Local-scale environmental gradients in ‘snail-shell’ stable isotopes from Holocene Jordanian archaeological sites

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Abstract
Reconstructing environments around archaeological sites is complicated by past land management practices and regional-scale climate proxies that can be contradictory and are often located at a distance from the sites themselves. Here we explore environmental information from fossil snail shells which, even when few in number on an archaeological site, may prove invaluable in constructing site-specific data. The palaeoecology of fossil snails and the stable isotopic composition of their shell carbonate can provide context-specific information on vegetation, water availability, and relative humidity during the occupation of a site. We studied terrestrial and aquatic snails from two later Neolithic archaeological sites in the Jordanian badia, Wadi al-Qattafi and Wisad Pools. At specific archaeological site-scale our study highlights the importance of aquatic snails in the reconstruction of semi-arid environments. At Wisad pools rare aquatic snails in contexts dating between ~8.0 and ~7.6 ka demonstrate episodes of wetness; moreover, their shell isotopic compositions indicate that local watercourses were well established, corroborating previous findings that during this period the immediate environs of Wisad Pools were host to C3 plant species more typical of the Mediterranean zone. Moreover, the δ18O signal in these snail shells allow tentative reconstruction of rainwater isotopic compositions and identify the effects of evaporation. Such fine-grained environmental information is much less evident from the terrestrial snail-shell data alone, showing that an ensemble of snail-shell data can be highly sensitive to environmental differentials across an archaeological site. Finally, at a regional palaeoclimate-scale our Wisad Pools snail-shell stable isotope data are consistent with a sustained, Rapid Climate Change (RCC)-driven wetness between 8.6 and 7.6/ka concurrent with cold and wet conditions in the wider Levant.

Keywords
Stable isotopes, terrestrial and aquatic snails, palaeoclimatic reconstruction, Holocene, Jordanian Neolithic

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Introduction
The Early to Middle Holocene (~11.7 to ~5 ka) encompasses two major cultural transitions in the Near East; the first from hunting and foraging to farming and herding and the second from small-scale agricultural communities to fully urban centres. Explanations for both transitions have considered the role played by climate change and climate variability at macro and micro scales (Blockley and Pinhasi, 2011; Brooks, 2012; Clarke et al., 2016; Roberts et al., 2018; Rosen and Rivera-Collazo, 2012). Despite the increasing resolution of palaeoclimatic data for the Eastern Mediterranean and surrounding regions, coupled with recent high-resolution regional archaeological and environmental landscape survey data (Palmisano et al., 2021), local short and medium-term environmental conditions around archaeological sites are still poorly understood. To move beyond ‘big-picture’ studies, where the linkage between environmental change and human action is often weakly articulated, local environmental proxies, specific to archaeological sites and independent of land management strategies, are required. Stable isotopes of terrestrial and freshwater snails found on archaeological sites have the potential to provide the kind of fine-grained, localised environmental reconstruction independent of land use practices needed for more nuanced environmental reconstructions. Here we sample and analyse snails found at two archaeological sites in the Jordanian badia, Wisad Pools and Wadi al-Qattafi.

Recent palaeoenvironmental evaluations of the climate and environmental of the Near East and Eastern Mediterranean for the last 20,000 years (Jones et al., 2019; Rohling et al., 2019) suggest that the Early Holocene was wetter than today (Clarke et al., 2016; Rohling et al., 2019). During the Early Holocene, centennial scale, cold (possibly wetter) winter-focussed, Rapid Climate

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The impacts, nature and scale of these RCCs on society are still debated (Mayewski et al., 2004; Rohling et al., 2019). The so-called 8.2 ka event, a 150-year cold interlude, is thought to have reduced sea-surface temperatures in the Eastern Mediterranean by up to 3°C (Rohling et al., 2019). At Jeita Cave (Lebanon) stalagmites record this event as an arid interlude superimposed upon a cold, wet 8.6–8.0 ka RCC (Cheng et al., 2015; Rohling et al., 2019). It is this event that has tended to dominate archaeological discussion around the drivers of contemporaneous cultural change, societal adaptation, and even societal collapse (Biehl and Nieuwenhuyse, 2016; Flohr et al., 2016; Nieuwenhuyse et al., 2016; van der Horn et al., 2015). As yet no clear correlation has been identified between the 8.2 ka event and stratigraphic discontinuities or site abandonments, instead, where relationships can be drawn, the evidence points to accommodation. The lack of evidence for societal dislocation across the 8.2 ka event has led to speculation that communities were resilient to RCCs (e.g. Flohr et al., 2016) but it is much more likely that two processes were taking place. First, that there was considerable environmental and hydrological variation across the region, with well-watered regions (where settlements tended to aggregate) being more resilient to climatic variability than regions where water stress existed. Second, that within the longer 8.6–8.0 ka RCC, the 8.2 ka event was correspondingly muted; societies had already adapted to climatic variability during the preceding centuries and were likely already resilient.

In this article we present pilot isotopic analyses of Jordanian snail-shell carbonate to investigate environmental conditions associated with human occupation between ~8.4 and ~7.6/7.5 ka.

