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Paleoenvironment of Jawa basalt plateau, Jordan, inferred from calcite speleothems from a lava tube

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Abstract

This paper explores the environmental conditions that faced the people of ancient Jawa during the Holocene, as well as previous prehistoric periods of the mid-late Pleistocene. Calcite speleothems in a lava tube are dated using the U-Th method, to marine oxygen isotope stage 7 from ~250 to 240 ka and from ~230 to ~220 ka; and the stage 5/4 transition between ~80 and 70 ka. The available evidence indicates general aridity of the Black Desert during most of the mid-late Quaternary, punctuated by short wetter periods, when the Mediterranean cyclonic systems intensified and penetrated the north Arabian Desert. These Mediterranean systems had a longer and more intense effect on the desert fringe closer to the Mediterranean and only rarely penetrated the Black Desert of Jawa. The results do not exclude some increase of rainfall which did not change water availability dramatically during the warm Holocene. The ancient Jawa city appears to have depended on technological ability to build elaborate runoff-collection systems, which became the prime condition for success.

Keywords: Levant paleoclimate; Lava cave; Speleothem dating; North Arabian Desert; Early Bronze city

The enigma of Jawa

The late Chalcolithic-Bronze Age (4–3rd millennium BC) city of Jawa, nicknamed "lost city of the Black Desert," is a perplexity for many workers in the proto-history of the Levant (Betts and Helms, 1991; Helms, 1981). This relatively large settlement is located on the basalt plateau desert of Harrat Ash-Shaam (Fig. 1), within the Jordanian part of the north Arabian Desert.

Jawa city is much larger than contemporary sites in the Arabian Desert. During the excavations, Helms (1981) found that Jawa consisted of several layers of domestic architecture, retaining walls serving as defenses and a complex system of water collection and storage facilities (Fig. 2). According to Helms, Jawa had several occupation phases throughout the second half of the fourth millennium BC, with a minor phase of resettlement during the Middle Bronze Age. The principal phase of desertion occurred at the beginning of the 3rd millennium BC.

With modern annual precipitation of ~140 mm (Fig. 3) and no permanent water sources, sedentary human settlements are limited. Therefore, explaining the growth, flourishing and decline of Jawa has been a challenge for researches during the last decades. The resiliency of a human settlement in such an arid zone largely depends on its ability to store and use runoff, groundwater, or a combination of the two (Evenari et al., 1971). Helms (1981), performed hydrological calculations based on modern climatic conditions, and suggested that ancient Jawa inhabitants stored runoff water for whole year use. He based his assumptions on the present climatic conditions, as he had no indication of the paleoclimate of the region. On the other hand, another hypothesis (Issar and Zohar, 2007) claims that the flourishing of Jawa was accomplished due to a wet phase during the mid-Holocene, and its collapse was a response to drying climate. Indeed, a wetter Early Bronze climate, followed by desertification in other parts of the Levant has been indicated by several proxies, and suggested to be the driving force behind human prosperity and collapse, respectively (Bar-Matthews et

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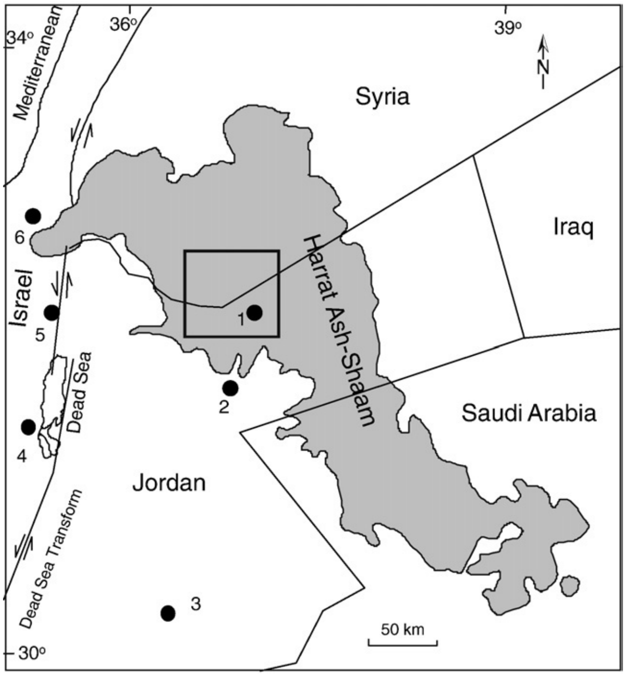

