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Abstract: Numerous palaeoenvironmental and archaeological studies from southern Arabia (Yemen and Oman) have revealed strong relations between phases of human settlements and climate change linked to the Indian monsoon system. Analyses on speleothems, cave fills, lacustrine deposits and palaeo-mangroves have shown that during the Early to Mid-Holocene, a humid Optimum culminated around 9000-8000 cal yr BP. New results on inland speleothems and cave sediments from the Jebel Qara (southern Oman) are crucial in our depiction of Early and Mid-Holocene climatic evolution and cultural dynamics of the region. These aspects are discussed here, based on new archaeological surveys, excavations, geoarchaeological and micromorphological studies, aiming to better understand connections with Terminal Pleistocene and Early Holocene autochthonous cultures of southern Arabia. Our results suggest that the final Pleistocene was marked by strong aridity, which promoted a widespread thermoclastism within rock shelter and deposition of aeolian sand; on the contrary, the transition towards the Holocene is marked (since c. 12000 cal yr BP) by a progressive increasing in environmental humidity, which permitted the formation of thick strata of peridesert loess. After this phase, the environmental humidity of the Jebel increased and permitted the existence of a large community of land snails; the latter were exploited by Early Holocene hunter-gatherers who lived in the rock shelters between c. 10500-9500 cal yr BP and left consistent accumulations of land shells (escargotières). The maximum of Holocene humidity was reached between 9000-8000 cal yr BP; regional aquifer were recharged and the deposition of calcareous tufa at the entrance of caves started, lasting up to c. 4500 cal yr BP. C and O stable isotopes from calcareous tufa highlights, in accordance with several regional records, the progressive decline of the intensity of the Indian Ocean monsoon and the transition towards arid conditions. In this phase, the area was abandoned and archaeological communities possibly relocated along the coast of central and southern Oman, where they exploited the mangrove environment.

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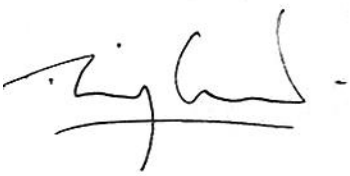

***Cover Letter**

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13 October, 2014

Re: Quaternary International, *"Early-Middle Holocene environmental changes and pre-Neolithic human occupations as recorded in the cavities of Jebel Qara (Dhofar, southern Sultanate of Oman)"*

Dear Editor:

We report here new results on inland speleothems and cave sediments from the Jebel Qara (southern Oman). They are crucial in our depiction of Early and Mid-Holocene climatic evolution and cultural dynamics of the region. These aspects are discussed here, based on new archaeological surveys, excavations, geoarchaeological and micromorphological studies, aiming to better understand connections with Terminal Pleistocene and Early Holocene autochthonous cultures of southern Arabia. Our results suggest that the final Pleistocene was marked by strong aridity, which promoted a widespread thermoclastism within rock shelter and deposition of aeolian sand; on the contrary, the transition towards the Holocene is marked (since c. 12000 cal yr BP) by a progressive increasing in environmental humidity, which permitted the formation of thick strata of peridesert loess. After this phase, the environmental humidity of the Jebel increased and permitted the existence of a large community of land snails; the latter were exploited by Early Holocene hunter-gatherers who lived in the rock shelters between c. 10500–9500 cal yr BP and left consistent accumulations of land shells (escargotières). The maximum of Holocene humidity was reached between 9000-8000 cal yr BP; regional aquifer were recharged and the deposition of calcareous tufa at the entrance of caves started, lasting up to c. 4500 cal yr BP. C and O stable isotopes from calcareous tufa highlights, in accordance with several regional records, the progressive decline of the intensity of the Indian Ocean monsoon and the transition towards arid conditions. In this phase, the area was abandoned and archaeological communities possibly relocated along the coast of central and southern Oman, where they exploited the mangrove environment.

We believe that this paper will fit with the general themes of the "Green Arabia" special issue of Quaternary International.

On behalf of myself and my co-authors, we thank you in advance for considering this article and look forward to a positive response from you.

Sincerely yours,

Dr. Rémy Crassard
Research Fellow / Chargé de Recherche
Centre National de la Recherche Scientifique, CNRS, UMR-5133 'Archéorient', Lyon, France.

Early-Middle Holocene environmental changes and pre-Neolithic human occupations as recorded in the cavities of Jebel Qara (Dhofar, southern Sultanate of Oman)

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Abstract

Numerous palaeoenvironmental and archaeological studies from southern Arabia (Yemen and Oman) have revealed strong relations between phases of human settlements and climate change linked to the Indian monsoon system. Analyses on speleothems, cave fills, lacustrine deposits and palaeo-mangroves have shown that during the Early to Mid-Holocene, a humid Optimum culminated around 9000-8000 cal yr BP. New results on inland speleothems and cave sediments from the Jebel Qara (southern Oman) are crucial in our depiction of Early and Mid-Holocene climatic evolution and cultural dynamics of the region. These aspects are discussed here, based on new archaeological surveys, excavations, geoarchaeological and micromorphological studies, aiming to better understand connections with Terminal Pleistocene and Early Holocene autochthonous cultures of southern Arabia. Our results suggest that the final Pleistocene was marked by strong aridity, which promoted a widespread thermoclastism within rock shelter and deposition of aeolian sand; on the contrary, the transition towards the Holocene is marked (since c. 12000 cal yr BP) by a progressive increasing in environmental humidity, which permitted the formation of thick strata of peridesert loess. After this phase, the environmental humidity of the Jebel increased and permitted the existence of a large community of land snails; the latter were exploited by Early Holocene hunter-gatherers who lived in the rock shelters between c. 10500–9500 cal yr BP and left consistent accumulations of land shells (*escargotières*). The maximum of Holocene humidity was reached between 9000-8000 cal yr BP; regional aquifer were recharged and the deposition of calcareous tufa at the entrance of caves started, lasting up to c. 4500 cal yr BP. C and O stable isotopes from calcareous tufa highlights, in accordance with several regional records, the progressive decline of the intensity of the Indian Ocean monsoon and the transition towards arid conditions. In this phase, the area was abandoned and archaeological communities possibly relocated along the coast of central and southern Oman, where they exploited the mangrove environment.

Keywords: Holocene; Oman; palaeoenvironment; speleothems; cave sites; land shell accumulations.

1. Introduction

The Early Holocene climatic (mostly precipitation regime) evolution in southern Arabia is now known thanks to studies of palaeolakes and speleothems in Yemen, Oman, Saudi Arabia and the United Arab Emirates (e.g., Fleitmann et al., 2003; Davies, 2006; Lézine et al., 2007; Parker, 2009). Furthermore, high-resolution oxygen isotope profiles of Holocene stalagmites from several caves in northern and southern Oman and Yemen (Socotra) recently published (Burns et al., 1998; Neff et al., 2001; Fleitmann et al., 2003, 2004, 2007, 2011) provide detailed information on Late Quaternary climatic fluctuations of southern Arabian Peninsula and western Indian Ocean. Palaeoclimatic data were also obtained from sand dunes, loess-like deposits, and paleosols (e.g., Nettleton and Chadwick, 1996; Wilkinson, 1997; Coque-Delhuille and Gentelle, 1998; Preusser et al., 2002; Parker et al., 2006; Pietsch and Kühn, 2009; Pietsch et al., 2010).

Early Holocene human occupation of south-east Arabian Peninsula is witnessed by lithic assemblages characterized by blade productions and the Fasad points, being considered as a lithic facies that still needs to be clearly defined (Charpentier 2008; Charpentier and Crassard, 2013). The so-called Fasad points are characteristic Early Holocene tanged points made on elongated flakes or blades/bladelets and are rarely found in stratigraphy (e.g., Uerpmann et al., 2013). Nevertheless, they are most often occurring as surface finds, thus making it difficult to understand the relationships between climatic changes and cultural dynamics. The caves and the rock shelters that dot the wadis cutting the southern part of Jebel Qara, a massif facing the coast of Dhofar (southern Oman) provide an important opportunity to fill this gap as they include anthropogenic sediments of the Early Holocene hunter-gatherers occupations interlayered with breccias, loess, and calcareous tufa, which were the products of the local effect of the early Holocene climatic changes. Geoarchaeological research previously performed in the area (Cremaschi and Negrino, 2002, 2004) was recently resumed and the results obtained are presented in this paper.

2. The study region

The region of Dhofar in south-western Oman, bordering the Hadramawt and Mahra regions of eastern Yemen, is a mountainous and plateau region, with one particular limestone massif (Fig. 1), which separates the coastal plain of Salalah from the Nejd Desert: the Jebel Qara (Cremaschi and Negrino, 2005), representing the continuation in Oman of the Yemeni Hadramawt plateau (Fig. 2). Jebel Qara's top is gently undulating and it reaches the maximum height of ~ 850 m above sea level. From the geological point of view, the massif consists of late Cretaceous to Tertiary limestone (Platel et al., 1992). Geological strata are gently tilted to the North and crossed by systems of faults in the area above the Salalah coastal plain and immediately south of the Nejd Desert. Loess deposits occur along the northern fringe of the jebel and are similar to deposits described on the Yemeni Plateau and dated to the Early Holocene (Nettleton and Chadwick, 1996; Cremaschi and Negrino, 2005). A well developed karst net is present in the Jebel Qara massif and many rock shelters are located along the steep slopes in the southern part of the jebel (Platel, 1992; Hanna and Al-Belushi, 1996); many of them can interpreted as inland notches (Shtober-Zisu et al., in press). The southern margins of the Jebel Qara are connected to the present-day coastline of the Indian Ocean by an alluvial apron consisting of steep alluvial fans, composed of gravel-dominated sediments and dating mostly to the Upper Pleistocene. At the foot of the fan extensive formations of beach rocks are present together with aeolian sand formations, hanging some meters (up to 3-4 m) above the present day shore, suggesting the position of the sea level at the time of the maximum postglacial rebound (Pirazzoli, 1991). Alluvial fans toward the sea also delimitate several fossil swamp basins, filled by organic matter-rich mud (Platel et al., 1992; Horn and Cremaschi, 2004; Cremaschi and Perego, 2008).