Non-marine snail shells can be common fossils in archaeological settings and while some have a burrowing life mode (notably the genus Cecelioidea) and are therefore likely to be an intrusive element of fossil assemblages, most species are surface dwellers. Thus, in certain archaeological contexts snail palaeoecology can provide important environmental information. Moreover, there is a strong relationship between snail-shell chemistry and local environmental conditions (Leng and Lewis, 2016; Prendergast et al., 2015). In particular, stable isotopic data from surface-dwelling snail-shell carbonate can provide key information on relative temperature, humidity, and vegetation type. The principal control on shell aragonite δ18O (δ18Oshell), albeit modified by vital effects (discussed later), is the isotopic composition of local rainfall (δ18Orain; e.g. Goodfriend and Ellis, 2002; Prendergast et al., 2015; Rech et al., 2021; Yanes et al., 2019). Higher δ18Oshell ratios broadly correspond to higher δ18Orain ratios and/or reduced rainfall amount. As such, δ18Oshell values can be a crude indicator of wetter (lower values) or drier (higher values) climatic conditions. There is also a relationship between the carbon isotopic composition of local vegetation and snail δ13Cshell (e.g. Baldini et al., 2007; Colonese et al., 2014; Goodfriend and Ellis, 2002). Plants in semi-arid settings, such as the Mediterranean climate zone, use either a C3 or C4 photosynthetic pathway, responding largely to water stress. C3 grasses, being more water efficient, become more common as aridity intensifies and this metabolism synthesizes organic matter with less negative δ13C values. Thus, snails from regions of predominately C3 vegetation and low water stress typically have more negative δ13Cshell values than snails from regions of predominately C4 vegetation and higher water stress, with intermediate values from those in mixed areas.

Local environments

Wisd Pools and Wadi al-Qattafi are respectively located on the eastern and western margins of the harra, an arid, stony desert plateau underlain mainly by Quaternary basalts (Figure 1). The archaeological structures are found on the edge of the plateau where the basalts overlie impure limestones of Palaeocene to Eocene age (Bender, 1975). Topography on these Northern Plateau basalts is gently undulating with elevations of ~800 m just north of Wisad, increasing northward to a maximum of ~1200 m in the foothills of the Syrian Jebel Druze (Allison et al., 2000). The modern climate is seasonal with hot, dry summers and cool winters (Wigley and Farmer, 1982). Mean annual maximum summer temperatures are ~35°C–38°C, while mean annual winter temperatures are between 2°C and 9°C (Al-Homoud et al., 1995; Allison et al., 2000). Mean annual rainfall ranges from <50 mm a−1 in the southern harra to ~250 mm a−1 in the north, the latter reflecting the orographic influence of the Jebel Druze. Eighty percent of this rainfall occurs between December and March, often as discrete storm events (Allison et al., 2000). Of this rainfall between 85% and 92% is lost to evaporation, 5%–11% infiltrates and just 2%–4% becomes surface flow (Allison et al., 2000). The resulting intermittent surface flow is focussed into wadis, the largest radiating out from the Jebel Druze (Al-Homoud et al., 1995). Some of these wadis are deeply incised, suggesting wetter climates in the past. Wadis may feed closed depressions or evaporative pans, the largest known as qi’an (sing. = qa‘). Soils in the eastern badia are either absent or very poorly developed (Allison et al., 2000) except in the topographic lows of wadis or in qi’an. At Qa‘ al-Qattafi and ‘small’ Qa‘ al-Wisad (immediately below the pools), the sediments are between 1.0 and 3.0 m thick (Jones et al., 2021) with underlying bedrock variously basalt (‘small’ Qa‘ al-Wisad) or limestone (Qa‘ al-Qattafi). At 60 cm depth OSL ages show the qa‘ sediments as being <7.9 ka and at these depths CaCO3 content is between 10% and 15% (Jones et al., 2021). This carbonate is probably derived from bedrock (Qa‘ al-Qattafi) or windblown dust, although Allison et al. (2000) describe gypsitic and calcitic deposits in some areas which they regard as “secondary”, that is, calcrete. There is currently little or no permanent vegetation in the south of the harra, but some in the north (Al-Homoud et al., 1995) and in wadis to the west such as the Azraq oasis and Shomari Wildlife Reserve.
Winter precipitation in the Middle East is mostly generated in the Mediterranean/Cyprus low system, where cool, dry air from continental Euro-Asia interfaces with the warmer Mediterranean Sea (Burstryn et al., 2019). Much of this precipitation, however, is unlikely to reach the eastern Jordanian desert directly from the west, being in the rain shadow of the Jordanian highlands. Instead, recharge is mostly sourced from the north (Figure 1) as recorded by the drainages radiating from the Jebel Druze (Al-Homoud et al., 1995) and by flow directions in the subsurface aquifers (Al-Homoud et al., 1995; Allison et al., 2000). Wet-season flows in the wadis of the Azraq Basin, west of the basalt plateau (e.g. Wadi Rajil) can be considerable (Al-Homoud et al., 1995). Until the 1980s four springs discharged a large quantity of water from the upper aquifer into the Azraq Wetland Reserve, creating shallow pools up to 2 m deep, including marshland extending to 8 km²; these subsequently dried out due to large-scale abstraction in the 1980s (Bajjali and Al-Hadidi, 2006). Today the shallowest aquifer is at ~50 m below surface in the Azraq Basin because of abstraction.

