sparry cements; Field 2 a mix of spar and micrite cements; and Field 3 calcretes with mainly micrite cements. d: (bottom right) $\delta^{13}C$ values for all the fluvial calcretes sampled against increasing height from the modern wadi bed. Values are grouped as: Field 1, C_3 environment dominated by tufa conditions; Field 2, mainly C_3 environment; Field 3, environment with greater mix of C_3 / C_4 plants; and Field 4, environment with greater preponderance of C_4 plants.

<109 ka but more than 17 ka and thus all appear to be last glacial in age but most likely not associated with the LGM (last glacial maximum). During the last glacial Lake Lisan's (the Dead Sea) water levels and climate varied over time, but overall were high and conditions were thought to be cool and wet (e.g. Bartov et al., 2002). How fluvial activity in Wadi Dana fitted in with is climatic variability is uncertain. The +7 m terrace (Faynan) is late last glacial through to mid-Holocene in age. Nine out of the twelve sample locations were between ~2.4 and 5.1 km from the confluence (i.e. Mid-lower and Mid wadi in Fig. 3). The samples denoted with a ‡ in Table 2 were all collected either near to the bottom of impermeable wadi channels, or were sampled at depths of more than 6 m in thick alluvial deposits, where any evaporation from the water table is insignificant (Mann and Horowitz, 1979). In these sediments, sparry cements dominate, all with low $\delta^{18}O$ which range from −4.2‰ to −6.2‰ and low $\delta^{13}C$ between −5.3‰ and −6.9‰ (Fig. 5c). Both spar and micrite cements are present in the samples displayed with a † in Table 2, (which were sampled in the central part of the rock-cut channel) have $\delta^{18}O$ values from −3.1‰ to −4.9‰ and $\delta^{13}C$ from −2.1‰ to −3.3‰. Three samples (Table 2—lower wadi) came from the west of the study area (~1.0–1.5 km from the confluence—see Fig. 3). Pore-infilling micritic cements dominate and they were sampled from near the top of channels (Fig. 5d), $\delta^{18}O$ are between −2.3‰ and −3.4‰ and $\delta^{13}C$ between −1.0‰ and −4.1‰ and may be influenced by the area being the driest part of the study area today.

Three micritic-cemented samples (Table 2—mid-lower wadi; Figs. 3 and 4b) from the late-Holocene +3 m terrace (Upper Dana Wadi) were collected close to the edge of the mountain front, from mid channel locations, $\delta^{18}O$ range between −5.9‰ and −6.3‰ and $\delta^{13}C$ between −3.1‰ and −7.0‰. One sample (Table 2—lower wadi), also has micritic cement, its stable isotope values are: ($\delta^{18}O$ −2.8‰ and $\delta^{13}C$ −7.0‰) and it is located at the edge of the mountain front where the plain/basin starts to open out (Fig. 6b).

5. Discussion

$\delta^{18}O$ and δD values from the rainfall stations show that as expected there is depletion in these isotopes as altitude increases. Thus from the

Table 2
Stable Isotope compositions of the Quaternary calcretes of Wadi Dana. ‡denotes samples collected from the bottom of channel calcretes; †denotes samples collected from mid location within channels.

Member	Location along the reach of the W. Dana studied	Approximate height above the modern wadi floor (m)	Age	$\delta^{18}O$(‰ PDB)	$\delta^{13}C$(‰ PDB)
Quabbah	mid wadi	125	Early Pleistocene?	−6.4	−6.5
Quabbah	mid wadi	125	Early Pleistocene?	−6.1	−6.4
Fass Yad	mid wadi	30	>109 ka	−4.0	−3.9
Fass Yad	mid wadi spring	30	>109 ka	−4.3	−9.1
Fass Yad	upper wadi	30	>109 ka	−6.4	−2.5
Fass Yad	mid wadi	30	>109 ka	−4.9	−4.4
Fass Yad	lower wadi	30	>109 ka	−2.9	−2.3
Mokeim	mid wadi †	22	<109 and >17 ka	−4.9	−2.1
Mokeim	mid wadi ‡	22	<109 and >17 ka	−4.5	−5.3
Mokeim	mid wadi ‡	22	<109 and >17 ka	−6.2	−6.9
Mokeim	mid wadi ‡	22	<109 and >17 ka	−4.2	−6.4
Mokeim	lower wadi	22	<109 and >17 ka	−3.4	−1.2
Dahlat	mid wadi ‡	15	<109 and >17 ka	−5.2	−5.4
Dahlat	mid lower wadi †	15	<109 and >17 ka	−4.2	−2.5
Dahlat	mid lower wadi †	15	<109 and >17 ka	−3.3	−3.0
Naqqazah	mid lower wadi †	12	<109 and >17 ka	−3.1	−3.3
Naqqazah	lower wadi	12	<109 and >17 ka	−2.7	−1.0
Naqqazah	mid lower wadi ‡	12	<109 and >17 ka	−6.3	−5.9
Faynan	lower wadi	7	c. 16–6 ka	−2.3	−4.1
Upper Dana Wadi	mid lower wadi	3	<5 ka and >400 yrs BP	−6.0	−3.1
Upper Dana Wadi	mid lower wadi	3	<5 ka and >400 yrs BP	−6.3	−4.8
Upper Dana Wadi	mid lower wadi	3	<5 ka and >400 yrs BP	−5.9	−7.0
Upper Dana Wadi	lower wadi	3	<5 ka and >400 yrs BP	−2.8	−7.0

Dead Sea Rift Valley up the eastern escarpment there is a gradual loss of heavy isotopes (resulting in lower $\delta^{18}O$ and δD) of the air masses as they ascend up onto the Jordanian plateau. The groundwater samples we collected have similar $\delta^{18}O$ and δD values to the other high altitude data suggesting that groundwater is largely recharged by the rains that fall on the escarpment and plateau in the east of the study area. The surface waters that lie on the LEL are evaporated relative to meteoric water. While there will be some effect of altitude on rainfall, given that most groundwater is recharged at altitude, the overriding influence on the modern waters is evaporation, and likely this would have been the case during formation of the fluvial calcretes.