Today, southern Oman is a semi-arid land, with annual precipitations ranging from 200 to 600 mm; most of them are concentrated between July and September (more than 80%), when the monsoonal rain from the Indian Ocean reaches the region (Fleitmann et al., 2004). Jebel Qara forms a barrier against the summer monsoon, which rains support shrubs and trees on the southern coastal side of the mountain; to the North, the plateau gradually becomes an arid steppe (Rogers, 1980; Sale, 1980), where overgrazing have recently enhanced the desertification process and soil loss (Sale, 1980a, 1980b; Rogers,1980). On the contrary, during the Holocene the climate of the region, as of the entire Arabian Peninsula, greatly changed. In fact, high-resolution oxygen isotope curves of Holocene stalagmites from caves in northern and southern Oman and Yemen provided detailed information on climatic fluctuations of southern Arabian Peninsula (Burns et al., 1998; Fleitmann et al., 2003, 2004, 2007, 2011). These variations, controlled by the position of the Intertropical Convergence Zone (ITCZ) and dynamics of the Indian monsoon, are briefly reported: in the Early Holocene rapidly decreasing of $\delta^{18}O$ values indicates a rapid northward displacement in the latitudinal position of the summer ITCZ and the associated monsoonal rainfall belt; while during the Middle to Late Holocene the summer ITCZ continuously migrated southward and monsoon precipitation decreased gradually in response to decreasing solar insolation (Fleitmann et al., 2004).

Dhofar archaeological record for the Early Holocene is mainly characterized by surface sites, but also some very few stratified (e.g., Zarins, 2001, 2013; Hilbert, 2013). The Early Holocene occupations of southern Oman, and more broadly of the whole southern Arabia, are in fact quite unclear, mostly known by blade productions, as well as tanged lithic projectiles (including Fasad points). Very little is known apart these rare typological elements, being even difficult to define the origins and the development of the makers of such industries. While researchers have used different terms to refer to this chronological period such as Late Paleolithic or Epipaleolithic (e.g., Cremaschi and Negrino, 2002; Hilbert, 2013), a consensus has not yet been reached in the scientific community working in this area on how to call this pre-Neolithic period. Discoveries have been too sparse up to now to resolve this debate, the lack of a clear Upper Paleolithic and the exact transition to fully neolithicized societies rending difficult to do so. The more recent sites dated to the Neolithic period (from c. 8000 cal yr BP) are mostly shell middens along the Omani coasts, with rich and consistent cultural material (e.g., Charpentier, 2008) and frequently linked to mangroves and lagoons (Berger et al., 2005, 2013). The lithic industries are well-known, with specific projectile point types, including trihedral and fluted points that are found in the broader southern Arabian Peninsula (Charpentier, 2004, 2008; Crassard 2009).

3. Materials and methods

Beyond deposits related to their recent pastoral use, most of the Jebel Qara's cavities preserve an older sedimentary infilling, which occurred in most of the visited cavities with the same characteristics and consists, form the base to the top, of angular breccia, loess deposits and accumulations of land snails (including charcoal and lithic artefacts), sealed by thick calcareous tufa in form of flowstones (Cremaschi and Negrino, 2005). During the field survey, preliminary test trenches were opened in the cavities KR-213 and GQ-13/23 to investigate the archaeological evidence and to collect samples for micromorphological analysis on the base deposits and geochemical analyses on calcareous tufa. Moreover, charcoal samples were collected and submitted to AMS-^{14}C radiometric dating; the results of new dating and those reported in Cremaschi and Negrino (2005) are indicated in text and in Tab. 1 as uncal and cal yr BP; calibration is according to the IntCal13 curve (Reimer et al., 2013).

Thin sections from undisturbed blocks from the archaeological infilling at the bottom of the Jebel Qara caves (KR-213 and GQ-13/23) have been used to identify the stratigraphic sequence-forming processes and to infer the environmental and anthropogenic factors for sediments accumulation and post-depositional changes (e.g., Courty, 2001; Goldberg and Macphail, 2006; Cremaschi et al., 2014). Oriented and undisturbed blocks from the sediments below the flowstones were collected. Thin sections (5x9 cm) were manufactured after consolidation according to standard methods (Murphy, 1986). Micromorphological observation under plane-polarized light (PPL), cross-polarized light (XPL), and oblique incident light (OIL) of sediment thin sections employed an optical petrographic microscope Olympus BX41 with a digital camera (Olympus E420). For the description and interpretation of thin sections, the reader should consider the terminology and concepts established by

Bullock et al. (1985), Stoops (2003) and Stoops et al. (2010). Properties of samples detected by thin section analysis are summarized in Tab. 2.

Two different samples were collected from the same flowstone decoration (KR1 and KR3) outcropping from the roof of the KR-213 rock shelter and submitted to geochemical analyses. These samples were cut in the laboratory, put in resin and polished. From polished surfaces, samples for U/Th dating and stable isotope analyses (C and O) were collected. Solid prisms of ca. 200 mg (ca. 3 mm wide along the lamina and 1 mm thick on growth axis) were used (e.g., Regattieri et al., 2014). Eight samples were taken for U/Th dating which was performed at the University of Melbourne (Victoria, Australia), following the method proposed by Hellstrom (2003). Correction for detrital Th content was applied using initial activity ratios of detrital thorium $[^{230}Th/^{232}Th]_i$ of 1.50±1.50. Results, indicated as years BP, are summarized in Tab. 3. Samples for stable isotope analyses were drilled using an air drill with a drill bit of 1 mm. Average distance between samples of ca. 1.5 mm. Stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope ratios were performed with a Gas Bench II (Thermo Scientific) coupled with an IRMS Delta XP (Finnigan Matt) at the Institute of Geosciences and Earth Resources of CNR in Pisa (Italy). Briefly, carbonate samples of ca. 0.15 mg were dissolved in H_3PO_4 (100%) for one hour at 70°C in sealed vials flushed with helium. The headspace gas (CO_2) is entrained in a helium stream, dried with 2 nafion gas dryer, purified by passing through a gas chromatographic column and then injected in the continuous flow isotope ratio mass spectrometer via an active open split. All the results were reported to the relative Vienna PeeDee Belemnite (VPDB) international standard. Sample results were corrected using the international standard NBS-19 and a set of 3 internal standards: two marbles, MOM and MS, and a carbonatite NEW12, previously calibrated using the international standards NBS-18 and NBS-19. Analytical uncertainty for replicated analyses of $\delta^{18}O$ and $\delta^{13}C$ were c. 0.15 ‰.

4. Results

4.1. Description of the cave infillings and micromorphology of the deposits

The entrance and the outer part of karst cavities and rock shelters, which are exposed at different heights along the slopes of the wadis of Jebel Qara, are systematically covered by calcareous tufa in shape of large flowstones, stalactites and stalagmites. Calcareous tufa accretion is today inactive and they are on the way to collapse and being dismantled; therefore, they are evidence of former higher precipitation in the area (Cremaschi and Negrino, 2005). The calcareous tufa flows cover and preserve a complex stratigraphic sequence composed from the base of angular breccia, aeolian dust and accumulations of land snails, which are associated to anthropogenic deposits. Lands snails and associated evidence of human activity (lithic industries and charcoal) have been found only inside the rock shelters and caves opening along the valley bottom, while they lack inside the cavities located to higher elevation along the slope of the wadis. In the latter type of rock shelter calcareous tufa lies directly on angular breccia and aeolian dust. The rock shelters here discussed, site KR-213 and GQ-13/23, are located along the Wadi Jenikermat and may be considered as the reference sequences for the region (Fig. 3).

The infilling of site KR-213 consists, from the bottom to the top of the sequence, of three main sedimentary Units (Figs. 3, 4), A to C, sealed by a thick layer of calcareous tufa, Unit D (Cremaschi and Negrino, 2005). The lowermost Unit (A) is a clast-supported angular breccia, associated with intergranular sand. The breccia, derived from the fragmentation of the rock shelter vault, is composed of coarse and medium clasts organized in irregular, discontinuous, non-parallel planar layers that dip towards the mouth of the cave and have an abrupt contact with the underlying bedrock. The intergranular fine fraction is composed of rounded and sub-rounded sand-sized quartz, feldspar, and other mineral grains, interpreted as an aeolian input to sedimentation. The overlaying Unit B is a matrix-supported breccia, consisting of very few medium-sized angular fragments of limestone interbedded with brown massive loam. Few thin (about 2 cm), discontinuous, dark brown archaeological layers, all rich in charcoal and flint artefacts, have been identified within this Unit. Cremaschi and Negrino (2005) have demonstrated that the fine fraction has a loess-like grain-size distribution, suggesting input of aeolian silt. A charcoal chunk from the upper part of this Unit permitted to date it at 9130±290 uncal yr BP (11092–9551 cal yr BP). The following Unit C consists of a high concentration of land snails dispersed in a silty matrix, often showing a clast-supported pattern; shells are arranged in discontinuous, nonparallel planar layers several centimetres thick. Unit B has been radiocarbon dated to 8720±60 uncal yr BP (9903–9547 cal yr BP). The mollusc assemblage mostly includes *Euryptyxis latireflexa* and *Revoilia dhofarense*, generally complete specimens in some cases broken and distributed on planar layers (Cremaschi and Negrino, 2005); these species are representative of mesophilous species, adapted to a dense grass cover and requiring wet conditions and vegetal cover (Wright, 1963; Wright and Brown, 1980). Finally, the uppermost Unit A is a thick flowstone deposits sealed with stalagmites, descending from the roof of the shelter and covering the sedimentary fill. The calcium carbonate that formed the flowstones also deeply penetrated in the underlying stratigraphic sequence and most of the layers are moderately to strongly cemented.

The sedimentary infilling of cave GQ-13/23, discovered during the field season 2013 along the same wadi a few kilometres downstream of the KR-213 shelter, displays a rather similar stratigraphic sequence (Fig. 4). Unit A is not represented in the section investigated, while the Unit B, occurring at the base of the sequence, consists of thin and discontinuous layers of clast- to matrix-supported breccia. Unit C is a particularly thick (~ 1 m) and strongly cemented layers, constituted of gently deepening silty layers including a high concentration of land snails. It is interesting to notice that Unit B at site GQ-13/23 is intercalated with silty layers very rich in angular fragments of charcoal and flint artefacts including a well preserved Fasad point (Fig. 5). A sample of charcoal from the Unit B has been dated to 10040±50 uncal yr BP (11798–11311 cal yr BP). Two radiocarbon dates were obtained on charcoal fragments collected at different levels of the Unit C (Tab. 1), giving 9150±50 uncal yr BP (Unit B; 10486–10226 cal yr BP) and 9010 uncal yr BP (Unit C; 10250–9934 cal yr BP). Also in the case of site GQ-13/23, a thick flowstone descending from the roof of the shelters (Unit D) seals the whole stratigraphic sequence.

