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 δ18O 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.

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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 palaeofluviol low gradient channels and straths preserved along river talwegs 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 CaCO3 derived largely from river and groundwaters (McLaren, 2004). The calcitised channels have subsequently been abandoned and preserved through downcutting in a tectonically subsiding basin and the remaining calcitrised 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 Khadidjikar (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 plain 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. Carcailliet 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...
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 calcitisation. 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), calcitisation has occurred because of the inorganic precipitation of CaCO₃ 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 diageneric 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 palaeoclimate 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 (\(\delta^{18}O\) and \(\delta^{13}C\)) 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 \(\delta^{18}O\) 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 $\delta^{18}O$ water composition. Evolved groundwaters may contain concentrated $\delta^{13}C$ values, but areas with high inputs of rainfall, may precipitate carbonates that have lighter $\delta^{18}O$ amounts (Jacobson et al., 1988). Carbon isotope ratios ($\delta^{13}C$) of the calcrite 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 calcrite: 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 calcrites, Wright and Tucker (1991) argue that groundwater calcrites are likely to have heavier $\delta^{13}C$ values “unless light C is introduced from phreatophytic vegetation” (p. 10). Heavier $\delta^{13}C$ 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 calcrites 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 calcrites exist/persist in the area around the village of Dana. Cenozoic basalts were extruded close to the village and most of the Dana and the Wadi Ghuwayr. In total 85 representative samples were collected from 13 sections along the river for thin sectioning and analysis. Field research involved logging, photographing and mapping the landscape. 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 (Braconnet et al., 2008), there were significant movements of wind belts associated with the ITZC. 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 calcrite 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. (2008) 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$^{-1}$ on the escarpment east of the Faynan catchment.

3. Methods

This study concentrates upon seven calcritised 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 (Moheim), +30 (Fass Yad) and +125 to 130 (Qubbah) 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 Ghwayr. In total 85 representative samples were collected from 13 sections along the river for thin sectioning and analysis.
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 CO₂ 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 (δ¹⁸O/¹⁶O and δ²H/¹H) are expressed in delta units, δ¹⁸O 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 δ¹⁸O 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 calcrite 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 CO₂ 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...
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 | Micrite | Sparite | Micrite | Sparite | Micrite | Sparite | Micrite | Sparite |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Fass Yad | Mean | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean | Min | Max |
| top |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| centre |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| bottom |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

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 (Figs. 3 and 4b) came from the channel close to a palaeo-spring (Fig. 6a), which appears to be associated with a fault, the highest isotope ratios (δ18O = +4.89‰, δD = +18.0‰).

4. Results: stable isotope geochemistry

4.1. Modern water isotope values

δ18O and δD were measured for ten rainfall stations from different locations in Jordan (from Bajjali and Abu-Jaber, 2001) as well as four water samples collected for this study are given in Fig. 4a. The rainfall data show that there is depletion in δ18O 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 δ18O 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 (δ18O = −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 (δ18O = +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 δ18O and δ13C (−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 (δ18O = −6.4‰, δ13C = −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 calcrites 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 δ18O values are −4.0‰ and −4.9‰ and the δ13C 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 δ18O value of −2.9‰ and δ13C 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 δ18O is −4.3‰ and the δ13C 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...
<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 δ18O which range from −4.2‰ to −6.2‰ and low δ13C 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 δ18O values from −3.1‰ to −4.9‰ and δ13C 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), δ18O are between −2.3‰ and −3.4‰ and δ13C 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, δ18O range between −5.9‰ and −6.3‰ and δ13C between −3.1‰ and −7.0‰. One sample (Table 2—lower wadi), also has micritic cement, its stable isotope values are: (δ18O = −2.8‰ and δ13C = −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

δ18O and δD values from the rainfall stations show that as expected there is depletion in these isotopes as altitude increases. Thus from the
Dead Sea Rift Valley up the eastern escarpment there is a gradual loss of heavy isotopes (resulting in lower δ18O and δD) of the air masses as they ascend up onto the Jordanian plateau. The groundwater samples we collected have similar δ18O 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 calcrites.

The calcrite 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 calcrites (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 calcrites from the Permian Abo Formation in New Mexico. They recorded a δ18O content that ranged from −0.4‰ to −7.2‰ (18O −4.0) and δ13C values between −2.8‰ and −7.2‰ (13C −5.3). In comparison, the Wadi Dana isotope measures range between −2.3‰ and −6.4‰ (18O −4.6) and −1.0 and −7.0‰ (13C −4.3) for δ18O and δ13C respectively (excluding the sample collected close to a palaesprings with tufa). The complexity of factors affecting δ18O values in the calcrites results in a lack of any clear spatial pattern or variation between terrace levels (Fig. 4b). In terms of hydrology, the isotope compositions for δ18O range from −6.4‰ to −2.7‰, the lower values most likely reflecting a dominant groundwater influence on δ18O in Wadi Dana (Fig. 4b). We can calculate the oxygen isotope composition of calcrites 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 calcrites would have δ18O 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 δ18O 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 calcrite that would have precipitated from the Dana evaporated water body. The δ18O value of a calcrite precipitated from this evaporated water body would range between +2.9‰ and +3.3‰. The theoretical modern groundwater calcrites are within the range of some of the fossil calcrites (Fig. 4b) although we have not analysed any material with values approaching calcrites that might potentially precipitate from the evaporating pond. Thus it would appear that calcrite 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 calcrites (see McLaren, 2004) (Table 1 and Fig. 5). As mentioned earlier, all of the stable isotope results for the channel calcrites 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 δ18O 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 calcitised 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 δ18O values near the top of the channel alluvium.