Modern interpolated wintertime (DJFM) meteoric water in the area has δ¹⁸O of −7.3‰ VSMOW (Figure 2). These modern values can be cross-compared with data from Bajjali and Abu-Jaber (2001) who studied Holocene-aged palaeogroundwaters from the Azraq Basin and the Ashquaf Heights (just west and north of the harra study area respectively). The Azraq groundwaters gave DIC¹⁴C ages between 2.5 and 8.0 ka and δ¹⁸O values in the range −6.8 to −5.2‰ VSMOW (Figure 2), the Ashquaf groundwaters having a similar δ¹⁸O range between −6.3 and −5.5‰ VSMOW. The most negative groundwater compositions are likely to be indicative of unevaporated winter recharge and compare well with the mean modern OIPC interpolated value of −7.3‰ VSMOW (Figure 2).

Wadi al-Qattafi
Wadi al-Qattafi is a major north-south drainage located approximately 60 km west of Wisad Pools, characterised by basalt-capped 'mesas' that rise 40–60 m above the wadi bed (Hill et al., 2020). On and around the mesas are hundreds of prehistoric structures of great diversity, including burial mounds, tower tombs, enclosures, 'wheels', hunting traps ('kites') and dwellings (Hill and Rowan, 2017). Two structures have been excavated to date, SS-1 on Mesa 7 and SS-11 on Mesa 4. SS-1 is a well-built, curvilinear stone structure with an interior plastered basin and a fire pit (Rollefson et al., 2016). SS-11 also had a corbelled wall construction, two low entranceways and a carefully paved floor (Wasse et al., 2020). Adjacent storerooms, and internal installations attest to a degree of domestic use for both.

**Chronological summary**
There are six radiocarbon dates for W-80 (Supplemental Table S1), these, combined with archaeological evidence, suggest that the building had two main foci of utilisation, one lasting about
200 years between ~8.6 and ~8.4 ka, and the second beginning at ~8.0 ka and ending at ~7.5 ka. Within this sequence are three dated archaeological phases, the first beginning at ~8.6 ka, the second beginning at ~8.0 ka, and the third phase dating around ~7.5 ka.

W-400 has not yet been assigned archaeological phases but two radiocarbon dates place the utilisation of the structure between 9.0 ka and 7.7 ka. RC sample 53 comes from an early room fill, while the second (sample 70) comes from a fill representing final utilisation before abandonment. The two dates top and tail the utilisation of the structure and indicate long-term intermittent use.

Structure SS-1 at Wadi al-Qattafi has six archaeological phases; the earliest is Phase 1 and the latest is Phase 6. Phase 6 and to a certain extent, Phase 5, postdate the primary use of the structure. Four radiocarbon dates (Supplemental Table S1) place Phases 2 and 3 between ~8.4 and ~8.2 ka, while lithics from SS-1 corroborate a reasonably compressed period of use compared to W-80 (Rollefson et al., 2016).

A single radiocarbon date from an expedient hearth sealed by flagstones places SS-11 at ~7.4 to ~7.3 ka (Rowan et al., 2015).

Materials and methods

Two hundred and one terrestrial and six freshwater molluscan remains, found within interior and exterior fills of W-80 and W-400 at Wisad Pools, SS-1 and SS-11 at Wadi al-Qattafi, were collected through flotation of archaeologically derived sediment. The surface dwelling terrestrial snails lived, died and were subsequently sealed in the archaeological contexts they were discovered in. As no mud brick or mud mortar was used in construction material at either site, aquatic snails could not have been introduced as part of such material. Instead, we suggest that these snails were introduced to the archaeological deposits as living individuals on reeds or rushes, that had been growing around the qa’in and the pools, brought into the structures as roofing or flooring material (discussed in detail later).

Snail identification

The assemblages of molluscan remains were sorted under a low-powered Wild binocular microscope and all identifiable specimens were quantified (see also supplemental information). To arrive at a minimum number of individuals (MNI) for each taxon, only apical fragments (representing the tip of the spire of the shell) were counted. For some taxa (e.g. clausiliids) apices were poorly preserved and other diagnostic elements were counted instead, usually the aperture (mouth). Species identified from shell fragments possessing distinctive microsculpture are listed as present (+) in Supplemental Table S2a, S2b, and S3. These were not quantified since it is impossible to know whether the fragments were derived from a single shell or from several specimens.

The taxonomic status of many ‘Middle East’ species requires revision, as minor conchological differences have given rise to a plethora of names across a wide region and are likely to be synonyms. This applies to land snail species within Hygromiidae (see, e.g. Neubert and Bariche, 2013), although since many of the differences in these taxa are based on shell characteristics it is still possible to identify them from well-preserved fossil specimens. The species listed here are therefore in some cases tentative, since the preservation of the material was not good enough for definitive species-level identifications.

Snail-shell sampling: Stable isotopes

For stable isotopes we sampled >10% of the terrestrial snails at each site and all the available freshwater snails from Wisad Pools as follows.