Figure 1. Location of the Black Desert study area (rectangle indicates Fig. 3) within the Harrat Ash-Shaam volcanic field of the western Levant. The surrounding white area is predominantly sedimentary plateau. Mentioned sites with paleoclimatic records: (1) Khsheifa Cave; (2) Azraq basin; (3) Qa' el-Jafr depression; (4) Kanaim Cave; (5) Ma'ale-Efrayim Cave; (6) Peqi'in Cave.

al., 1998; Cullen et al., 2000; deMenocal, 2001; Frumkin et al., 1994; Weiss and Bradley, 2001; Wilkinson, 1997), but this has not been studied until now in the north Arabian Desert.

The resilience of the agricultural systems on which the Jawa society probably depended (Helms, 1981), was vulnerable to climate change, because the city was built between the sown land and the desert where agricultural settlements spread during wetter periods and declined during drier ones. It is well known that negative feedback effects may drive the collapse in the peripheral regions. For example, continuous cultivation downgrades the soil's fertility and structure, which in turn fosters erosion. Such processes could have resulted from the natural increase in population, but a drastic climate change would heighten the vulnerability of human societies as well as of the natural system (Wilkinson, 1997).

The timing of humid events in this region is thus critical for understanding their impact on the Levant, the "cradle of civilization." Yet, paleoclimatic proxies are only sporadically available in an arid terrestrial environment like the Black Desert, which is also subject to a wide range of destructive processes.

In this paper we determine some climatic events in the Black Desert by ^{230}Th–U dating of calcite cave deposits (speleothems) from a lava tube in basalt. This allows us to infer the timing of the last moist events in the region, in which climate was considerably wetter than today. This may shed some light on the environmental conditions that faced the people of ancient Jawa during the mid-Holocene, as well as previous prehistoric periods of the mid-late Pleistocene.

Geology and geomorphology

The study is conducted within the Cenozoic volcanic field of Harrat Ash-Shaam (Fig. 1), which covers ~50,000 km^2 in Israel, Syria, Jordan and Saudi Arabia (Fig. 1) (Bender, 1974; Shaliv, 1991; Sharkov et al., 1994; Steinitz et al., 1978). The volcanic activity in this field within Jordan is dated to the Oligocene to early Miocene (26–22 Ma), middle to late Miocene (13–8 Ma), and late Miocene to recent (Camp and Roobol, 1992; Ilani et al., 2001; Moffat, 1988; Tarawneh et al., 2000).

The archaeological site of Jawa is located on flood basalts (Bender, 1974; Nawasra, 1997) dated to 3.47 + 0.04 Ma (Ilani et al., 2001; Tarawneh et al., 2000). Its surface is weathered and often covered with soils, comprising fluvio-eolian dust deposits and weathered basalt products. Highly indurated calcrete (caliche) layers have developed within the loess-type deposits, indicating leaching, translocation and accumulation of carbonates within the B horizon of the soil profile.