The calcrete cement types and patterns that have developed indicate that the deposits being studied are monogenetic. The stable isotope record has preserved the palaeoenvironmental conditions that existed at the time of cement precipitation, which shows subtly variable environmental conditions both within and between deposits. There are similarities in the range of stable isotope values from published calcretes (e.g. Talma and Netterberg, 1983) and the results presented here. This includes the work of Mack et al. (1991) who studied the stable isotope ratios of fluvial calcretes from the Permian Abo Formation in New Mexico. They recorded a $\delta^{18}O$ content that ranged from −0.4‰ to −7.2‰ ($\overline{\chi}$ −4.0) and $\delta^{13}C$ values between −2.8‰ and −7.2‰ ($\overline{\chi}$ −5.3). In comparison, the Wadi Dana isotope measures range between −2.3‰ and −6.4‰ ($\overline{\chi}$ −4.6) and −1.0 and −7.0‰ ($\overline{\chi}$ −4.3) for $\delta^{18}O$ and $\delta^{13}C$ respectively (excluding the sample collected close to a palaeospring with tufa). The complexity of factors affecting $\delta^{18}O$ values in the calcretes results in a lack of any clear spatial pattern or variation between terrace levels (Fig. 4b). In terms of hydrology, the isotope compositions for $\delta^{18}O$ range from −6.4‰ to −2.7‰, the lower values most likely reflecting a dominant groundwater influence on $\delta^{18}O$ in Wadi Dana (Fig. 4b). We can calculate the oxygen isotope composition of calcretes that would theoretically precipitate in the modern environment to compare to the fossil values. Assuming a mean annual temperature of 25 °C (Greenbaum et al., 2006a) and using the Dana groundwater oxygen isotope composition (−5.19‰) then the resulting calcretes would have $\delta^{18}O$ of between −7.2‰ and −6.8‰ (using the mineral-water fractionation equation of Hays and Grossman (1991) which was modified from O'Neill et al.'s (1969) experimental data). The $\delta^{18}O$ value of the modern day evaporated water body is +4.89‰ (Fig. 4a), which falls within the range of +1.8‰ and +5.9‰ measured from evaporating lakes in the Badain Jaran Desert in western China by Yang et al. (2010). Thus it is reasonable to calculate the oxygen isotope composition of calcrete that would have precipitated from the Dana evaporated water body. The $\delta^{18}O$ value of a calcrete precipitated from this evaporated water body would range between +2.9‰ and +3.3‰. The theoretical modern groundwater calcretes are within the range of some of the fossil calcretes (Fig. 4b) although we have not analysed any material with values approaching calcretes that might potentially precipitate from the evaporating pond. Thus it would appear that calcrete formation is largely not the result of processes of evaporation.

Variations in the diagenetic environment associated with the position within the rock cut channel can be distinguished and this is supported by analyses of the cement crystals and fabric making up the fluvial calcretes (see McLaren, 2004) (Table 1 and Fig. 5). As mentioned earlier, all of the stable isotope results for the channel calcretes are negative, which indicates that the crystals are not forming at the final stage of drying out and high rates of evaporation of the river after flooding, but during ponding or slow-draining of river waters allowing slow meteoric diagenesis, probably at depth initially. The $\delta^{18}O$ values in these environments at depth in the channel are very close to both groundwater and rainwater values that exist today. As the channel becomes calcretised at the base it is then less able to carry the same volume of water during flood events and that water being closer to the ground surface is then more prone to some evaporation leading to fine micritic crystals with less negative $\delta^{18}O$ values near the top of the channel alluvium.

Fields of $\delta^{18}O$ values against channel height (and hence age) are shown in Fig. 4c. Three clusters of data have been distinguished on the basis of cement fabric and associated $\delta^{18}O$ values. In Field 1, the samples have the lowest $\delta^{18}O$ and are either those containing coarse sparry cements that have precipitated at depth in the channel over time or are those that represent the oldest deposits that have become recrystallised (samples at 125 m; Table 1, Fig. 5a and c). The source of the water is probably a mix of groundwater and rainfall sources, with no evidence of evaporative enrichment occurring. In Field 2, the samples have