W-80, Wisad Pools

Six snail samples for isotopic analysis came from structure W-80 at Wisad Pools (Supplemental Table S2a). The samples derive from post-8.0 ka deposits except one terrestrial sample deriving from a pre-8.0 ka deposit. The three terrestrial samples were recovered from contexts within the building, one from a pre-8.0 ka hearth and the other samples from post-8.0 ka hearths or firepits (Supplemental Table S2a). The three aquatic samples (all different species) were all from post-8.0 ka occupation deposits.

W-400, Wisad Pools

Two aquatic snails were recovered from Structure W-400 from post-8.0 ka deposits (Supplemental Table S2a), which likely represent the final occupation of the structure sometime after ~7.7 ka.

M4 SS-11, Wadi al-Qattafi

A single terrestrial snail sample came from structure M4 SS-11. This single example was collected from an upper fill of the structure. As the sample is identifiable as Pupoides coenospectus it has been included in the isotopic analyses, but its location suggests its chronological and archaeological integrity may be in doubt. Accordingly, it has not been included in the subsequent discussion and interpretation.

M7 SS-1, Wadi al-Qattafi

Twenty terrestrial snail samples came from structure M7 SS-1 at Wadi al-Qattafi (Supplemental Table S2b). Snail samples were derived from Phases 1 to 5, extending...
the chronology of the snail data back beyond ~8.4 ka. The contexts from which the snail samples derive are mostly from hearths or firepits, although some samples derive from a plaster basin and another from a paved surface.

**Mineralogy and stable isotopes methods**

Thirty-five fossil snail shells were selected for stable-isotope analysis after identification, including all six aquatic snails from Wisad Pools; all but two specimens were adults that varied in size from 3 to 10 mm. We avoided known burrowing species to eliminate the risk of analysing material younger than the context sediments. Four bulk sediment samples were also analysed for stable isotopes.

Snail shells were crushed gently to expose internal surfaces and adherent sediment was removed with a steel seeker. Shell fragments were then immersed in 30% H2O2 at room temperature for 24 h, and then placed in an ultrasonic bath for 30 min. The fragments were air dried, then ground gently in an agate pestle and mortar to a fine powder. Isotope data from these homogenised powders should thus represent mean values representative of the snails’ lifetime. Shell mineralogy from a subsample of individuals was checked by powder X-ray diffraction (XRD).

Snail-shell stable isotopes

All snail shells were composed of pure aragonite. Terrestrial snails *G. granum* and *P. coenopictus* from Wadi al-Qattafi (M7 structure SS-1) and Wisad Pools (structure W-80) have similar shell δ13C values ranging from −3.1 to −5.6‰ (Table 1 and Figure 5). Three species of freshwater aquatic snails (*Melanoides* cf. *buccinoidea*, *Melanopsis* cf. *buccinoidea* and *Melanopsis* cf. *costata*) from structures W-80 and W-400 (Wisad Pools) have quite different isotopic values; individuals from W-400 have δ18O values ranging from +2.8 to 3.0‰ while individuals from W-80 have δ18O between +2.2 to −5.5‰ while *G. granum* individuals had the more restricted δ13C values ranging from −0.4 to +0.8‰ (Table 1 and Figure 5).

**Results**

**Molluscan assemblages**

The most numerous molluscan remains recovered from Wadi al-Qattafi, Mesa 7 (structure M7 SS-1) and Wisad Pools (structure W-80) comprise two tiny terrestrial species: *Pupoides coenopictus* (Hutton, 1834) and *Granopupa granum* (Draparnaud, 1801) (Table 1). Adult snails are typically 1–3 mm long. A few fragments of cm-sized freshwater taxa were also present in samples from structures W-80 and W-400 at Wisad Pools (Table 1), although it was notable that terrestrial and freshwater species were mutually exclusive and never occurred within the same sample, suggesting incorporation into archaeological contexts followed different pathways. The only other terrestrial species represented in the Wadi al-Qattafi samples was a single shell of the semi-slug *Daudebardia saucyi* (Bourguignat, 1852).