Interesting information can be detected at the micro-scale; thin sections from the infilling of both caves display similar features (Tab. 2). Thin sections of the clast-supported breccia Units A and B highlight the presence of limestone angular clasts (breccia), probably deriving from thermal degradation of the vault of the rock shelter. In and intergranular position with respect of the limestone clasts sand grains (Unit A) and loess-like (Unit B) sandy silt (increasing in percentage from Unit A to Unit B) occur. The local origin of limestone clasts is confirmed by the occurrence of marine microfossils typical of the rock formations constituting the Jebel Qara (Fig. 6). On the contrary the intergranular sediments, as rich in quartz, feldspar and heavy minerals (Cremaschi and Negrino, 2005), are unrelated to the local geological context and were originated from the deflation of the sands of the Nejd desert. At the microscopic scale, the overlaying Unit C includes a high concentration of large fragments of land snails, in some cases broken and distributed in planar layers (Fig. 7). The occurrence of loess sediments as in this unit indicates that the dust supply from the Nejd desert was still active, but the occurrence of pedorelicts due to colluvial processes indicates wetter environmental conditions in comparison with those that drove the formation of the underlying deposit.

4.2. Flowstone chronology and geochemical analyses

A total of eight U-series dating have been performed on two samples KR1 and KR3 collected from the same flow stone decoration sealing the base deposits of the KR-213 shelter. Unfortunately, due to the low U content and high level of detrital (Th) contamination, only the result of five out eight ages can be considered as reliable (Tab. 3). U/Th ages indicate that flowstone KR1 is basically older than KR3 (Tab. 3 and Fig. 8); KR1 formed in the Early Holocene between c. 9500 and 7500 yr BP, whereas KR3 precipitated in the Middle Holocene between 5500 and 4500 yr BP.

Despite this, stable isotopes from both samples show some similarities, which are particularly strong in the top sections, where isotopes (both oxygen and carbon) show significant excursion toward higher values (Figs. 8 and 9). Carbon values range between -12 and -3 and oxygen values are between -2 and 1. Kinetic fractionation sometimes occurs in cave-entrance speleothems and calcareous tufa (Mickler et al., 2006), but in the present case (Fig. 9) carbon isotopic composition shows a low positive correlation with oxygen record (R^2=0.52 for KR1 and R^2=0.2 for KR3). In sample KR3 at ~20 mm from the top, there is a sharp change in texture and fabric, marked by a thin whitish layer, suggesting the possibility of a hiatus. Because this interval is not chronologically constrained, it would correspond to the top of sample KR1. Owing to this uncertainty the upper interval of KR3 at this stage was not further considered. A simple, linear age model was then constructed for both samples; the ages model need considered as largely indicative (Fig. 8).

4.3 Archaeological content of the deposits

At GQ-13/23, as previously observed in neighbouring sites and in those located along Wadi Darbat (Cremaschi and Negrino, 2002, 2005), the Fasad points are present, attesting a human occupation by hunter-gatherers during the Early Holocene. One point in particular (Fig. 5), which has been collected *in situ* (in Unit C, dated to 10486-10226 yr cal BP), is made on a pointed blade showing a bi-lateral convergent preparation with the removal of two previous blades creating a Y-shape guiding arises in order to obtain a final pointed blade. This method of blade production reminds the (probably) contemporaneous methods observed in inland Dhofar sites (Hilbert, 2014) or in Hadramawt, Yemen (Crassard, 2008). The Fasad point from GQ-13/23 is 62 mm long with an abrupt-retouched tang along about one quarter of the piece total length, being typologically much closed to the specimens found in the vicinities (Cremaschi and Negrino, 2002). More broadly, it has many typological resemblances with other examples known from surface sites in Dhofar and elsewhere in Oman and the United Arab Emirates (Charpentier and Crassard, 2013). Very few lithics have been found in relation to this point at GQ-13/23, making difficult to propose a precise technological assessment of the complete lithic assemblage. Nevertheless, both type and technology observed on this single artefact at GQ-13/23, confirm the chronological and thus cultural affiliation of this industry to the Early Holocene. However, it is not firmly known, still highly debated, if the makers of this kind of projectiles have a local origin related to autochthonous Late Paleolithic groups. As well, it is not known if the occupants at GQ-13/23, and their counterparts in the region who were making these Fasad points, are actually the direct ancestors of the Neolithic populations that rapidly spread inland and along the coasts about two millennia later. Only a complete stratigraphic sequence yielding remains of occupations from the Terminal Pleistocene up to the Neolithic period would help in answering such a crucial archaeological issue .

5. Discussion

5.1. Evolution of the climate during the Early and Middle Holocene

The four different units described in the rock shelters of Jebel Qara permit to trace the Late Quaternary environmental evolution of the massif. The whole sequence ranges from c. 11798–11311 cal yr BP (calibrated ^{14}C age) to c. 4230 yr BP (U/Th age), including the whole Early and Middle Holocene.

The sedimentary processes leading to the formation of the clast- to matrix-supported breccia at the bottom of the stratigraphic sequences appear to be related to thermoclastic shattering of the rocky walls of the cave (Cremaschi and Negrino, 2005) and has to be related to arid climatic conditions. Aeolian sand and silt included in the fine fraction indicate dust transport by strong northerly winds from the Nejd desert. This phase can be dated to a Late Pleistocene/very Early Holocene dry phase (Sanlaville, 1992; Fleitmann et al., 2004). In the Unit B, the breccia decreases or completely disappears and the loess fraction becomes dominant and may be correlated with the peridesert loess deposits of the same age occurring at the northern fringe of Jebel Qara (Cremaschi and Negrino, 2005), and suggests a phase in which northerly winds are still important. The deposition of peridesert loess in southern Arabian Peninsula was put in relation to slightly humid environmental conditions, allowing the growth of vegetation (herbs and bushes) able to trap dust particles (Pye, 1987, 1995; Coudé Gaussen, 1991; Wright, 2001). Therefore, the transition between Units A to B occurred under progressively more humid environmental conditions, presumably triggered by the resumption of the Indian Ocean monsoon system and the northward shift of the ITCZ.

The Unit C is mainly characterized by a large content of shells of mesophilous land snails, indicating the spreading of a savannah-like environment; the sedimentation of this Unit has been interpreted (Cremaschi and Negrino, 2005) as a consequence of the onset of wetter conditions in comparison to that of the underlying loess and breccia deposits. While the ecology of the molluscs supports a climatic interpretation, their occurrence in high concentration inside the rock shelters has to be interpreted as due to human activity as it will be discussed in detail in the next section.

An outstanding increase in precipitations intensity is indicated by calcareous tufa, which constitutes the Unit D. Their formation was triggered by the progressive reinforcement of the Indian Ocean monsoon system and the northward shift of the ITCZ, which contrasted the northern winds responsible of sand and loess transport recorded in the underlying units. The stratigraphic sections of the Jebel Qara recorded the progressive increasing in the intensity of precipitations toward the uppermost Unit D of calcareous tufa. In fact, the deposition of freshwater carbonates in arid lands requires a major shift in geomorphologic processes and in climate (e.g., Smith et al., 2004; Cremaschi et al., 2010). Calcareous tufa at Jebel Qara formed since the beginning of the wet Holocene at c. 9000 yr BP (U-series age) and survived up to the start of its decline, at the beginning of the late Holocene arid phase (Hoorn and Cremaschi, 2004).

The investigation on the speleothems collected from Unit D offers a more detailed palaeoenvironmental reconstruction. In fact, even though they are generally less laminated and pure than speleothems, cave-entrance calcareous tufa may represent a powerful tool for palaeoenvironmental reconstruction in arid lands (e.g., Smith et al., 2004; Moeyersons et al., 2006; O'Brien et al., 2004; Cremaschi et al., 2010). Following the interpretation reported for speleothem of the area, lower oxygen isotope values indicate higher humidity related (amount effect) to northward displacement of Indian monsoon domain, which occurred at time of higher summer insolation in the northern Hemisphere (Burns et al., 1998; Fleitmann et al., 2003, 2004, 2007, 2011). On the contrary, higher oxygen isotope values are connected to phases of reduced precipitation associated to weakening of the monsoon system and increasing importance of northern, drier winds. The composite record of samples KR1 and KR3 is (up to now) too discontinuous for inferring detailed short term oscillation, but we note that the most negative $\delta^{18}O$ values were reached at the beginning of the Holocene, suggesting the maximum of precipitation. This was followed by a progressive increase of $\delta^{18}O$ values, interpreted as a decline in the intensity of the monsoon system. Carbon isotopic compositions show a low positive correlation with oxygen record (Fig. 9); correlation between C and O is often interpreted as indicative of kinetic fractionation (Mickler et al., 2006), this can be also driven by climatic effect (Drysdale et al., 2004; Cremaschi et al., 2010). In particular, during drier period reduction in soil development can produce effect like decreasing in soils productivity and decreasing recharge promoting, for instance prior calcite precipitation (e.g., Genty et al., 2003; Drysdale et al., 2006). These processes can produce increasing of carbon isotopic composition along with higher oxygen isotope values due to the decreasing in monsoon strength. The apparent significant increasing in both oxygen and carbon isotope composition at the top of both samples may indicate the progressive obsolescence of the flow preannouncing the end of calcite deposition, which would have been occurred for the definitive reduction in water recharge due to climate condition.

In our case study, an independent control on acquired data is offered by the comparison (Fig. 10) with many curves from Holocene speleothem of Oman discussed by Burns et al. (1998) and Fleitmann et al. (2003, 2004, 2007, 2011). The range of oxygen isotope values measured in our flowstones partially overlaps the values measured in cave speleothems from northern and southern Oman (Fleitmann et al., 2004, 2007). Arguably, this is a good indication of the potential of these flowstones to preserve important hydrological information despite their high superficiality, which often can promote isotopic kinetic fractionation. Moreover, the composite record of samples KR1 and KR3 is evidently similar to Fleitmann's record from Q5 speleothems is quite evident (Fig. 10). Notably, the $\delta^{18}O$ record of sample KR3 is basically lower than the KR1, in agreement with the general trend of speleothems form site Q5. Finally, in sample KR1 the end of deposition can be roughly constrained at ca. 7.5 ka BP, when Q5 speleothem show a clear monotonic increasing of $\delta^{18}O$ values.

At the regional scale, in the Early and Middle Holocene the southern Arabia experienced a generalized increasing of environmental humidity (e.g., Lézine et al., 1998; Neff et al., 2001; Fleitmann et al., 2004; Parker et al., 2004), triggered by the intensification of the monsoonal precipitation as a consequence of an enhanced solar heating across the northern Hemisphere (Berger and Loutre, 1991; Sirocko et al., 1993; Gasse and Van Campo, 1994). This span has been identified as a major phase of permanent lacustrine environment in the Rub' al-Khali sand sea and in the arid regions of Yemen (e.g., McClure, 1976; Schulz and Whitney, 1986; Parker et al., 2004, 2009; Lézine et al., 2007).