The Khsheifa Cave lava tube is located within the younger Jawa flow (Figs. 2, 3), dated by K–Ar to 0.46 + 0.01 Ma (HAS-7) (Ilani et al., 2001; Tarawneh et al., 2000). The Jawa

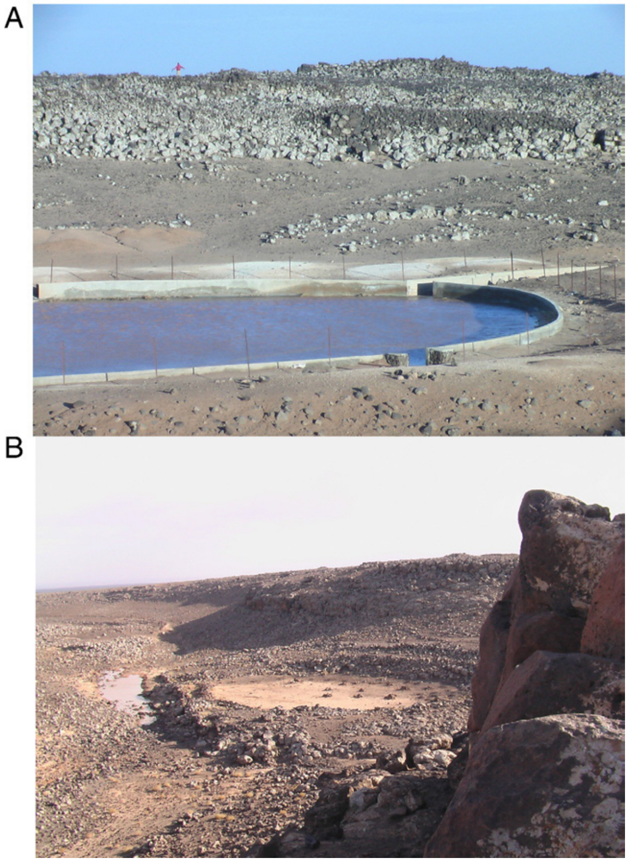

Figure 2. The Bronze-Age city of Jawa and its water systems: (A) The ruins of the city at the background of a recently renovated water-storage system, filled by runoff on February 2006. (B) The remains of a flood within Wadi Rajil (left), which dissects the Black Desert basalt plateau (background). An ancient water-storage pool (center) is partly filled with silt deposits. The eastern defense wall of Jawa (right), is built on the escarpment of Wadi Rajil.

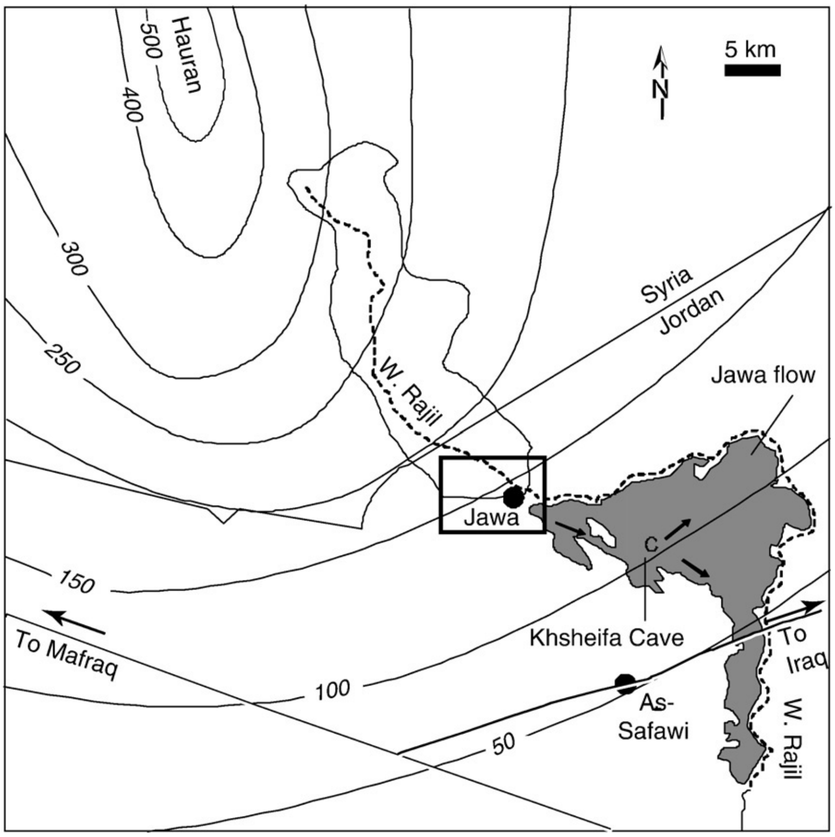

Figure 3. The volcanic Black Desert of the southern Hauran with isohyets (mm). The site of ancient Jawa is located west of the eruption point of Jawa lava flow, whose direction was along the prevailing topography gradient, deflecting Wadi Rajil to its margins. Arrows within Jawa lava flow indicate reconstructed directions of lava flow.