**Snail-shell stable isotopes**

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| Table 1. Summary of non-marine mollusc identification, numbers of individuals (n) and isotopic data (see Supplemental Table S2 for details of sample contexts). |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| **Terrestrial taxa**            | **n**           | **δ18O (‰, range)** | **δ13C (‰, range)** | **δ18O (‰, range)** | **δ13C (‰, range)** |
| *Pupoides coenopictus* (Hutton, 1834) | WaQ             | 126              | −5.5 to 2.2       | −4.5 to 1.4       | −2.5             | 13               |
| *Granopupa granum* (Draparnaud, 1801) | WaQ             | 65               | 0.6 to 1.6        | −3.8 to −0.8      | −2.4             | 7                |
| *Daudebardia saucyi* (Bourguignat, 1852) | WaQ             | 1                |                   |                   |                   |                  |
| *Pupoides coenopictus*           | WP(W80)         | 8                | 0.8 to 2.4        | −4.5 to −2.1      | −3.5             | 3(ID)            |
| *Melanoides tuberculata* (Muller, 1774) | WP(W80)        | 1                | −5.8              | −3.1             |                   | 2(ID)            |
| *Melanopsis cf. costata*          | WP(W80)         | 1                | −5.9 to −4.9      | −9.0 to −8.5      | −8.5             | 2(ID)            |
| *Melanopsis cf. buccinoidea*      | WP(W80)         | 1                | −4.1 to −3.8      | −8.5 to −8.0      | −8.0             | 2(ID)            |
| *Melanoides tuberculata* (Muller, 1774) | WP(W400)      | 1                | 0.4 to 0.8        | 2.0              | 2.1              | 2(ID)            |
| *Melanopsis cf. buccinoidea*      | WP(W400)        | 1                | 0.7 to 1.9        | 2.6              | 2.8              | 2(ID)            |
| *Theodoxus cf. jordani*           | WaQ             | 1                |                   |                   |                   |                  |
| indet. bivalve fragment           | WaQ             | 1                |                   |                   |                   |                  |
| Qa’ Sediment samples              |                 |                  |                   |                   |                   |                  |
| **Freshwater taxa**               | **n**           | **δ18O (‰, mean)** | **δ13C (‰, mean)** | **n (isotopes)** |
| QQQX 16 60 cm                     | WaQ             | 0.0              | −0.4              |                  |
| QQQX 16 80 cm                     | WaQ             | 0.5              | 0.3               | 2(ID)            |
| Wisad IA 40–50 cm                 | WP              | 0.3              | −0.4              |                  |
| Wisad IA 50 cm                    | WP              | −0.4             | −1.0              |                  |

D: duplicate.
possible that these tiny terrestrial snails are present but inactive during our field seasons. However, comparison with modern snails from the southern Levant and Negev desert show that *Sphincterochila* sp. collected from the same sites as *Trochoidea seetzeni*, are enriched in both $^{13}$C and $^{18}$O by an average of 3 and 2‰ respectively (Goodfriend and Magaritz, 1987). These differences are tentatively attributed to the relative metabolic activity of the taxa, perhaps the snails’ overall activity, or shell deposition at different times in the activity cycle of the snail species (Goodfriend and Magaritz, 1987). Whatever the precise cause, the data show isotopic variation of 2-3‰ in the fossil Jordanian snails should not be attributed to environmental drivers without supporting evidence. There are no aquatic taxa living at Wisad Pools today; however, there is comparative stable isotope data for modern *Melanopsis* sp. from the Jordan Valley (Zaarur et al., 2016; Figure 5).

**Interpretation**

**Terrestrial snails**

*Pupoides coenopictus* and *G. granum* are both characteristic of rocky habitats in relatively arid regions. The distribution of *P. coenopictus* is most extensive in tropical regions, centred on Asia and tropical sub-Saharan Africa, but at the edges of its range it is known from northwest Africa, around the Arabian Peninsula, and across southwest and central Asia (Neubert, 1998; Seddon, 1992). *Granopupa granum*, which is often found in association with *P. coenopictus*, is also found in rocky habitats and in scree and leaf litter amongst rock ledges and crevices (Gittenberger, 1973; Kerney and Cameron, 1979), with a circum-Mediterranean distribution. On a more local scale *G. granum* is widely distributed in Israel and Palestine, whereas *P. coenopictus* seems to be rarer in this region (Amr et al., 2018; Heller, 2009). The carnivorous semi-slug *D. saulcyi* feeds on earthworms and lives within the soil (Mienis, 1976), and the presence of both the slug and its inferred prey implies some development of humic soils derived from decaying plant matter, in contrast to the arid environments suggested by the aforementioned species.

Terrestrial snails: stable isotopes. It is well known that terrestrial snail shells are composed of aragonite such that presence of calcite is usually thought indicative of dia genetic alteration (e.g. Colonese et al., 2014). The Jordanian snail-shell mineralogy is 100% aragonite indicative of little or no alteration. Snail-shell aragonite forms from body-fluid bicarbonate which has three potential carbon sources with different isotopic signatures: (1) metabolic CO$_2$ from respiration, (2) atmospheric CO$_2$ that exchanges (and fractionates) through the snails’ body tissues and (3) CO$_2$ generated in the stomach from ingested CaCO$_3$ (Goodfriend and Ellis, 2002). In our Jordanian samples, calcite or limestone bedrock could be a component of ingested CaCO$_3$. The significance of atmospheric CO$_2$ exchange through snail tissues is not well understood. However, as terrestrial snails are exposed mostly to plant root respired CO$_2$, shell isotopic compositions are strongly related to the feeding behaviour of the snail which in turn reflects the vegetation type the animal consumed during its life (Balakrishnan et al., 2005; Colonese et al., 2014). The $\delta^{13}$C composition of plants is primarily controlled by their photosynthetic pathway, C$_3$, C$_4$ or CAM which are also linked to water stress (Cerling et al., 1993; Colonese et al., 2014; Deines, 1980; Liu et al., 1996; Smith and Epstein, 1971). In brief, C$_3$ plants are not well adapted to water stress and typically thrive in...
moist or wet climates, whereas C₄ (including most grasses) and CAM plants like cacti are better adapted to aridity and can be common in semi-arid steppe conditions and arid deserts.