Fields of δ18O 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 δ18O values. In Field 1, the samples have the lowest δ18O 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
intermediary $\delta^{18}O$; 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 $\delta^{18}O$ values are heavier. Finally, in Field 3 the samples have the highest $\delta^{18}O$ 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 calcrites 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 calcitised 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 $\delta^{18}O$ than any temporal effect and perhaps indicates that all the calcrites 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 calcitisation 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 calcite crystals would have been gradually lost and substituted for secondary neo-morphic 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 $\delta^{18}O$ 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 $\delta^{13}C$ 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 $\delta^{13}C$ may be a result of one of a number of factors, including equilibration with atmospheric CO$_2$, CO$_2$ loss or reaching equilibrium with $\delta^{13}C$ 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 $\delta^{13}C$ 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 $\delta^{13}C$ 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 $\delta^{13}C$. The $\delta^{13}C$ 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 $\delta^{13}C$ 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...
the active channels, including Phragmites, Typha, and Tamarix (Kurschner, 1986; Palmer et al., 2007); or C₄ 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 δ¹³C, which may indicate a greater representation and mix of C₄ short annual grasses from the surrounding arid hillslopes and riparian C₃ plants (e.g. Phragmites, Typha, Tamarix and Retama raetam, Baierle et al., 1989). However, high values of δ¹³C (as well as δ¹⁸O) 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 δ¹⁸O values do not support high levels of evaporation. Schlesinger (1985) has argued that mixing of atmospheric and soil respiration CO₂ can result in enriched δ¹³C values. Low vegetation density under arid conditions can mean that CO₂ levels in the 'soil' zone contain significant amounts of atmospheric CO₂, which is more enriched than soil CO₂ and can give the impression that C₄ plants are present, even when they are not. However, as there are C₄ 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 δ¹³C signatures of the groundwater calcrites from Wadi Dana. However, as there is a good correlation between the distribution of modern C₃ and C₄ plants in the valley and the δ¹³C values of the calcrite 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 C₃ and C₄ vegetation signatures identified in the calcrites spatially along the steep sides of the Dana valley. This pattern matches the modern day distribution of C₃ and C₄ plants. The uppermost Quabbah Member, on the cooler mountain top shows a dominance in C₃ 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 calcrites show a dominance of C₄-dominated steppe

![Fig. 6](image_url)
desert vegetation, that includes grasses, *Salsola, Halogea* 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, $\delta^{13}C$ values can be significantly elevated above typical $\delta^{13}C$ values for C3 plants (France and Cattaneo, 1998), which may be reflected in the results but has been interpreted as a C4 signature. Between ~2 and 5 km (Fig. 3), the samples show a mix of C3 riparian vegetation alongside C4 vegetation from the much drier surrounding hillslopes. There is an increase in the C3 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 asl, an extreme steppe-desert exists (Kurschner, 1986) with C4 vegetation, such as grasses, *Calligonum comosum* and *Traganum nudatum* (Baierle et al., 1989).

Unfortunately, the actual ages of calcrite formation are largely unknown, which limits the usefulness of this study in terms of palaeoecological reconstruction. Despite these limitations the combination of stable isotope analyses and petrographical studies still provide important insights into the palaeoenvironmental conditions required for channel calcrite development. From the temporal evidence available, it is known that the +3 m terrace (and hence the calcrite) 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 $\delta^{13}C$ composition of the groundwaters would have a greater contribution of C from C3 plants while C4 vegetation would have remained on the natural slopes away from the crops. Like all the terraces, the Upper Dana Wadi terrace (+3 m) calcrites have a range in $\delta^{13}C$ 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 calcritisation 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 calcrite formed are similar to the younger calcrites. The lack of a good chronological framework means that terrace and calcrite formation cannot be tied in specifically with these climatic changes. However, the conditions of calcritisation did not involve large amounts of evaporation and because it has been asserted that current conditions are too arid for calcrite 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 calcritisation occurred under relatively cooler and wetter conditions than today.

6. Conclusions

Calcitrised 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 $\delta^{18}O$ and $\delta^{13}C$ within channel calcrites from Wadi Dana.

The key findings are:

- $\delta^{18}O$ values have the potential to provide information about the hydrological environment in which the channel calcrites formed. All of the $\delta^{18}O$ results are negative and some are similar to theoretical calcrites formed from the modern groundwater. While some precipitated in moderately arid conditions at the edge of the mountain front ($\delta^{18}O$ values up to $-2\%$), there is a lack of evidence of any strong evaporational control on the calcrite formation suggesting cooler conditions than today.
- Location within the landscape appears to be important. There is some variation in the $\delta^{13}C$ values between the cooler mountains and the exposed low altitude plain that has been affected by more evaporation. However, any changes in the $\delta^{13}C$ 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 $\delta^{18}O$ 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 $\delta^{13}C$ values of the calcrites is highly complicated with many controls on the measured $\delta^{13}C$ signature. However, the proposed influences of vegetation on the calcrite $\delta^{13}C$ 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 calcrites 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 C3 vegetation, which gives way to C4 vegetation in the lowland basin to the west. However, in up-stream locations in the mountains, there appears to be less riparian
vegetation in the channels and there is a dominance of C₃ 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 C₄ vegetation. Thus there appears to be a good relationship between the distribution of the modern vegetation and the δ¹³C 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 δ¹⁸O and δ¹³C 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 δ¹⁸O or δ¹³C 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) macro morphological and micromorphological analyses of ground-water (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 palaeo environmental reconstructions.

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