flow covers ~250 km^2 east and south east of Jawa site (Moffat, 1988; Nawasra, 1994).

Since its eruption, the Jawa flow basalt experienced only slight weathering, but its topographic depressions were locally covered by loess-type deposits. These comprise mainly eolian dust originating from the surrounding carbonate environments (Betts, 1998). Following eolian deposition, these sediments often experienced fluvial transport by runoff water. Locally they accumulate in semi-closed depressions forming mud-flats. These sediment-traps appear as distinct white patches on the background of the black basalt (Fig. 4A). Where the runoff water can escape laterally, the mud flats are periodically leached and suitable for cultivation, a practice which is still taking place today. Where water cannot escape laterally, it forms terminal intermittent lakes which evaporate quickly, giving rise to sabkhas (playas) which are useless for agriculture. Hard, roughly fractured basalt rock is exposed over Most of the Jawa flow surface (Fig. 4A).

Jawa is located above the bank of Wadi Rajil, whose ~300 km^2 catchment, upstream of Jawa, drains the south-eastern flanks of the Hauran (Jebel Druze), where the climate is dry Mediterranean to semi-arid (Fig. 3). Downstream of Jawa, Wadi Rajil flows along the northern and then eastern border of the Jawa basalt flow, which had diverted it from its original course. Ultimately, Wadi Rajil drains into the Azraq basin, the terminal base level of a large endoreic catchment which includes the Black Desert (Besançon and Sanlaville, 1988; Cane, 1992; Garrard et al., 1988).

Climate, environment, and water

The Black Desert is part of the north Arabian Desert, close to its boundary with the Syrian semi-arid steppe regions, which occupies the higher land to the north-west of Jawa (Fig. 3).

The Arabian Desert is the eastern part of the Saharo-Arabian Desert, which is influenced by two main climate systems. One is associated with polar fronts that originate in the northeast Atlantic Ocean, producing cyclones that pass over western Europe before reaching the Mediterranean Sea. These cyclones move eastwards above the warm Mediterranean Sea, which provides a secondary moisture source for winter rainfall. This rainfall mainly affects the north Arabian Desert (Enzel et al., 2008; Eshel, 2002). The second system originates in the Indian Ocean, and is manifested as the low latitude monsoon that mainly affects the southern parts of the Arabian Desert (Burns et al., 2001; Lézine et al., 1998; Neff et al., 2001).

During the Middle-Late Quaternary, the boundaries of the Arabian Desert have shifted, as demonstrated by several proxies. They indicate that wetter climate conditions prevailed during parts of the mid-late Quaternary. These humid episodes were associated with the migration of the Mediterranean and Indian Ocean systems (Almogi-Labin et al., 1998; Burns et al.,