Laboratory studies with Cornus (Helix) aspersa showed that shell carbonate has δ¹³C ~12‰ less negative than shell-bound organic carbon, this organic carbon being related directly to the vegetation type ingested (Stott, 2002). The difference is caused by fractionations during production of metabolic CO₂ and between this CO₂ and the bicarbonate from which shell aragonite precipitates. As C₄ plants typically produce organic matter with a δ¹³C around ~26‰, these fractionations mean that shell carbonate should have a value of ~−14‰. In practise values between −8 and −12‰ are commonly reported for C₁ ingestion snails (e.g. see Balakrishnan et al., 2005), because in nature they can ingest other vegetation types and soil carbonate, have differing water use efficiencies (Prendergast et al., 2017), and because the exact metabolic fractionations probably differ between species. In contrast C₂ and CAM plants have less negative δ¹³C which typically translates to shell aragonite δ¹³C less negative than ~−5‰ (e.g. see Balakrishnan et al., 2005).

The δ¹³C compositions of G. granum and P. coenopictus shell aragonites, ranging from +1.5 to ~−4.5‰ (Table 1), largely reflect ingestion of C₃ arid scrub vegetation (Goodfriend and Magaritz, 1987), much more enriched in δ¹³C relative to C₁ ingesting snails (e.g. see Balakrishnan et al., 2005), because in nature they can ingest other vegetation types and soil carbonate, have differing water use efficiencies (Prendergast et al., 2017), and because the exact metabolic fractionations probably differ between species. In contrast C₂ and CAM plants have less negative δ¹³C which typically translates to shell aragonite δ¹³C less negative than ~−5‰ (e.g. see Balakrishnan et al., 2005).

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The clear distinction between samples containing freshwater taxa and those containing terrestrial species can be explained if the freshwater snails entered W-80 on plant material – perhaps reeds or rushes – found growing in or around nearby pools and q‘in, while the terrestrial snails lived and died in the archaeological structures in which they were found. Two shells of M. costata were found in the interior of W-80 in an occupation layer with a high density of chipped stone and bone associated with large grinding slabs and fire pits (Table S2a). Two shells of M. buccinoides came from an area of pitting outside W-80 adjacent to the main doorway and two shells of M. tuberculata came from a basalt cobbled roof collapse and may be associated with squatter occupation within the upper part of the collapsed structure, likely dating to the end of the structure’s sequence (Supplemental Table S2a).

Aquatic snails

While aquatic taxa were very rare, the few recovered from structures W-80 and W-400 at Wisad Pools included M. tuberculata, a common species ranging across North Africa and southern Asia known for its tolerance of fluctuating salinities and water temperatures, and also rapid dispersal of dispersal and colonisation due to its parthenogenetic mode of reproduction. At least two species of the variable genus Melanopsis (see Grossowicz et al., 2003) were also noted rarely in several samples, although due to the fragmentary nature of the specimens the precise identity of these taxa remains tentative (Table 1). A single fragment of another variable species, Theodoxus cf. jordani, was recovered from one of the Wadi al-Qattafi samples (Table 1). Both Melanopsis and Theodoxus are widespread in the Near East found in desert springs (Tchernov, 1975) and clear, relatively fast-flowing waterbodies across the region, the latter preferring stony substrates. Melanopsis favours the presence of succulent aquatic vegetation (Moskowitz and Magaritz, 1987), feeds on algae and can live for several years.

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Aquatic snails: stable isotopes

Freshwater aquatic snail-shell δ¹⁸O is more typically an equilibrium value and may thus record ambient water temperatures (Grossman and Ku, 1986; White et al., 1999). They are less prone to species-specific effects (White et al., 1999) and clumped isotope data from modern Melanopsis
sp. in the Jordan Valley confirm that this genus forms its shell carbonate under isotopic equilibrium (Zaarur et al., 2016).

The Wisad pools freshwater aquatic snails (*M. tuberculata, M. cf. buccinoides*) plot in quite distinct isotopic space when compared to the terrestrial snail data (Figure 5). Individuals collected from structure W-400 have low positive isotopic compositions, while individuals from Structure W-80, near a semi-permanent seasonal runoff-fed pool (pool 8, Rollefson, 2013; Rowan et al., 2017), have the most negative isotopic compositions. The difference in δ18O values reflect local pool-water isotopic compositions which, although fed by the same seasonal runoff (as today), appear to have suffered strong evaporation and desiccation in the upper qa near W-400, compared to pool 8 near W-80 where evaporative effects are less marked (see also Rollefson, 2013). If the snails were feeding on cyanobacteria and algae, the shell δ13C values reflect the isotopic composition of this food source inherited from the dissolved inorganic carbon (DIC) in the pool water (cf. Deines, 1980). By contrast at W-400 the δ13C values are consistent with very shallow pool environments where DIC had fully or partially equilibrated with atmospheric CO2, resulting in δ13C enrichment. The freshwater aquatic snail data thus define endmembers of an ‘evaporative/evolved trend’ (Figure 5) with W-80 values representing pool environments with lower water stress/evaporation and W-400 values representing evaporative environments (cf. McLaren et al., 2012) with higher water stress and a snail food source dominated by cyanobacteria that had inherited isotopically enriched 13C from the DIC. This interpretation is corroborated by comparison with modern *Melanopsis* data from the Jordan Valley (Zaarur et al., 2016). Unevaporated springs and streams in the Jordan Valley have *Melanopsis* shell stable isotope values that partially overlap the W-80 fossil data suggesting that rainwater isotopic compositions were broadly similar. A more evaporated Sea of Galilee datum from Zaarur et al. (2016); blue star on Figure 5) plots on the ‘evaporative/evolved trend’ between the Wisad fossil end members.