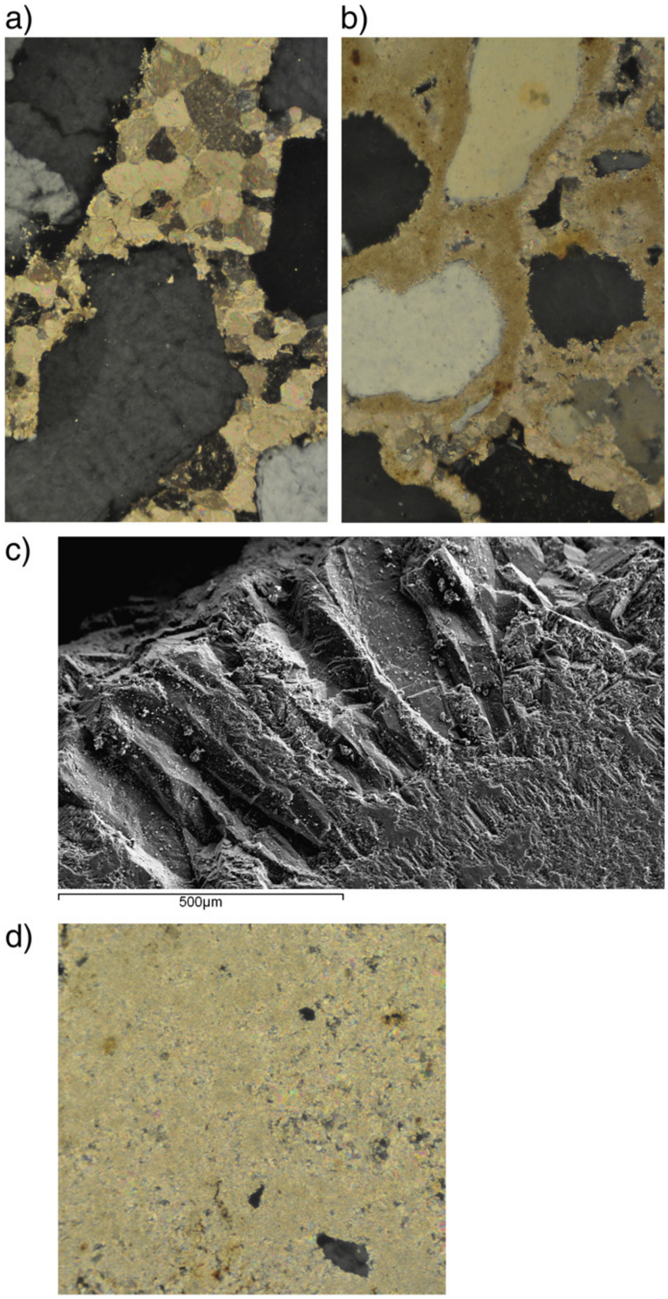

Fig. 5. a: Fass Yad Member—wadi channel base: spar pore-filling cement separating floating grains; note that the edges of the dark coloured quartz clasts display displacive replacement by calcite (cross-polarised light; ×25). b: Fass Yad Member—central channel: micritic rim cements surrounding quartz clasts, with a later stage of displacive spar cement (cross-polarised light; ×25). c: Mokeim Member—wadi channel base: SEM image of very coarse spar cement. Scale bar is 500 μm. d: Faynan Member—near surface sample (0.4 m from the top of the sequence): Micritic calcrete cement (cross-polarised light; ×25).

intermediary δ^{18}O; they contain a mix of spar and micrite and are found more centrally in the wadi channel (Table 1 and Fig. 5b). There is no evidence of significant evaporation although δ^{18}O values are heavier. Finally, in Field 3 the samples have the highest δ^{18}O and mainly comprise micritic cements that precipitated out rapidly near the surface (Table 1 and Fig. 5d) probably as a result of a combination of fluvial drainage, with some evaporation and evapo-transpiration. Salomons et al. (1978) found that calcretes sampled at shallow depths (<30 cm in Cyprus) showed an increase in both O and C isotopes up towards the surface, which they linked to evaporation. It may be that once the base of the channel had become calcretised the upper parts were cemented partly as a result of evaporative pumping resulting in micrite and heavier stable isotope values. All 3 types (fields) of data span the entire timeframe suggesting that depositional environment is more important for distinguishing the range in δ^{18}O than any temporal effect and perhaps indicates that all the calcretes formed under similar climatic conditions. Thus the length of time of the wetting phase has affected the rate of carbonate cement precipitation and thus crystal size (Wright and Tucker, 1991) in the wadi channels.

The Quabbah Member (+125 m; Tables 1 and 2, Fig. 4b) is the oldest and these deposits comprise poorly sorted conglomerates cemented by neomorphic sparry calcite. Using the analogy of the younger terraces in the Wadi Dana, the original primary cements would have been precipitated from groundwater and overland flow into the wadi channels. None of the other terrace levels have had enough time to undergo any significant secondary alteration of the cements and thus it is likely that recrystallisation occurred prior to the lower Palaeolithic, i.e. at some point after initial calcretisation and during the incision of the wadi from its current height of ~125 m above the modern wadi in the early Quaternary down to the formation of the Fass Yad Member (about 95 m of incision). During this time, the primary calcrete crystals would have been gradually lost and substituted for secondary neomorphic spar. Under such environmental conditions, the water required for wet recrystallisation of the cements is likely to have come from rain waters because base level and thus the groundwater table would have been falling over time, putting it beyond the influence of the diagenetic overprinting taking place within the phreatic environment of the impermeable wadi channels. When compared with the lower terraces (other Field 1 data in Fig. 4c), the δ^{18}O values in the cements do not appear to have changed during secondary recrystallisation of the Quabbah terrace, which suggests that either that the cement crystals have simply been consumed and reprecipitated *in situ* or that the source and isotopic composition of the water for precipitation of the cements is the same for both the primary and the secondary cements i.e. meteoric or groundwater.

Interpreting the δ^{13}C values of the samples is also highly complicated. There are numerous factors that may play a role, many of which are inter-related. Talma and Netterberg (1983) indicated that enrichment of the amount of δ^{13}C may be a result of one of a number of factors, including equilibration with atmospheric CO_2, CO_2 loss or reaching equilibrium with δ^{13}C of bicarbonates dissolved in ground, river or soil water. Many stable isotope studies now indicate that groundwater carbonates that have not been buried to any significant depth (which includes the deposits from Wadi Dana) tend to be near or in isotopic equilibrium with plant-derived carbon dioxide (e.g. Quade and Roe, 1999). As there is a notable variation in the modern vegetation associated with changes in altitude in the Dana Valley (Baierle et al., 1989; Baierle, 1993), the δ^{13}C values are compared to what is known about both the modern distribution of vegetation and that preserved in the Holocene (the Pleistocene deposits in Wadi Dana are generally unfossiliferous) (Hunt et al., 2004). The δ^{13}C values are plotted against channel height/time in Fig. 4d. These data cluster into four groups on the basis of a number of factors discussed below. Field 1 sample was collected adjacent to a spring where there are some small accumulations of tufa and has the lowest δ^{13}C. The δ^{13}C value of the sample in Field 1 is not dissimilar to other ambient temperature tufas discussed in the literature (e.g. Viles and Pentecost, 2007) and is influenced by C from incipient soils from C_3 vegetation, which fix carbon via the C_3 pathway that today includes *Nerium* and algae (Baierle et al., 1989). Field 2 δ^{13}C data contains samples from a range of environments. These settings include (Fig. 3): the relatively climatically cooler, older, higher, altitude samples where both today and during much of the Holocene *Juniperus* and *Retama raetam* (both C_3 plants) can be found (Baierle et al., 1989; Hunt et al., 2004); riparian C_3 vegetation from within or surrounding