Finally, it is interesting to take into account the work of Lézine et al. (2007) on the response of a freshwater environment of the Ramlat as-Sabatayn sand sea in continental Yemen to the increase of the Indian monsoon strength. Their archive shows a maximum of Holocene water availability at c. 9000-8000 cal yr BP, as in the whole region; but it also highlights some differences respect to the highly detailed record of precipitation of speleothems (Fleitmann et al., 2003). At Ramlat as-Sabatayn the initial increase of monsoon precipitation is dated from c. 12000 cal yr BP, whereas due to the necessity to the recharge of the mountain aquifers the sedimentation of speleothems started later. In the Jebel Qara this phase corresponded to the beginning of loess sedimentation and therefore, according to our interpretation, to the initial spread of vegetation able to trap dust particle as consequence of enhanced precipitation. This possibly confirms that the strengthening of the Indian Ocean monsoon started at the very beginning of the Holocene.

5.2. Early Holocene human occupation of the cavities Jebel Qara

Evidence of human occupation (lithic industry and charcoal) in the cavities of Jebel Qara is mostly concentrated in the Unit C, a part of the occasional find of charcoal in Unit B, and it is systematically associated with high concentration of mollusc shells. At the macroscopic scale, molluscs and archaeological evidence occur only in the cavities located in the valley floors of easy accessibility. On the contrary in the caves and shelters, hanging at different heights along the steep valley slopes, molluscs and artefacts are absent and calcareous tufa directly overly Units A and B. Inside the cave deposits molluscs are associated to organic layers, charcoal, in some case to small fragments of burned bones and to lithic artefacts. In thin section, the evidence of human activity is clearer as shells of land snail are often broken and redistribute in flat layers with planar distribution of clasts and associated to finely subdivided organic matter and charcoal lenses; these are indicative for occupational trampling (e.g., Gé et al., 1993; Zerboni, 2011). Moreover, the micromorphological investigation of the mollusc rich strata showed, in some cases, evidence for heating of shells, represented by peculiar interference colours and pores within the shell microstructure (see Maritan et al., 2007). Archaeological features similar to those observed at Jebel Qara have been recently described at the micro-scale by Balbo et al. (2010) and Zerboni (2011); due to the many analogies with them, we interpreted the shells layers inside the studied rock shelters as intentional accumulations related to human activities. The land snails-bearing layers occurring in the rock shelters of the Jebel Qara have to be interpreted as anthropic accumulation of land shells or *escargotières* (*sensu* Lubell et al., 1976).

The lithic assemblages associated to these sites, including laminar debitage, sometimes Fasad points, represent the remains of hunter gathers populations (Charpentier, 2008; Charpentier and Crassard, 2013). Nevertheless, the identification of accumulations of land snails at Jebel Qara represents an unprecedented evidence of foraging strategy adopted by the Early Holocene human groups in southern Arabia. The frequentation of the area was made possible thanks to a main climatic shift towards wet conditions, in contrast with the aridity that dominated in the area at the transition between the Late Pleistocene and the Early Holocene. New and wetter environmental conditions promoted the ecological settings suitable to the development of the molluscs fauna of the Jebel Qara, representing another type of food resources for these populations. At present, we have no evidence for any kind of connection between the Early Holocene sites of Jebel Qara and the coastal area, as for example no marine shell has been found in the inland sites. Along the coast, sites of that age are extremely rare, as one single cave site has been discovered so far dated to the Early Holocene: the Natif 2 site at about 100 km to the East (publication in preparation).

After this phase, the increasing of the Indian Ocean monsoon system and the northward shift of the ITCZ, which was in charge of the formation of calcareous tufa, made the rock shelters at the southern margin of the Jebel Qara unsuitable for life and consequently they were abandoned. During the phase characterized by the most wet environmental conditions at Jebel Qara (between c. 8000 and 5000 cal yr BP), the occurrence of many shell middens distributed along the coast of central Oman (Biagi and Nisbet, 1992, 2006; Biagi, 1994, 2005, 2013; Berger et al., 2013) suggests that later prehistoric groups shifted from the mountains to coastal Oman. Therein, they exploited the resources rendered available by the formation of the mangroves, which was triggered by the oscillations of the level of the sea, but also enhanced thanks to the input of freshwater from inland due to reinforced by the monsoon rain (Lézine et al., 2002; Berger et al., 2005, 2013).

6. Conclusions

The infilling of caves and rock shelters of Jebel Qara gave the opportunity to reconstruct the climate changes occurred in the area in the Early to Middle Holocene and to confirm previous regional studies. Furthermore, the geoarchaeological investigations allowed to discover a peculiar and unprecedented strategy of exploitation of natural resources performed by the Early Holocene hunter gatherers.

The stratigraphic record represented in the Jebel Qara rock shelters indicates that in this span of time the climate of the area changed from dry conditions, dominated by northern winds, to a wet climate, which was on the contrary dominated by the southern monsoon system, and back again to progressively drier conditions. Our evidence is substantially in accordance with data from the caves of Oman (Fleitmann et al., 2007), which indicate a northward advance of the latitudinal position of the ITCZ (and increased monsoonal precipitation) in the period 10500-9500 cal yr BP, a part of the beginning of monsoon reinforcement, which possibly started some centuries before, as confirmed for instance by Lézine et al. (2007). We can find a good correlation also with the beginning of the withdrawn of the summer monsoon (and southward migration of the ITCZ), which began since c. 7800 cal yr BP and reached its maximum at c. 3500 cal yr BP, in response to the decreasing of solar heating (Hoorn and Cremaschi, 2004; Fleitmann et al., 2007). Also in the case of Jebel Qara, the palaeoenvironmental archive suggests a progressive weakening of the intensity of the Indian monsoon, rather than its abrupt interruption.

After the arid climate at the Pleistocene/Holocene transition, from c. 10500 to 9500 cal yr BP the climatic conditions became more humid, probably in relation with the shift of the monsoon front in a closer position to the Dhofar coast; ecological conditions in this period were favourable to a large development of land mollusc fauna and the land snails were exploited as a food resource by human groups, which settled the rock shelters opening at the wadi bottom. After that, since c. 9000 cal yr BP the enhanced intensity of the monsoon system led to the formation of calcareous tufa and the cavities of Jebel Qara were abandoned and the later prehistoric groups were attracted by other regions. They possibly moved to the coastal plain of Salalah, but the Neolithic archaeological record indicates intensive occupations along the coast of central Oman; therein they exploited the resources rendered available in the mangroves, whose development was favoured by the inland expansion of the monsoon rains.

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List of tables

Tab. 1. Results of conventional and AMS-^{14}C dating; calibrated age results are reported as years BC and BP. Calibration according to IntCal13 curve (Reimer et al., 2013).

Tab. 2. Essential micromorphological descriptions of samples representative for the four stratigraphic units composing the infilling of the rock shelters.

Tab. 3. Results of U/Th dating on calcareous tufa samples KR1 and KR3. The activity ratios [^{230}Th/^{238}U] and [^{234}U/^{238}U] have been standardized to the HU-1 secular equilibrium standard. Ages were calculated using decay constants of 9.195×10^{-6} yr^{-1} (^{230}Th) and 2.835×10^{-6} yr^{-1} (^{234}U), and an assumed initial [^{230}Th/^{232}Th] of 1.5±1.5 except KK215-3B, for which a value of 0.8 has been assumed. Depths are from the sample top, and numbers in brackets are the 95% uncertainties in the last digits given.

List of figures

Fig. 1. (A) Location of the study area in Oman. (B) Satellite imagery (Google Earth™) representing the main regions cited in the text; the dashed box indicates the position of Fig. 2.

Fig. 2. Geomorphology of the Jebel Qara region (modified from Cremaschi and Negrino, 2005); the position of the rockshelters whose Holocene infillings were studied is indicated by labels. The location of the archaeological sites identified in the field work is also shown. Key: 1) pediment of the Nejd Desert and gravely wadi bed; 2) desert loess deposits; 3) deep-cut fluvial net; 4) main Holocene calcareous tufa deposits; 5) slope deposits and Holocene alluvial fans; 6) coastal deposits and marine erosion terrace; 7) main scarps; 8) possible Holocene front of the monsoon rain; 9) rock shelters or caves with shell accumulations (Unit C); 10) rock shelters or caves without shell accumulations; 11) open-air sites (see Cremaschi and Negrino, 2005).

Fig. 3. Field pictures of (A) a rock shelter in the Jebel Qara area; note the columnar calcareous tufa sectioning its entrance. (B) The sedimentary infilling of a rock shelter sealed by a thick calcareous tufa. Details of the stratigraphic sequence: (C) the

lowermost part of the calcareous tufa sealing the sequence (Unit D); (D) the accumulation of land shells (Unit C); (E) the angular breccia with a loessic matrix (Unit B).

Fig. 4. Sketches of the infillings of the rock shelters KR-213 (modified from Cremaschi and Negrino, 2005) and GQ-13/23 in the Jebel Qara; the description of each stratigraphic Unit is in the text. Key: 1) bedrock (limestone); 2) clast-supported breccia (Unit A); 3) matrix-supported breccia and loess (Unit B); 4) organic matter-rich layers; 5) accumulations of land shells/*escargotières* (Unit C); 6) calcareous tufa (Unit D); 7) fragments of charcoal; 8) lithic artefacts.

Fig. 5. (A) Recovery during field operations of a Fasad point (indicated by the arrow) in the Unit C of GQ-13/23 site (note that it displays a planar orientation, according to the stratigraphy); (B) the drawing of the same item (by. G. Devilder, CNRS).

Fig. 6. Photomicrographs of thin sections of the deposits of rock shelter GQ-13/23. (A) Lower part of Unit B, planar orientation of rock fragments forming a matrix-supported angular breccia (XPL). (B) Unit B, transition between a clast to matrix-supported breccia; note the occurrence of micrite pendents on rock fragments (PPL). (C) Unit B, brown silty fine matrix deeply cemented by calcium carbonate with common quartz grains; the arrows indicated small shell fragments (PPL). (D) Upper Unit B, strong redistribution of calcium carbonate cement forming crystalline pedofeatures and enclosing charcoal fragments (indicated by the arrows; XPL).

Fig. 7. Photomicrographs of thin sections of the deposits of rock shelter GQ-13/23. (A) Unit C, deep concentration of mollusc fragments in the *escargotières*; note the clast-supported structure and the presence of evidence of heating (see: Maritan et al., 2007) on several shell fragments (PPL). (B) Unit C, note the strong distribution of micrite on shell fragments and in the micromass (XPL). (C) Unit C, brown matrix between two large shell fragments; note the occurrence of charcoal fragments (c) and a fragment of bone (b) (PPL). (D) Lower part of Unit D, note the transition between the accumulation of land shells and the calcareous tufa (XPL). (E) Concentration of charcoal fragments

cemented by micrite at the transition between Unit C and Unit D (PPL). (F) Laminated microstructure with common fenestral voids of the calcareous tufa at the basis of Unit D (PPL).