**Discussion**

**Regional palaeoclimate**

During the Early Holocene of the Near East and Eastern Mediterranean, centennial scale, cold (possibly wetter) winter-focussed, Rapid Climate Change (RCC) events punctuated warmer, dryer interstadials (Rohling et al., 2019). The presence of aquatic snails and the aquatic snail isotopic data from Wisad Pools between ~8.4 to ~7.6/7.5 ka define a ~800-year time window with clear evidence of wetter conditions than today. This is in broad agreement with wetter climatic conditions in northern Arabia between 8.7 and 8.0 ka (Dinies et al., 2015; Petraglia et al., 2020) and recharge ages in the Aqraq Basin (Bajjali and Abu-Jaber, 2001). This time window is coincident with the 8.6–8.0 ka RCC event which, downstream of the Aegean and Levantine seas, corresponds to modelled winter-time cold and wet conditions in the coastal Levant (Rohling et al., 2019). While it is therefore tempting to ascribe wintertime wetness between 8.6 and 7.6 ka in the eastern *badia* to an RCC driven mechanism there is currently no evidence of Holocene speleothem deposition in the rain shadow region east of the central mountains in Israel (Bar-Matthews et al., 2019) and none until at least ~6 ka and mostly after 3.3 ka in northwestern Jordan (S. Robinson pers. comm. 2021). This suggests that even when the coastal Levant was wet, for example during sapropel one (S1) deposition in the early Holocene, Mediterranean moisture did not penetrate east into Jordan. This raises the possibility that early Holocene moisture in the eastern *badia* was sourced from either more northerly or southerly sources. It is well established that southern Arabia can receive southerly monsoon-associated precipitation resulting from a northward displacement of the summer Intertropical Convergence Zone (ITCZ) (Fleitmann et al., 2007). Such a scenario, based on climate models, has been proposed to explain a significantly wetter than present central Arabian peninsula during the last interglacial (Jennings et al., 2015), that is, increased rainfall sourced from the North African summer monsoon. This mechanism also explains well-documented lake development south of 25°N during the early Holocene (10.5–7.0 ka; Berger et al., 2012). However, the eastern *badia* is beyond the northernmost penetration of this modelled ITCZ displacement. While it is likely that most palaeoclimate models underestimate northward movement of the ITCZ and coincident increase in rainfall compared to palaeoecological reconstructions (Braconnot et al., 2007; Perez-Sanz et al., 2014) it remains to be proven that this source penetrated beyond 30°N.

On balance it seems plausible that Holocene rainfall in the eastern *badia* was mostly sourced from the north or northwest, that is, by mid-latitude westerlies (Petraglia et al., 2020) that picked up moisture in the eastern Mediterranean (Figure 1). The W-80 aquatic snail δ18O values suggest the isotopic composition of this rainfall was similar to present day (Figure 2) and most likely fell locally because the drainages feeding Wadi al-Qattafi and Wisad Pools both originate on the nearby basalt plateau. This scenario is consistent with an RCC-driven timing of sustained wetness at Wisad Pools between 8.6 and 7.6 ka concurrent with cold and wet conditions in the Levant from 8.6 to 7.8 ka (Rohling et al., 2019). At the regional-scale, wetter conditions are recorded in northeastern Arabia, where ‘grasslands . . . reached their max-imal expansion ca 8.600–8.000 cal BP’ before retreating abruptly at ~8.0 ka (Dinies et al., 2015). Pollen records from Tayma indicate the period of ~8.7–8.0 ka to be the wettest conditions of the Holocene (Petraglia et al., 2020) although other proxy records indicate that a freshwater palaeolake at Tayma, present between ~9.3 and 8.5 ka shrank to a wetland environment between 8.5 and 4.8 ka (Petraglia et al., 2020). The available palaeoenvironmental and archaeological data therefore indicate that the whole region experienced climatic variability – with changing availability of surface water particularly in more arid regions – but broadly characterised by wet (and possibly cold) winter conditions between 8.6 ka and 8.0 ka.

**Local archaeological and environmental reconstruction**

**Wisd Pools.** There were no terrestrial snails found at W-400 and the isotopic signature of the aquatic snails indicate that they lived in a locale characterised by a highly evaporative hydrological environment. This aligns well with what is understood of the qa immediately north of W-400. Although the sample is small the aquatic snails indicate water must have been periodically available. However, the absence of terrestrial snails from W-400 indicates that the immediate environment was generally very arid.