Fig. 6. a: Fass Yad Member preserved +30 m above the modern wadi (black arrows mark the base of the rock-cut channel); note the abundance of vegetation including C_3 *Nerium* (oleanders). b: Low altitude plain in the west of the study area, looking east towards the Edom Mountains.

the active channels, including *Phragmites*, *Typha*, and *Tamarix* (Kurschner, 1986; Palmer et al., 2007); or C_3 cereal crops in the archaeological terraced fields developed above and adjacent to the lower fluvial +3 m terrace (see below). Fields 3 and 4 have mid to high $\delta^{13}C$, which may indicate a greater representation and mix of C_4 short annual grasses from the surrounding arid hillslopes and riparian C_3 plants (e.g. *Phragmites*, *Typha*, *Tamarix* and *Retama raetam*, Baierle et al., 1989). However, high values of $\delta^{13}C$ (as well as $\delta^{18}O$) have been interpreted by Talma and Netterberg (1983) as reflecting nearness to the surface and the free atmosphere as well as the effects of evaporation, which are typical in arid environments with low levels of vegetation, although in Wadi Dana the $\delta^{18}O$ values do not support high levels of evaporation. Schlesinger (1985) has argued that mixing of atmospheric and soil respiration CO_2 can result in enriched $\delta^{13}C$ values. Low vegetation density under arid conditions can mean that CO_2 levels in the 'soil' zone contain significant amounts of atmospheric CO_2, which is more enriched than soil CO_2 and can give the impression that C_4 plants are present, even when they are not. However, as there are C_4 short annual grasses in the hyper-arid study area today, it is likely that they were also present in the past. For example, Hunt et al.'s (2004) study shows that climatic change on the scale of the Holocene has resulted in altitudinal shifts in vegetation, except the phreatophytes along the wadi channel, but no major changes in species. Thus there is likely to be a complex range of controls on the $\delta^{13}C$ signatures of the groundwater calcretes from Wadi Dana. However, as there is a good correlation between the distribution of modern C_3 and C_4 plants in the valley and the $\delta^{13}C$ values of the calcrete it is proposed that, along with other controls discussed earlier, the role of landscape position affecting the type and amount of vegetation present plays an important role.

The uppermost line in Fig. 3 shows the changes in significance of C_3 and C_4 vegetation signatures identified in the calcretes spatially along the steep sides of the Dana valley. This pattern matches the modern day distribution of C_3 and C_4 plants. The uppermost Quabbah Member, on the cooler mountain top shows a dominance in C_3 vegetation such as *Juniperus*, *Retama* and *Artemisia* (Baierle et al., 1989). In the higher reaches of the study area between 5 and 6 km, the channel calcretes show a dominance of C_4-dominated steppe desert vegetation, that includes grasses, *Salsola*, *Halogeton* and *Atriplex halimus* (Ehleringer et al., 1997), similar to today (Kurschner, 1986), from the steep arid hillslopes with little evidence of any significant riparian vegetation in the wadi channels. Although, research has found that where stagnant ponds/pools are present (which occur in the channels today), algae may experience C-limitation, and as such primary producers, δ^{13}C values can be significantly elevated above typical δ^{13}C for C_3 plants (France and Cattaneo, 1998), which may be reflected in the results but has been interpreted as a C_4 signature. Between ~2 and 5 km (Fig. 3), the samples show a mix of C_3 riparian vegetation alongside C_4 vegetation from the much drier surrounding hillslopes. There is an increase in the C_3 signature downstream in the mountains associated with increasing riparian vegetation, overland and channel flow from upstream. Beyond the mountain front, the drainage becomes less confined and there is a far more rapid dissipation of water through the wadi deposits. Today, the western plain receives far less rainfall than the mountains and on the lower slopes of the Wadi Dana up to about 100 m amsl, an extreme steppe-desert exists (Kurschner, 1986) with C_4 vegetation, such as grasses, *Calligonum comosum* and *Traganum nudatum* (Baierle et al., 1989).