Fig. 8. Isotopic profiles (C and O) of the considered samples of flowstones (KR1 and KR3) and position of U/Th dating results according to flowstones' depth.

Fig. 9. The cross plots of $\delta^{18}O$ versus $\delta^{13}C$ for each sample (Hendy test); the correlation between C and O values are also reported.

Fig. 10. Composite oxygen isotope profiles of flowstones KR1 and KR3 compared with the oxygen curve of the Q5 site (Qunf cave, southern Oman) elaborated by Fleitmann et al. (2003). Changes in Holocene summer insolation (according to Berger and Loutre, 1991) are also reported.

Figure

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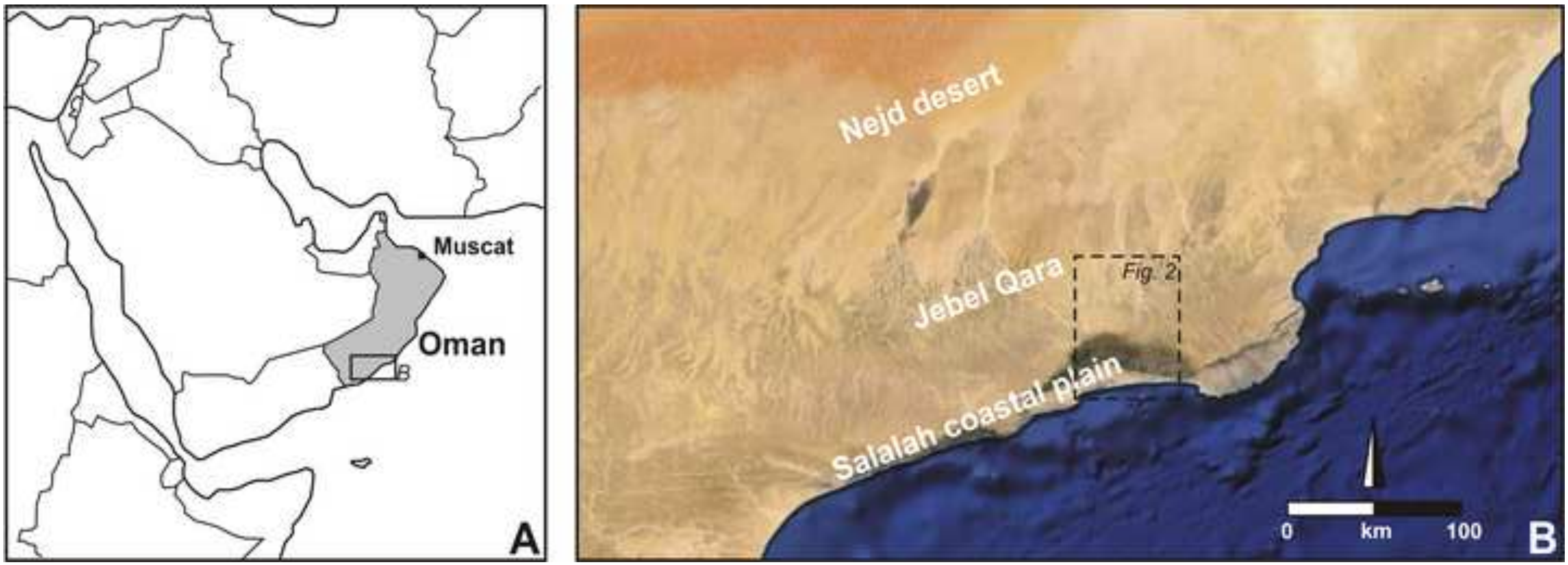

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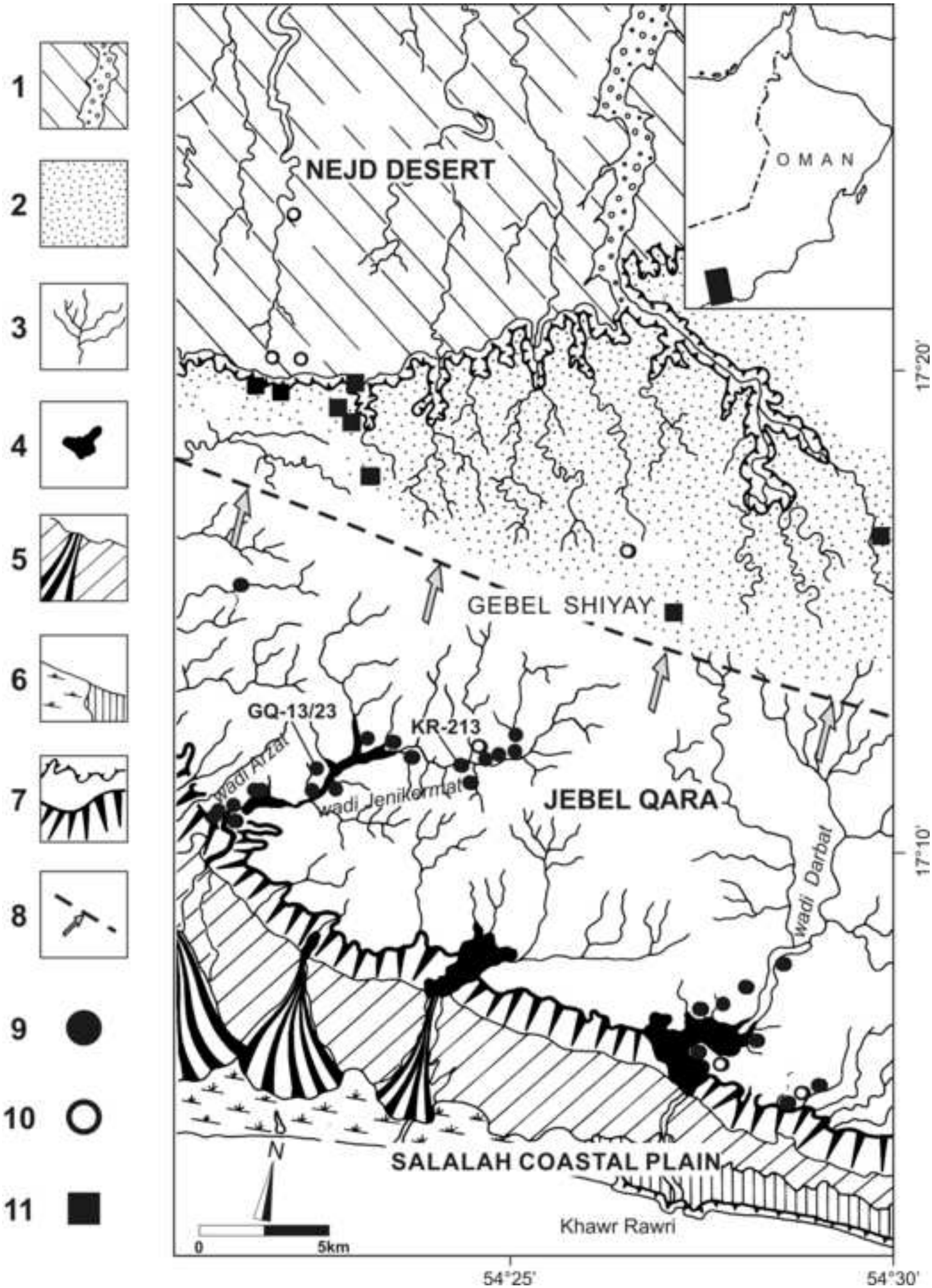

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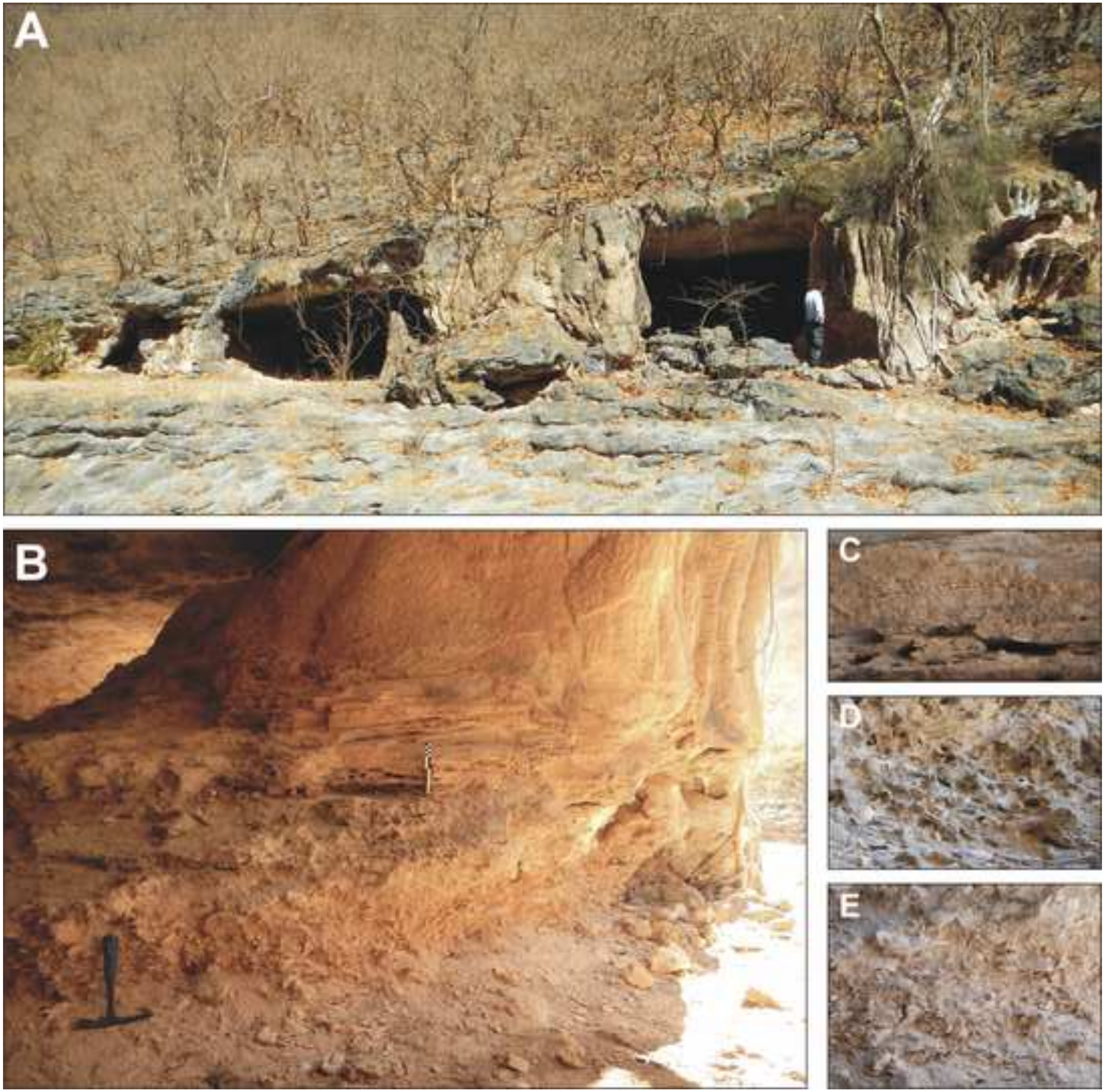