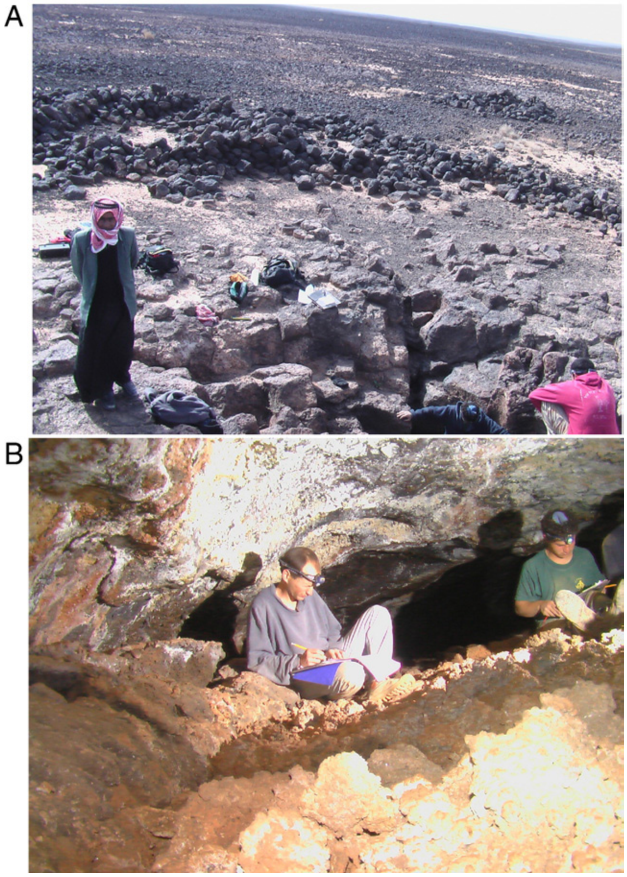

Figure 4. The Jawa basalt flow of the Black Desert: (A) The rugged lava surface covered locally with patches of loess (background). The main entrance into Khsheifa Cave, being entered during the study is at the bottom right. (B) The survey of the downstream part of Khsheifa lava tube. The bottom comprises rugged aa-type basalt of the last lava that flowed within the cave and filled the tube up to its ceiling further downstream. A lava bench on the left is a relict of a previous lava flow within the cave.

2003; Huckriede and Weisemann, 1968; Petit-Maire et al., 2002; Whitney, 1982), allowing some pluvial deposits to develop during the late Quaternary in Saudi Arabia (McClure, 1976; Whitney, 1982). Information on the past climates in the north Arabian Desert is very limited, however. Preliminary data from sediments in terminal depressions of the Jordan desert plateau, east of the Dead Sea transform, seem to indicate that moister conditions occurred mainly within interglacial periods and possibly also during some episodes within glacial periods (Abed et al., 2000; Besançon and Sanlaville, 1988; Cane, 1992; Davies, 2005; Garrard et al., 1988; Huckriede and Weisemann, 1968; Petit-Maire et al., 2002).

Present precipitation at the site of Jawa (Fig. 3) is below the amount needed for the dry farming of cereals (Kennedy, 1995; Sherratt, 1980). The precipitation is predominantly from a Mediterranean source, and it falls during the cool winter, while the summer is dry and hot. There is a large range of temperatures, both daily and yearly. Vegetation is Saharo-Arabian to Irano-Turanian, with severe impact of grazing. The basalt surfaces are almost devoid of vegetation (Fig. 4A), except for the wadi stream-beds and a short blooming spring period on the plateaus. The predominant form of land-use today is pastoralism of mixed goat/sheep/camel, with hardly any agriculture. The semi-settled Bedouin practice some casual agriculture in soil patches and mud-flats, visiting their barley "fields" during harvest time in the hope of finding some crops if rainfall was enough. These limited areas have played a life-supporting part for the Bedouin population (Helms, 1981).

In the vicinity of Jawa there are no springs or perennial streams today, and there is no shallow ground water aquifer that could be reached by wells. Under such conditions, a significant run of dry years would have resulted in considerable production deficits which in turn could cause collapse (Wilkinson, 1997). Carbonate speleothems in limestone karst caves are good proxies for dating humid periods in presently arid regions, because they are deposited above annual precipitation, and they are easily dated (Holmgren et al., 1994; Vaks et al., 2003; 2006). Naturally, the volcanic Black Desert contains no limestone caves. Here we use, for the first time, calcite speleothems deposited within a lava tube as indicators of wet episodes. The speleothems must be younger than the ~460,000 ka old basalt country rock; thus they are within the limit of the U–Th dating method. This is a great advantage in the Levant deserts, where most speleothem deposition occurred beyond the limit of U–Th dating (Fleitmann et al., 2004; Vaks et al., 2007).