Unfortunately, the actual ages of calcrete formation are largely unknown, which limits the usefulness of this study in terms of palaeoclimatic reconstruction. Despite these limitations the combination of stable isotope analyses and petrographical studies still provide important insights into the palaeoenvironmental conditions required for channel calcrete development. From the temporal evidence available, it is known that the +3 m terrace (and hence the calcrete) is younger than mid-Holocene. During the mid-Holocene some findings suggest that conditions were slightly wetter than present (e.g. Frumkin et al., 1994; Hunt et al., 2004). Climatic conditions over this period were becoming increasingly hotter and drier (Frumkin, 2009) and Bar-Matthews et al. (2003) have calculated palaeorainfall levels indicating increasing aridity after the mid-Holocene in the eastern Mediterranean. People were now well established in the study area, farming and irrigating the land (Barker et al., 2008 and chapters therein). Farming may have had an anthropogenic affect due to cultivation as the δ^{13}C composition of the groundwaters would have a greater contribution of C from C_3 plants while C_4 vegetation would have remained on the natural slopes away from the crops. Like all the terraces, the Upper Dana Wadi terrace (+3 m) calcretes have a range in δ^{13}C values so there is no definite evidence for cultivated crops (Fig. 4d). The source of the water that led to the precipitation of the +3 m terraces is variable with two very low groundwater (possibly via irrigation) values (Field 3, Fig. 4c) and one high value (Field 1, Fig. 4c) indicating some evapo-transpiration on the plains, which may have led to the deposition of the fluvial channel deposits. Although Hunt et al. (2004), utilising pollen and palaeobotanical proxies, have argued for wetter conditions (~200 mm p.a.) prior to 8.0 cal ka BP with marginal Mediterranean forest in the Wadi Faynan. Numeric dating of fluvial sediments from the +7 m terrace gives ages from late last glacial through to mid-Holocene age. Terrace formation and calcretisation is associated with a phase of climate change from cooler and drier to warmer and wetter conditions, which Bridgland and Westaway (2007) and Maddy et al. (2005) amongst others have argued is conducive for terrace formation. The +12, +15 and +22 m terraces are all thought to be last glacial in age and data from the Levant area (e.g. Bartov et al., 2002; see Robinson et al., 2006) indicates that water levels were variable but at times high during the last glacial due to cooler and wetter conditions (excluding the LGM when aridity is thought to have prevailed). During the last glacial, Greenbaum et al. (2006b) found evidence for significant wetter events due to increased frequency of the Red Sea Trough low pressure system and between 40 and 20 ka, due to the influence of Mediterranean pressure systems made the wetter. The +30 m terrace is older than 109 ka and may be as old as 400–450 ka. The highest terrace is probably early Quaternary and as such, one can only use the isotope data to suggest that the palaeoenvironmental conditions under which the calcrete formed are similar to the younger calcretes. The lack of a good chronological framework means that terrace and calcrete formation cannot be tied in specifically with these climatic changes. However, the conditions of calcretisation did not involve large amounts of evaporation and because it has been asserted that current conditions are too arid for calcrete formation, the climate must have been slightly wetter and cooler.

The fluvial deposits themselves all represent significant wet events by their existence. Although the catchment is relatively small, the size of the bedload is largely of rounded cobbles and boulders, which indicates that high energy events have occurred. Research on the role palaeoclimate on river terrace formation has led some researchers to argue that terrace formation/accumulation of sediment in rock cut channels occurred under more arid conditions with reduced vegetation density and greater slope instability (e.g. Macklin et al., 2002; Bridgland and Westaway, 2007). These findings contradict those of de Jaeger and de Dapper (2002), working in the Mujib Canyon in central Jordan, who argued that fluvial accretion occurred during periods of higher rainfall during the Pleistocene. The climatic conditions under which the Dana terraces formed remains unknown but the results of this research indicates that calcretisation occurred under relatively cooler and wetter conditions than today.

6. Conclusions

Calcretised alluvial deposits preserved in impermeable rock-cut channels have been investigated for their stable isotope composition, petrography and stratigraphy in order to make a contribution towards understanding the palaeoenvironmental conditions under which they formed. This paper has considered the potential environmental effects of hydrology, topography, vegetation, diagenetic environment and time on the stable isotope values of δ^{18}O and δ^{13}C within channel calcretes from Wadi Dana.

The key findings are:

- δ^{18}O values have the potential to provide information about the hydrological environment in which the channel calcretes formed. All of the δ^{18}O results are negative and some are similar to theoretical calcretes formed from the modern groundwater. While some precipitated in moderately arid conditions at the edge of the mountain front (δ^{18}O values up to −2‰), there is a lack of evidence of any strong evaporational control on the calcrete formation suggesting cooler conditions than today.
- Location within the landscape appears to be important. There is some variation in the δ^{18}O values between the cooler mountains and the exposed low altitude plain that has been affected by more evaporation. However, any changes in the δ^{18}O values associated with altitudinal variations in rainfall isotope values (evident in the modern rainfall values) appear to be masked by the effects of other environmental factors.
- There is variation associated with diagenetic environment in the δ^{18}O data spatially within individual rock-cut channels, associated with distance from the surface of the channel and its localised affect on slow draining at depth and some evaporation near the surface.
- Interpreting the δ^{13}C values of the calcretes is highly complicated with many controls on the measured δ^{13}C signature. However, the proposed influences of vegetation on the calcrete δ^{13}C values do match the modern spatial variations in vegetation with altitude, indicating that climate may not have been too dissimilar to today just slightly wetter, as the climate today is too arid for calcretes to form in Wadi Dana.
- The type and amount of the modern-day vegetation is affected by the position of the terraces in the landscape. At the highest altitude studied, there is a dominance of C_3 vegetation, which gives way to C_4 vegetation in the lowland basin to the west. However, in upstream locations in the mountains, there appears to be less riparian

vegetation in the channels and there is a dominance of C_4 plants such as desert grasses from the surrounding slopes. Further downstream there is a gradual increase in the size of the channel, which results in environments that are more conducive to a stabilised channel with more riparian C_3 vegetation. Thus there appears to be a good relationship between the distribution of the modern vegetation and the $\delta^{13}C$ signatures within the calcretes from the various locations in the valley.

- In one location in the Wadi Dana, there is a spring-line, which is controlled by a geological fault. Ground water upwelling along the fractures had both low $\delta^{18}O$ and $\delta^{13}C$ values in an otherwise hyper- arid environment, suggesting that geology can have a large effect on the calcrete isotope composition.
- There are no significant changes in the range of either $\delta^{18}O$ or $\delta^{13}C$ from each level of terraces over time. This suggests that the environmental controls on the isotope composition are similar between periods of calcrete formation.

The use of stable isotope data from calcrete cements thus provides an important tool to solidify (and in the case of this study support) macromorphological and micromorphological analyses of groundwater (channel) calcretes in terms of helping to comprehend the environmental conditions under which they formed. This paper has demonstrated the potential of monogenetic channel calcretes as a proxy for palaeoenvironmental reconstructions.

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References

Abdul-Salem, A., 1966. Morphologische studien in der Syrischen Wüste und dem Antilibanon. Berliner Geographische Abhand-lungen 3, 1–55.