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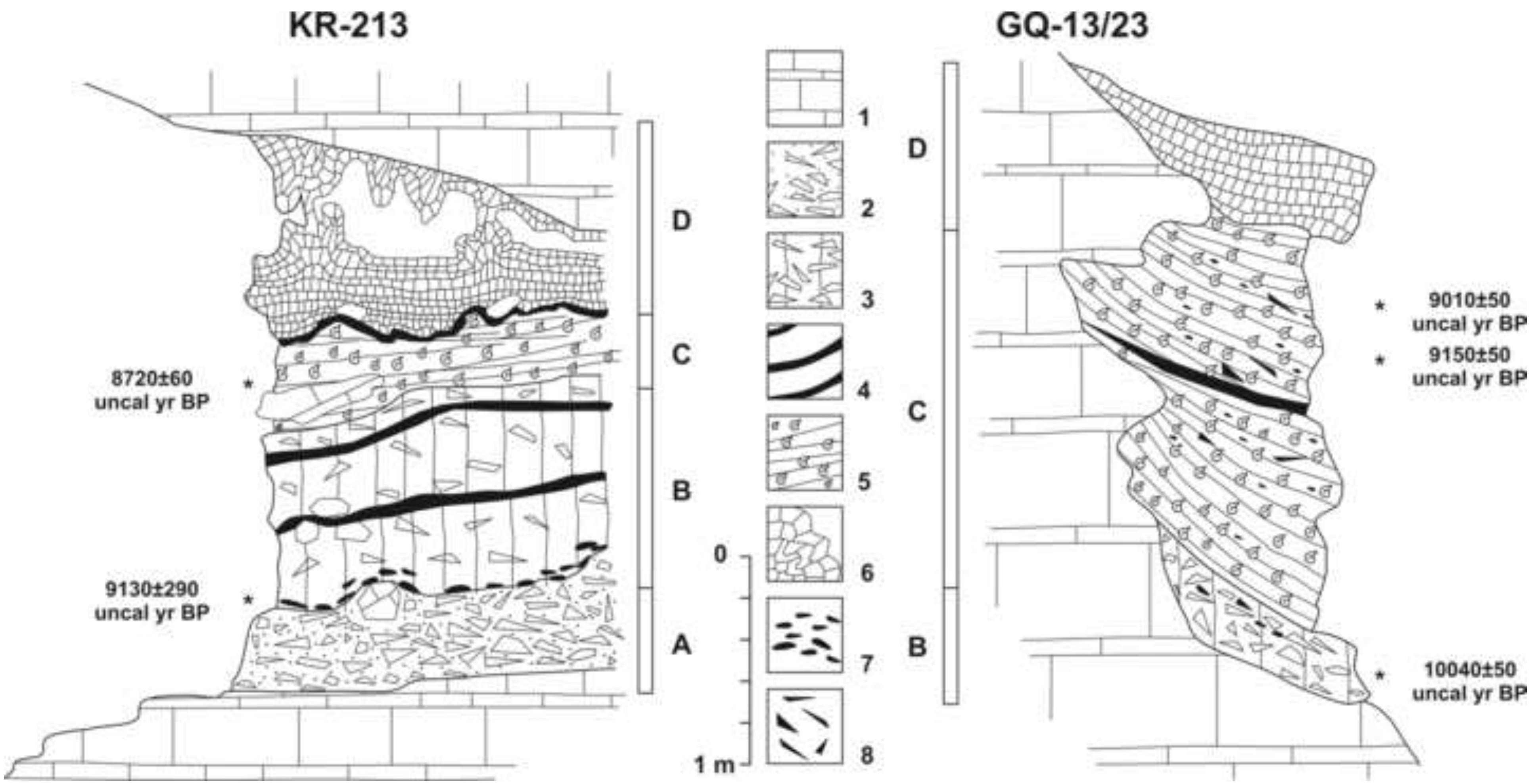

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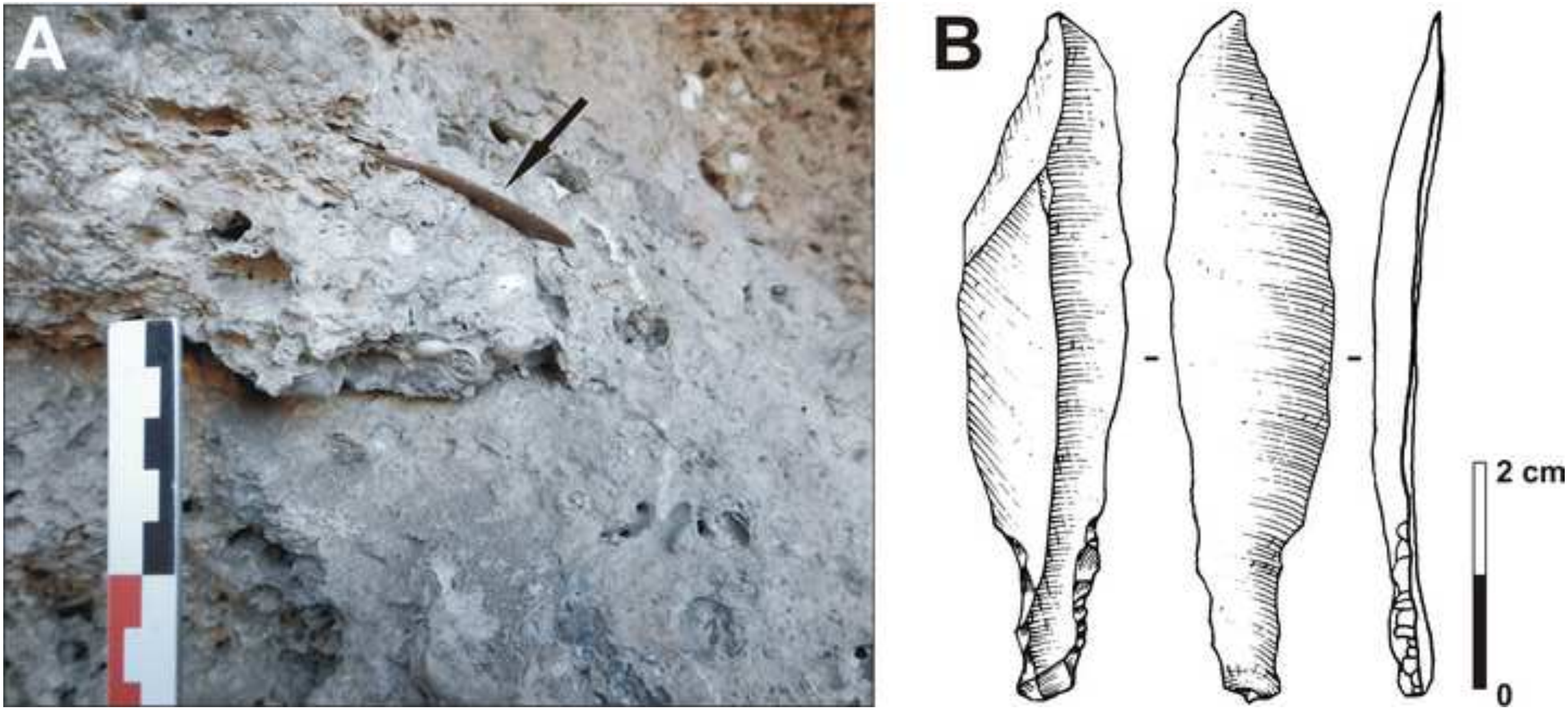

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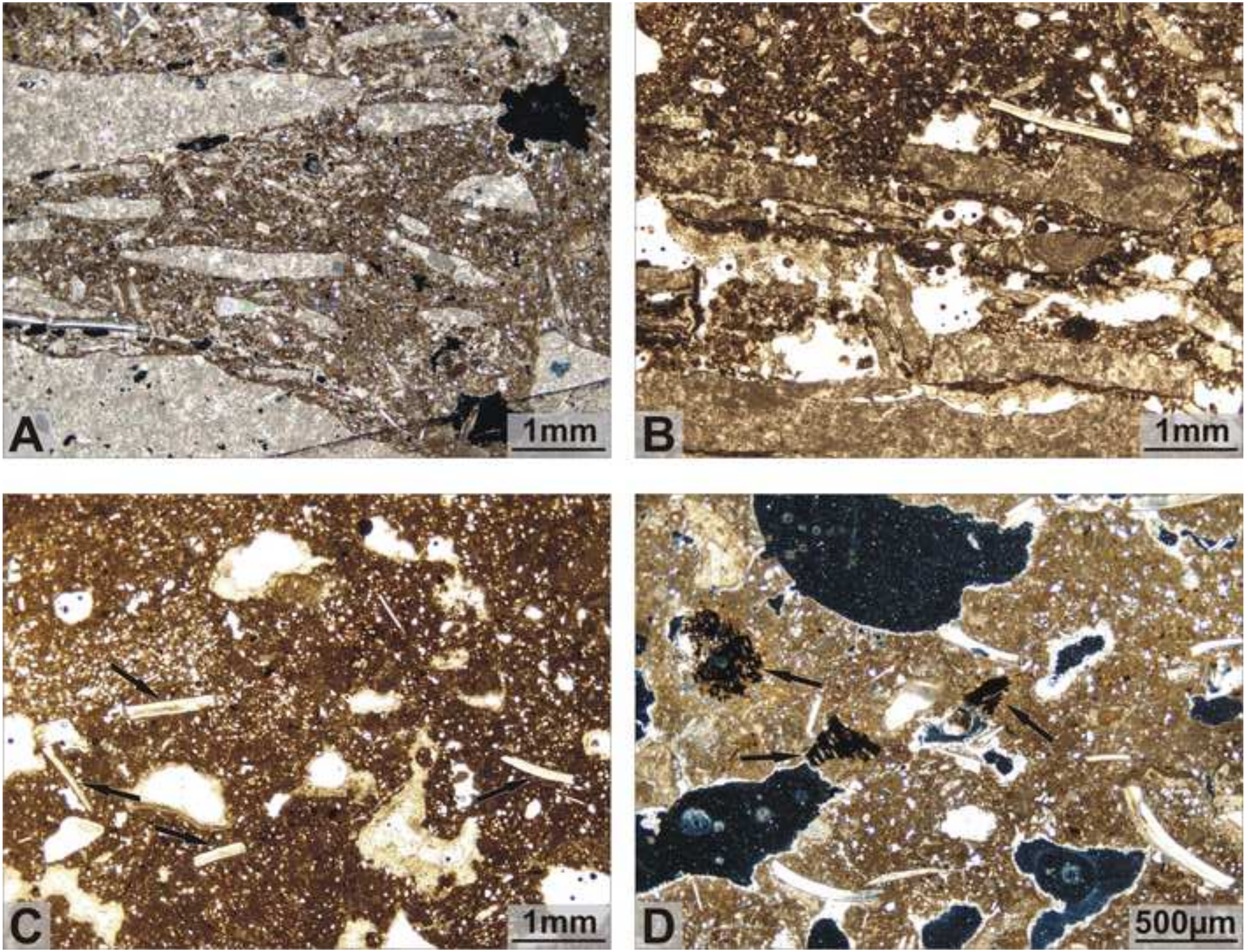