In contrast, at W-80 both terrestrial and aquatic snails were present although the terrestrial snails all had isotopic signatures characteristic of feeding on C4 vegetation. The presence of terrestrial snails at W-80 may thus indicate an environment better vegetated than W-400, but one that was still relatively arid. The aquatic snails found in W-80 were presumably transported in on plants growing in nearby pools and their δ18O values indicate relatively unevaporated freshwater. Thus, between 7.6 and 8.6 ka, Wisad Pools may have looked rather similar to Aqraq today with the general landscape being arid, while the pools themselves supported lush, marshy, Mediterranean type vegetation (pollen dated by OSL to 7.9 ± 0.7 ka; Jones et al., 2021; Rowan et al., 2017) that included C4 deciduous species such as *Quercus, Prunus, Tamarix* sp. and *Salix* sp. (Rowan et al., 2017; Wasse et al., 2022).

The reason why pool-marginal plants, perhaps rushes and reeds, were brought into the structures can only be surmised. However, prior to modern building materials becoming available,
Levantine bedouin are known to have used reed matting to roof their dwellings (Supplemental Figure S4) (Hula reed hut 1920, https://en.wikipedia.org/wiki/Hula_Valley).

Wadi al-Qattafi. Wadi al-Qattafi today is hyper-arid like Wisad Pools but both the molluscan and isotopic data suggest that during the 9th millennium BP it may have been marginally more humid than Wisad. The fossil snail P. coenopictus is much more abundant at M7 SS-1 than at Wisad (Table 1); moreover, some of their δ¹⁸O values were markedly negative which imply less arid conditions with decreased water stress and increased relative humidity. This is also supported by the much larger number of terrestrial snails found at M7 SS-1 and the presence of the semi-slug D. saulcyi; this feeds on earthworms, which require humid conditions. It should be noted that the snail samples from M7 SS-1 are all from deposits dating to ~8.4 to 8.2 ka.

One important observation arising from the discussion above is that at Wisad Pools snails were present in contexts postdating the regional 8.6–8.0ka RCC. This is not the case at Wadi al-Qattafi where snails were found only within the chronological window of the 8.6–8.0ka RCC. This, combined with an isotopic signature suggesting decreased water stress and increased relative humidity at Wadi al-Qattafi in comparison to Wisad Pools, supports wetter conditions in the region prior to 8.0 ka. Notwithstanding the inexplicable absence of snails in pre-8.0 ka contexts at Wisad Pools (Figure 4), it is not surprising that snails continued to survive later (albeit in more water-stressed conditions) in an environment where the pools may have continued to contain water well after the wider region became more arid. This supports the theory mentioned in the introduction that considerable environmental and hydrological variation has had the tendency to mask regional patterns of human and environmental responses to periods of RCC.

Conclusions
The presence of aquatic snails at two sites in the Jordanian badia (dating between ~8.4 and 7.6 ka) define a ~800-year time window when wetter conditions than present day prevailed. Water courses were established and C₄ vegetation grew on the marshy margins, while the wider environment was largely arid and stony desert dominated by C₃ vegetation. These inferences are consistent with a sustained, RCC-driven wetness between 8.6 and 8.0ka concurrent with cold and wet conditions in the wider Levant. While the isotope data are not diagnostic regarding moisture provenance, the timing is consistent with a north or north westerly source from mid-latitude westerlies that picked up moisture in the Eastern Mediterranean.

In an archaeological context our pilot study shows the importance of aquatic snails in the reconstruction of semi-arid environments. The combination of terrestrial and aquatic species, combined with plant fossil data, allows a detailed reconstruction of land cover in the immediate vicinity of the structures, as well as land cover around nearby water sources. The difference in the stable isotope signatures of the qi’an and the pools allow for a nuanced reconstruction of a varied but mostly arid environment. The most negative δ¹⁸O signal in these aquatic snails, are closest to an equilibrium value, and are consistent with modern regional rainwater isotopic compositions, while the more positive values record the effects of evaporation. Such fine-grained environmental information is not available from the terrestrial snail-shell data when taken alone.

Methodologically, we have identified a bridge between differences in scale of palaeoenvironmental proxies for use in archaeology. Clarke et al. (2016) highlighted the lack of environmental proxies local to archaeological sites that can be used to reconstruct environments relative to human generations. This study has demonstrated that when snails with appropriate ecologies are collected from well-dated contexts, supporting isotopic data can inform on environmental change at the kind of localised spatial, and short-term temporal scales that should be broadly compatible with the lived experience of past human communities. As human populations would have chosen to modify (or not) their cultural and economic practices in response to locally observable environmental circumstances, the approach presented here offers a means to address the gap between large-scale environmental proxies, and human action as evidenced through changes in the archaeological record at individual sites. In that sense it may start to close one of the gaps in the chain of evidence that was noted by Clarke et al. (2016).

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Supplemental material
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Note
1. Although radiocarbon dates from Wisad Pools and Wadi al-Qattafi attest to intermittent human occupation in the study region over a period of at least 1700 years from ~9.0 to ~7.3 ka, snail samples are clustered in two chronological windows between ~8.4 and ~8.2 ka at Wadi al-Qattafi and ~8.0 ka and ~7.6/7.5 ka at Wisad Pools.
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