Abed, A.M., Yasin, S., Sadaqa, R., Al-Hawari, Z., 2008. The palaeoclimate of the eastern desert of Jordan during marine isotope stage 9. Quaternary Research 69, 458–468.

Al-Qawabah, M.S., Johnson, C., Ramez, H., Al-Fattah, M.Y.A., 2003. Assessment and evaluation methodologies report: Dana Biosphere Reserve, Jordan. Sustainable management of marginal drylands (Sumamad). Second International Workshop on Combating Desertification: Sustainable Management of Marginal Drylands (SUMAMAD). UNESCO-MAB, Shiraz, Islamic Republic of Iran, pp. 56–69.

Amundson, R.G., Chadwick, O.A., Sowers, J.M., Diner, H.E., 1988. Relationship between climate and vegetation and the stable carbon isotope chemistry of soils in the Eastern Mojave Desert. Quaternary Research 29, 245–254.

Baierle, H.U., 1993. Vegetation und flora im sudwestlichen Jordanien (Diss. Bot. 200), Cramer Stuttgart.

Baierle, H.U., Frey, W., Jagiella, C., Kurscher, H., 1989. Die Brennstoffresourcen im Raum Fenan (Wadi Araba, Jordanien) und die bei der Küpfererzverhüttung Verendeten Brennstoffe. In: Hauptmann, A., Pernicka, E., Wagner, G.A. (Eds.), Archäometallurgie der Alten Welt. : Der Anschnitt 7. Bochum, Selbstverlag des Deutchen Bergbau-Museums, pp. 213–222.

Bajjali, W., Abu-Jaber, N., 2001. Climatological signals of the palaeogroundwater in Jordan. Journal of Hydrology 243, 133–147.

Barjous, M.O., 1992. The Geology of the Ash Shawbak Area: Map Sheet No 3153 III. Amman: Hashemite Kingdom of Jordan. Ministry of Energy and Natural Resources, Natural Resources Authority, Geology Directorate, Geological Mapping Division Bulletin, 19.

Barker, G., Gilbertson, D.D., Mattingly, D., 2008. Archaeology and Desertification: The Wadi Faynan Landscape Survey, Southern Jordan. Oxbow Books, Oxford.

Bar-Matthews, M., Ayalon, A., Gilmour, M., Matthews, A., Hawkesworth, C.J., 2003. Sea–land oxygen isotopic relationships from planktonic foraminifera and speleothems in the Eastern Mediterranean region and their implication for paleorainfall during interglacial intervals. Geochimica et Cosmochimica Acta 67, 3181–3199.

Bartov, Y., Stein, M., Enzel, Y., Agnon, A., Rech, Z., 2002. Lake levels and sequence stratigraphy of Lake Lisan, the late Pleistocene precursor of the Dead Sea. Quaternary Research 57, 9–21.

Bender, F., 1974. Geology of Jordan. Contribution to the Geology of the World. Gebrueder Borntraeger, Berlin.

Bender, F., 1975. Geology of the Arabian Peninsula, Jordan. U.S. Geol. Surv. Prof. Pap., 560-I.

Braconnot, P., Marzin, C., Grégoire, L., Mosquet, E., Marti, O., 2008. Monsoon response to changes in Earth's orbital parameters: comparisons between simulations of the Eemian and of the Holocene. Climate of the Past 4, 459–493.

Bridgland, D.R., Westaway, R., 2007. Climatically controlled river terrace staircases: a worldwide Quaternary phenomenon. Geomorphology 98, 285–315.

Budd, D.A., Pack, S.M., Fogel, M.L., 2002. The destruction of palaeoclimatic isotopic signals in Pleistocene carbonate soil nodules of Western Australia. Palaeogeography Palaeoclimatology Palaeoecology 188, 249–273.

Burns, S.J., Matter, A., 1995. Geochemistry of carbonate cements in surficial alluvial conglomerates and their palaeoclimatic implications, Sultanate of Oman. Journal of Sedimentary Research A65, 170–177.

Carcaillet, J., Mugnier, J.L., Koci, R., Jouanne, F., 2009. Uplift and active tectonics of southern Albania inferred from incision of alluvial terraces. Quaternary Research 71, 465–476.

Cerling, T.E., 1984. The stable isotopic composition of modern soil carbonate and its relationship to climate. Earth and Planetary Science Letters 71, 229–240.

Cordova, C.E., Foley, C., Nowell, A., Bisson, M., 2005. Landforms, sediments, soil development, and prehistoric site settings on the Madaba-Dhiban Plateau, Jordan. Geoarchaeology 20, 29–56.

de Jaeger, Ch., de Dapper, M., 2002. Tectonic control in the geomorphic development of the Wadi el-Mujib canyon (Jordan). EGU Stephan Mueller Special Publication Series 2, 83–94.

Dhir, R.P., Tandon, S.K., Sareen, B.K., Ramesh, R., Rao, T.K.G., Kailath, A.J., Sharma, N., 2004. Calcretes in the Thar Desert: genesis, chronology and palaeoenvironment. Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences 113, 473–515.

Dutta, S., Suresh, N., Kumar, R., 2011. Climatically controlled late Quaternary terrace staircase development in the fold- and -thrust belt of the Sub Himalaya. Palaeogeography Palaeoclimatology Palaeoecology, http://dx.doi.org/10.1016/j.palaeo.2011.05.006.

Ehleringer, J.R., Cerling, T.E., Helliker, B.R., 1997. C_4 photosynthesis, atmospheric CO_2 and climate. Oecologia 112, 285–299.

EMWATER, 2005. Prospects of Efficient Wastewater Management and Water Reuse in Jordan, Country Study. Prepared within the Framework of the EMWATER-Project, "Efficient Management of Wastewater, its Treatment and Reuse in the Mediterranean Countries". Al al-Bayt University, Mafraq, Jordan, InWEnt, Amman Office, Amman, Jordan.