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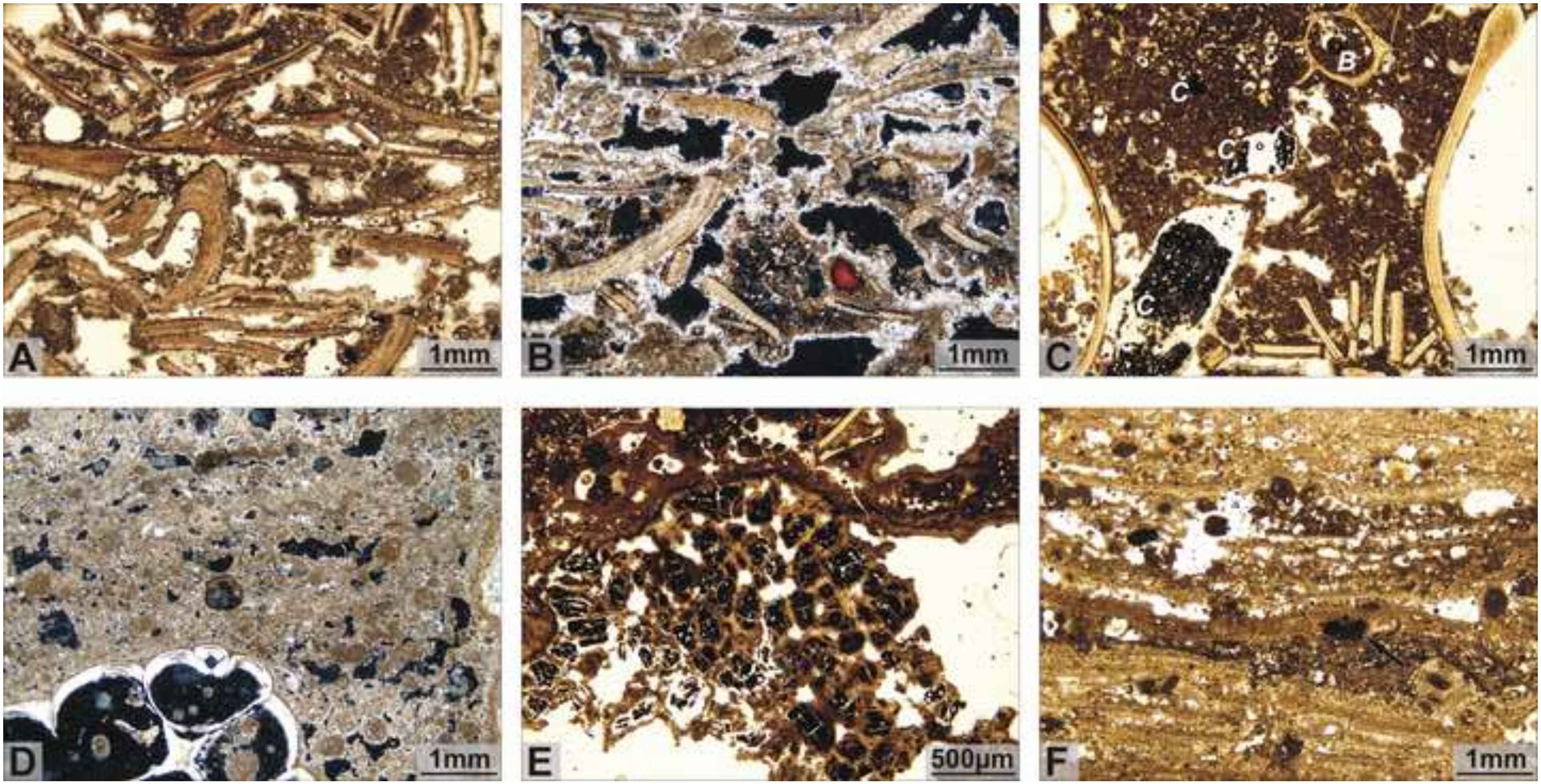

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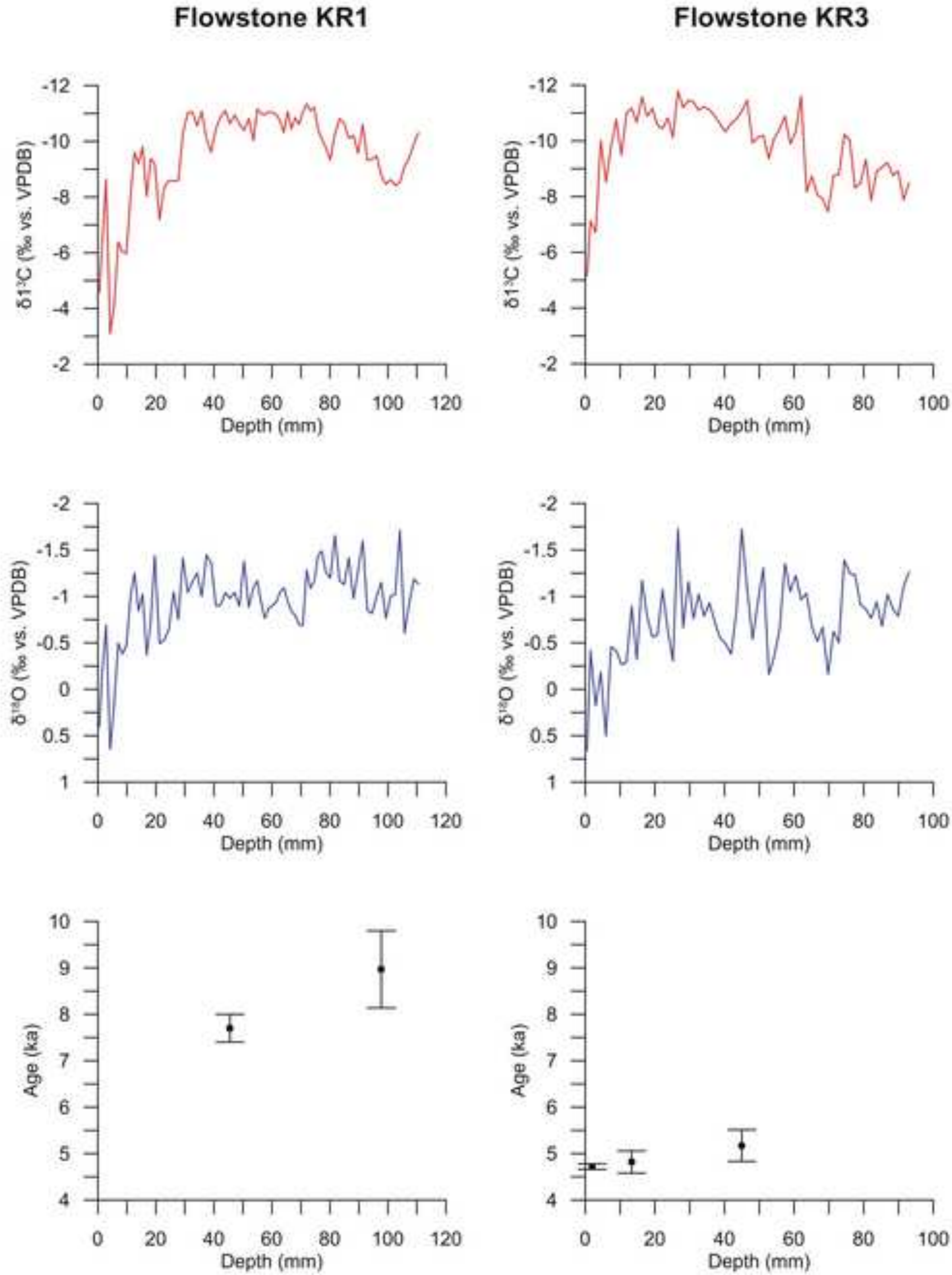