Eren, M., 2011. Stable isotope geochemistry of Quaternary calcretes in the Mersin area, southern Turkey—a comparison and implications for their origin. Chemie der Erde 71, 31–37.

France, R., Cattaneo, A., 1998. $\delta^{13}C$ variability of benthic algae: effects of water colour via modulation by stream current. Freshwater Biology 39, 617–622.

Frumkin, A., 2009. Stable isotopes of a subfossil Tamarix tree from the Dead Sea region, Israel, and their implications for the intermediate Bronze Age environmental crisis. Quaternary Research 71, 319–328.

Frumkin, A., Carmi, I., Zak, I., Magaritz, M., 1994. Middle Holocene environmental change determined from the salt caves of Mount Sedom, Israel. In: Bar-Yosef, O., Kra, R. (Eds.), Late Quaternary Chronology and Paleoclimates of the Eastern Mediterranean. The University of Arizona, Tucson, pp. 315–322.

Frumkin, A., Bar-Matthews, M., Vaks, A., 2008. Palaeoenvironment of Jawa basalt plateau, Jordan, inferred from calcite speleothems from a lava tube. Quaternary Research 70, 358–367.

Greenbaum, N., Ben-Zvi, A., Haviv, I., Enzel, Y., 2006a. Hydrology and palaeohydrology of Dead Sea tributaries. In: Enzel, Y., Agnon, A., Stein, M. (Eds.), New Frontiers in Dead Sea Palaeoenvironmental Research: Geol. Soc. Am. Spec. Pap., 401, pp. 63–93.

Greenbaum, N., Porat, N., Rhodes, E., Enzel, Y., 2006b. Large floods during late Oxygen Isotope Stage 3, southern Negev desert, Israel. Quaternary Science Reviews 25, 704–719.

Hancock, G.S., Anderson, R.S., 2002. Numerical modelling of fluvial strath-terrace formation in response to oscillating climate. Geological Society of America Bulletin 114, 1131–1142.

Hays, P.D., Grossman, E.L., 1991. Oxygen isotopes in meteoric calcite cements as indicators of continental paleoclimate. Geology 19, 441–444.

Hunt, C.O., Elrishi, H.A., Gilbertson, D.D., Grattan, J.P., McLaren, S.J., Pyatt, F.B., Rushworth, G., Barker, G., 2004. Early Holocene environments in the Wadi Faynan, Jordan. The Holocene 14, 921–930.

Jacobson, G., Arakel, A.V., Yijian, Chen, 1988. The central Australian groundwater discharge zone: evolution of associated calcrete and Gypcrete deposits. Australian Journal of Earth Sciences 35, 549–565.

Khadkikar, A.S., Mehr, S.S., Malik, J.N., Chamyal, L.S., 1998. Calcretes in semi-arid alluvial systems formative pathways and sinks. Sedimentary Geology 116, 251–260.

Kurschner, H., 1986. A physiognomical–ecological classification of the vegetation of southern Jordan. In: Kurschner, H. (Ed.), Contributions to the Vegetation of South West Asia. Reichert, Wiesbaden, pp. 45–79.

Mack, G.H., Cole, D.R., Giordano, T.H., Schaal, W.C., Barcelos, J.H., 1991. Paleoclimatic controls on stable oxygen and carbon isotopes in caliche of the Abo Formation (Permian), South-Central New Mexico, USA. Journal of Sedimentary Petrology 61, 458–472.

Macklin, M.G., Fuller, I.C., Lewin, J., Maas, G.S., Passmore, D.G., Rose, J., Woodward, J.C., Black, S., Hamlin, R.H.B., Rowan, J.S., 2002. Correlation of fluvial sequences in the Mediterranean basin over the last 200ka and their relationship to climate change. Quaternary Science Reviews 21, 1633–1641.

Maddy, D., 1997. Uplift-driven valley incision and river terrace formation in southern England. Journal of Quaternary Science 12, 539–545.

Maddy, D., Demir, T., Bridgland, D.R., Veldkamp, A., Stemerdink, C., van der Schriek, T., Westaway, R., 2005. An obliquity-controlled Early Pleistocene river terrace record from Western Turkey? Quaternary Research 63, 339–346.

Maddy, D., Demir, T., Bridgland, D.R., Veldkamp, A., Stemerdink, C., van der Schriek, T., Westaway, R., 2008. The early Pleistocene development of the Gediz river, Western Turkey: an uplift-driven, climate controlled system? Quaternary International 189, 115–128.

Malik, J.N., Khadkikar, A.S., 1996. Paleoflood analysis of channel fill deposits, Central Tapi river basin. India. Zeitschrift fuer Geomorphologie 106, 99–106.

Mann, A.W., Horowitz, R.D., 1979. Groundwater calcrete deposits in Australia: some observations from Western Australia. Journal of the Geological Society of Australia 26, 293–303.

McLaren, S.J., 2004. Characteristics, evolution and distribution of Quaternary channel calcretes, southern Jordan. Earth Surface Processes and Landforms 29, 1487–1508.

McLaren, S.J., Gilbertson, D.D., Grattan, J.P., Hunt, C.O., Duller, G.A.T., Barker, G., 2004. Quaternary palaeogeomorphologic evolution of the Wadi Faynan area, Southern Jordan. Palaeogeography Palaeoclimatology Palaeoecology 205, 129–152.

McLaren, S.J., Reynolds, T., Gilbertson, D.D., Grattan, J.P., Hunt, C.O., el-Rishi, H., Barker, G., Duller, G.A.T., 2008. Pleistocene environments and human settlement. In: Barker, G., Gilbertson, D.D., Mattingly, D. (Eds.), Archaeology and Desertification: The Wadi Faynan Landscape Survey, Southern Jordan. Oxbow Books, Oxford, pp. 177–198.

Migowski, C., Stein, M., Prasad, S., Negendank, J.F.W., Agnon, A., 2006. Holocene climate variability and cultural evolution in the Near East from the Dead Sea sedimentary record. Quaternary Research 66, 421–431.

Nash, D.J., McLaren, S.J., 2003. Kalahari valley calcretes: their nature, origins and environmental significance. Quaternary International 111, 3–22.

O'Neill, J.R., Clayton, R.N., Mayteda, T., 1969. Oxygen isotope fractionation in divalent metal carbonates. Journal of Chemical Physics 51, 5547–5558.

Palmer, C., Gilbertson, D., el-Rishi, H., Hunt, C., Grattan, J., McLaren, S., Pyatt, B., 2007. The Wadi Faynan today: landscape, environment, people. In: Barker, G., Gilbertson, D.D., Mattingly, D. (Eds.), Archaeology and Desertification: The Wadi Faynan Landscape Survey, Southern Jordan. Oxbow Books, Oxford, pp. 177–198.

Petit-Maire, N., Sanlaville, P., Abed, A.M., Yasin, S., Bourrouillh, R., Carbonel, P., Fontugne, M., Reyss, J., 2002. New data for an Eemian lacustrine phase in Southern Jordan. Episodes 25, 279–280.

Quade, J., Roe, L.J., 1999. The stable-isotope composition of early ground-water cements from sandstone in palaeoecological reconstruction. Journal of Sedimentary Research 69, 667–674.

Quade, J., Cater, J.M.L., Ojha, T.P., Adam, J., Harrison, T.M., 1995. Dramatic carbon and oxygen isotopic shift in palaeosols from Nepal and late Miocene environmental change across the northern sub-continent. Geological Society of America Bulletin 107, 1381–1397.

Rabb'a, I., 1994. The Geology of the Al Qurayqira (Jabal Hamra Faddan): Map Sheet No 3051 II. Amman: Hashemite Kingdom of Jordan. Ministry of Energy and Natural Resources, Natural Resources Authority, Geology Directorate, Geological Mapping Division. Bulletin 28.

Robinson, S.A., Black, S., Sellwood, B.W., Valdes, P.J., 2006. A review of palaeoclimates and palaeoenvironments in the Levant and Eastern Mediterranean from 25,000 to 5000 years BP: setting the environmental background for the evolution of human civilisation. Quaternary Science Reviews 25, 1517–1541.

Royer, D.L., Berner, R.A., Beerling, D.J., 2001. Phanerozoic atmospheric CO_2 change: evaluating geochemical and palaeobiological approaches. Earth-Science Reviews 54, 349–352.

Salomons, W., Goudie, A., Mook, W.G., 1978. Isotopic composition of calcrete deposits from Europe, Africa and India. Earth Surface Processes and Landforms 3, 43–57.

Schlesinger, W.H., 1985. The formation of caliche in soils of the Mojave Desert, California. Geochimica et Cosmochimica Acta 49, 57–66.

Singer, A., 2007. The Soils of Israel. Springer-Verlag, Berlin Heidelberg. 306 pp.

Spötl, C., Wright, V.P., 1992. Groundwater dolocretes from the Upper Triassic of the Paris Basin, France: a case study of an arid, continental diagenetic facies. Sedimentology 39, 1119–1136.

Talma, A.S., Netterberg, F., 1983. Stable isotope abundances in calcretes. In: Wilson, R.C.L. (Ed.), Residual Deposits: Surface Related Weathering Processes and Materials: Geol. Soc. Spec. Publ., 11, pp. 221–233.

Tandon, S.K., Kumar, S., 1999. Semi-arid/arid zone calcretes: a review. In: Singhvi, A.K., Derbyshire, E. (Eds.), Palaeoenvironmental Reconstruction in Arid Lands. Oxford and IBH Publishing Co., New Delhi, India, pp. 109–152.

Turner, B.R., Makhlouf, I., 2005. Quaternary sandstones, northeast Jordan: age, depositional environments and climatic implications. Palaeogeography Palaeoclimatology Palaeoecology 229, 230–250.

Viles, H.A., Pentecost, A., 2007. Tufa and Travertine. In: Nash, D.J., McLaren, S.J. (Eds.), Geochemical Sediments and Landscapes. Blackwell, Oxford, pp. 173–199.

Waldmann, N., Stein, M., Ariztegui, D., Starinsky, A., 2009. Stratigraphy, depositional environments and level reconstruction of the last interglacial Lake Samra in the Dead Sea basin. Quaternary Research 27, 82–88.

Waldmann, N., Torfstein, A., Stein, M., 2010. Northward intrusions of low- and mid-latitude storms across the Saharo-Arabian belt during past interglacials. Geology 38, 567–570.

Wright, V.P., 2007. Calcretes. In: Nash, D.J., McLaren, S.J. (Eds.), Geochemical Sediments and Landscapes. Blackwell, Oxford, pp. 10–45.

Wright, V.P., Tucker, M.E., 1991. Calcretes: an introduction. In: Calcrete Wright, V.P., Tucker, M.E. (Eds.), International Association of Sedimentologists Reprint Series, Volume 2. Blackwell Scientific Publications, Oxford, pp. 1–22.

Yang, X., 2001. Late Quaternary evolution and palaeoclimates. Western Alashan Plateau, Inner Mongolia, China. Zeitschrift für Geomorphologie N.F. 45, 1–16.

Yang, X., Zhu, Z., Jaekel, D., Owen, L.A., Han, J., 2002. Late Quaternary palaeoenvironment change and landscape evolution along the Keriya River, Xinjiang, China: the relationship between high mountain glaciations and landscape evolution in foreland desert regions. Quaternary International 97–98, 155–166.

Yang, X., Ma, N., Dong, J., Zhu, B., Xu, B., Ma, Z., Liu, J., 2010. Recharge to the inter-dune lakes and Holocene climatic changes in the Badain Jaran Desert, western China. Quaternary Research 73, 10–19.