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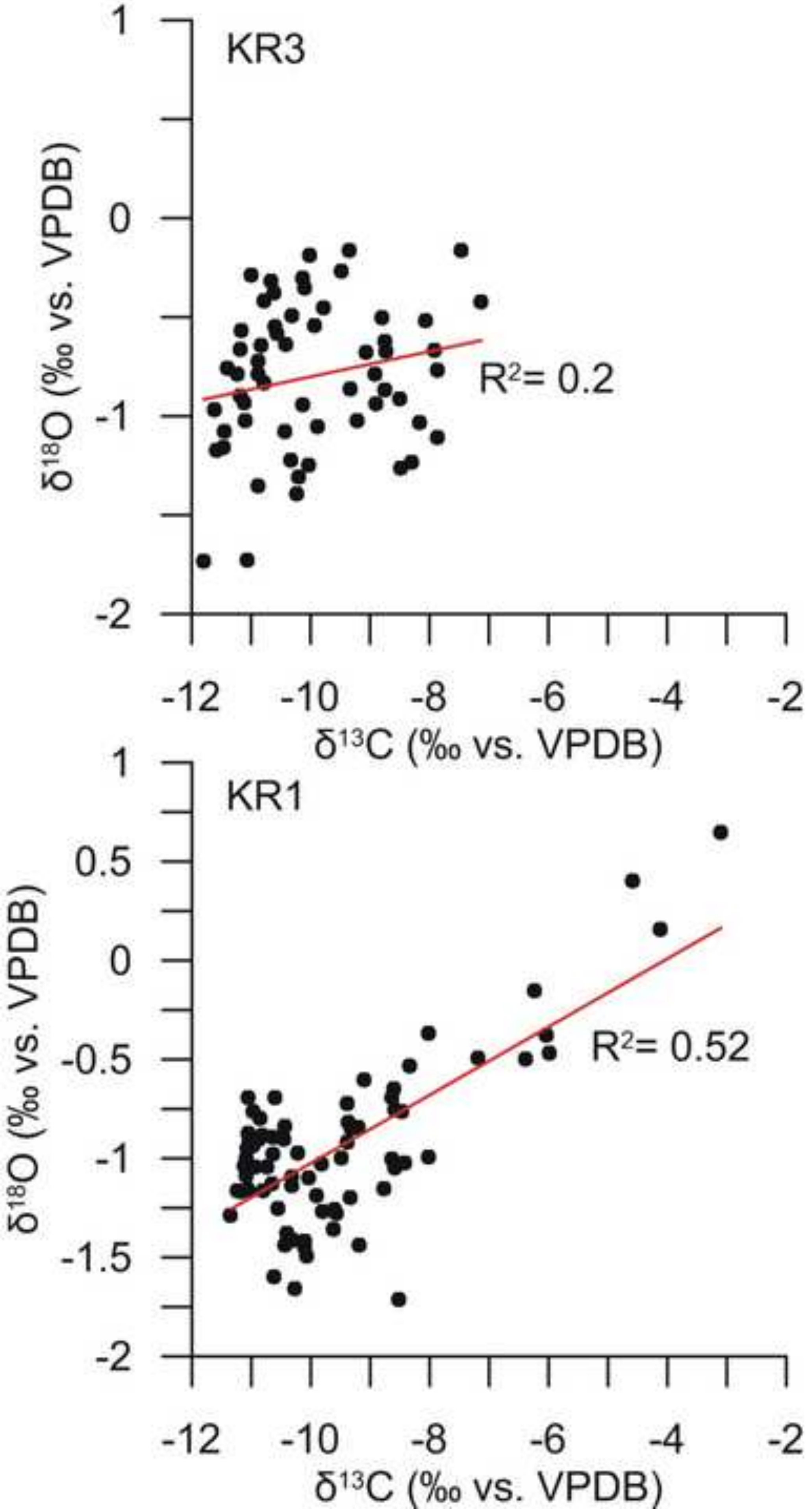

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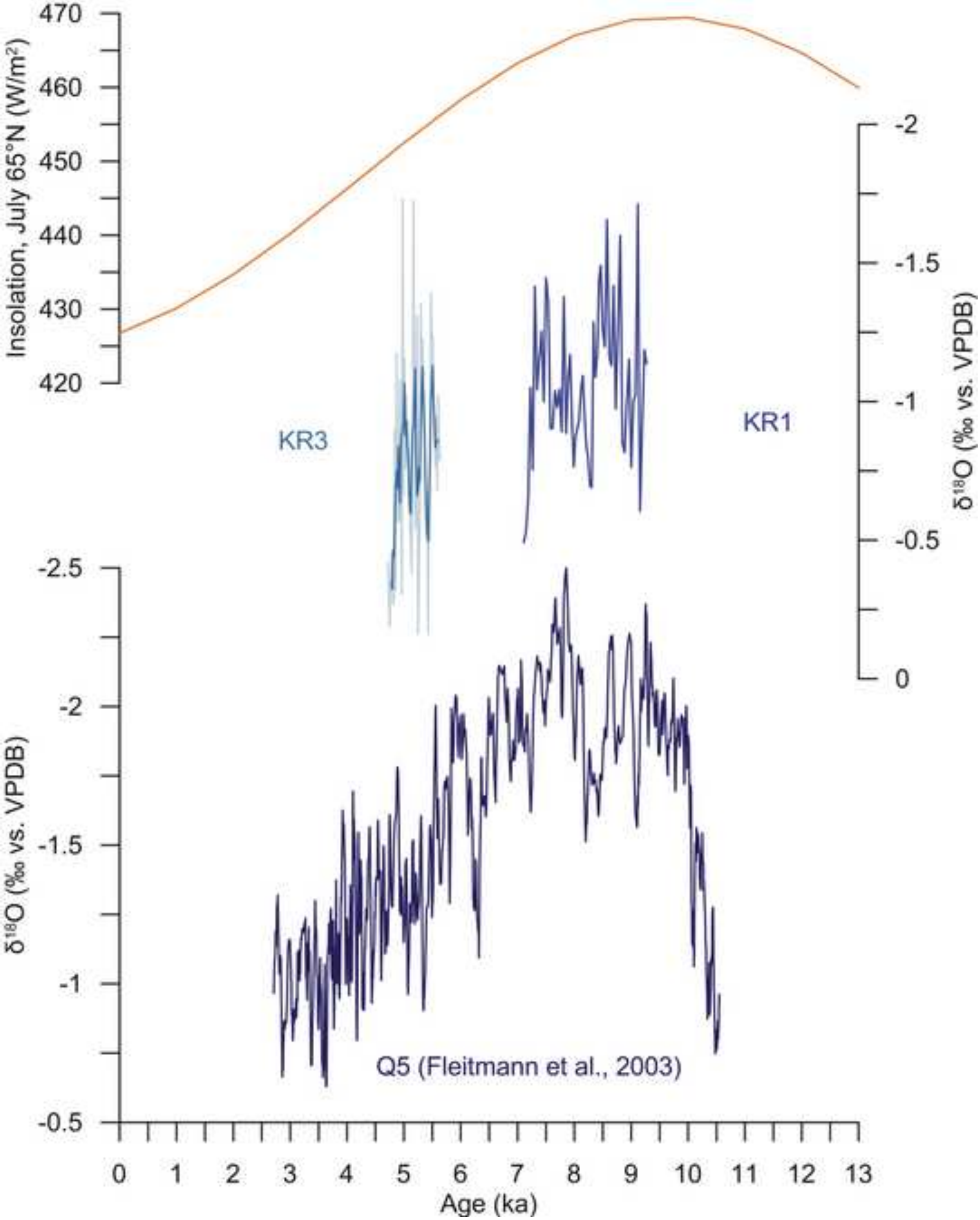

Table 1

Table 1. Results of conventional and AMS-^{14}C dating; calibrated age results are reported as years BC and BP. Calibration according to IntCal13 curve (Reimer et al., 2013).

Rock shelter	Unit	Lab.-code	AMS-^{12}C age (yr BP)	AMS-^{12}C age cal 2σ (yr cal BC)	(yr cal BP)
GQ-13/ 23	B	Poz-56575	10040±50	9848-9361	11798-11311
GQ-13/ 23	C	Poz-56576	9150±50	8536-8276	10486-10226
KR-213*	B	GX-24065	9130±290	9142-7601	11092-9551
GQ-13/ 23	C	Poz-56574	9010±50	8300-7984	10250-9934
KR-108*	B	GX-23159	8750±50	7965-7603	9915-9553
KR-213*	C	GX-2470-AMS	8720±60	7953-7597	9903-9547

*Radiocarbon dating from Cremaschi and Negrino (2005).

Table 2

Table 2. Essential micromorphological descriptions of samples representative for the four stratigraphic units composing the infilling of the rock shelters.

Unit	Field interpretation	Mineral consituents	Biogenic constituents	Porosity	Microstructure	b-fabric	c/f related distribution	Pedofeatures
A	Clast-supported angular breccia	Dominat angular fragments of limestone and scarce to common quartz and feldspar grains (sand size) in a silty-clayey micromass	–	Common packing voids and vughs	Intergrain microaggregate	Cristallittic	Gefuric to enaulic	Common micrite coatings on grains and microaggregates, scarce calcite pendent on rock fragments; few calcite nodules; few Fe-nodules; very few clay papulae
B	Matrix-supported angular breccia and loess	Common to scarse angular fragments of limestone, common silt-sized quartz grains and few sand-sized quartz grains in a clay micromass	Few to scarse fragments of shells, few concentrations of angual charcoal fragments; very few, small angular fragments of bone	Common vesicular voids, chanbers, and vughs; scarce channels	Spongy to crumb	Cristallittic	Spaced to open porphyric	Common micrite and sparite coatings on voids, scarce calcite pendent on rock fragments; scarce calcite nodules; groundmass impregnated by calcite; few Fe-nodules; very few rounded clay pedorelicts
C	Accumulation of land shells	Scarse quartz and feldspar grains and few subangular fragments of limestone in a silty-clayey matrix	Very abundant to abundant land snails and fragments; scarce to common angular charcoal fragments; few phytoliths; very few weathered vegetal remains; very few fragments of coprolites; shell fragments locally organized in thin horizontal layers with scarce matrix	Common chambers, channels and vughs; locally, packing voids	Crumb to spongy	Cristallittic	Double spaced porphyric; locally, close porphyric	Abundant micrite and sparite coating on crumbs and voids; scarde calcite nodules; groundmass locally impregnated by calcite; few excremental infillings; few Fe-nodules; very few rounded clay pedorelicts
Transition from C to D	Accumualtion of land shells to calcareous tufa	Alternating micritic and sparitic layers, including very few fragments of limestone and quartz grains	Common to scarse shell fragments; scarse angular charcoal fragments	Mostly fenestral voids; palnar voids	Laminated	Cristallittic	–	–

Table 3

Table 3. Results of U/Th dating on calcareous tufa samples KR1 and KR3. The activity ratios [^{230}Th/^{238}U] and [^{234}U/^{238}U] have been standardized to the HU-1 secular equilibrium standard. Ages were calculated using decay constants of 9.195x10^{-6} yr^{-1} (^{230}Th) and 2.835x10^{-6} yr^{-1} (^{234}U), and an assumed initial [^{230}Th/^{232}Th] of 1.5±1.5 except KK215-3B for which a value of 0.8 has been assumed. Depths are from the stalagmite tip, and numbers in brackets are the 95% uncertainties in the last digits given.

Sample ID	Depth (mm)	^{238}U (ng/g)	[^{234}U/^{238}U] (±95%)	[^{230}Th/^{238}U]*10^{3} (±95%)	[^{234}U/^{238}U]$_{initial}$ (±95%)	Age (ka)	Age corr. (ka)
KR3-B	1	348(1.4)	1.0684(0.0009)	4.78(0.6)	1.0695(0.0009)	4.999(0.064)	4.730(0.06)
KR3-E	13.3	-	1.0637(0.0039)	4.81(0.6)	1.0646(0.0040)	5.029(0.006)	4.820(0.24)
KR3-D	45	-	1.0645(0.0040)	5.25(0.4)	1.0664(0.0041)	5.495(0.046)	5.174(0.34)
KR1-E	45.5	-	1.0788(0.0039)	7.62(0.7)	1.0805(0.0040)	7955(0.075)	7.700(0.30)
KR1-A	97.7	272(20)	1.0820(0.0023)	9.31(0.8)	1.0841(0.0023)	9.770(0.09)	8.990(0.83)