Methods

Field survey, local help, remotely sensed images and air photographs were used to locate caves in the Black Desert. The largest one, Khsheifa Cave, was surveyed and its morphology and speleothems were recorded, using a laser distance meter (Disto), hand-held inclinometer, and compass.

Broken speleothems from the cave were sampled and sectioned using a diamond saw to expose their internal structure and to eliminate diagenetically altered samples. In addition, calcrete from the surface was sampled in two sites. The chemical composition was determined using Perkin Elmer Sciex ICP-MS Elan 6000 for U, Th and Pb, and Optima 3300 ICP-EAS for other elements (Supplemental material table).

For dating purposes up to 1 g material was drilled using 0.8–4 mm drill bits along the growth axis. ~0.3 g of calcite powder was dissolved in 7 N HNO_3 and ^{236}U–^{229}Th Harwell spike was added prior to U and Th purification. The sample was loaded onto mini-columns that contained 2 mlBio-Rad AG 1X8 200–400 mesh resin. The evaporated U was eluted by 1 N HBr and Th with 6 N HCl. Afterwards the U and Th solutions were evaporated to dryness and dissolved in 2 ml and 5 ml of 0.1 N HNO_3, respectively.

^{230}Th–U dating was performed using Nu Instruments Ltd (UK) MC-ICP-MS equipped with twelve Faraday counters and three ion counters. The sample was introduced to the MC-ICP-MS through an Aridus® micro-concentric desolvating nebuliser sample introducting system. The instrumental mass bias was corrected (using exponential equation) by measuring the ^{238}U/^{235}U ratio and correcting with the natural ^{238}U/^{235}U. The calibration of the ion-counters relatively to the Faraday cups was performed using several cycles of measurements with different collector configurations in each particular analysis.

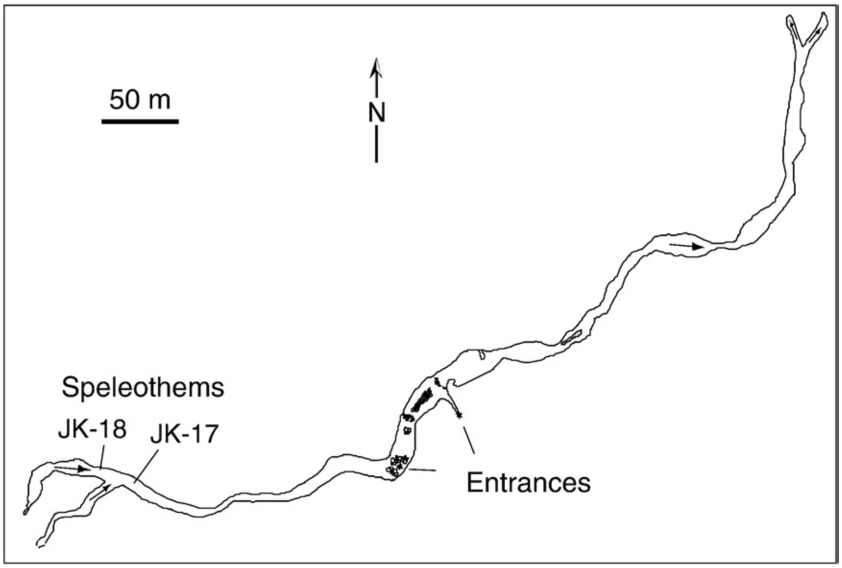

Figure 5. A map of Khsheifa Cave lava tube with sampling sites of speleothems. Lava flow direction had been from lower left to upper right.

The age determination was possible due to the accurate determination of ^{234}U and ^{230}Th concentrations by isotope dilution analysis using the ^{236}U–^{229}Th spike. $^{230}Th/U$ ages were not corrected for detrital ^{230}Th because the $^{230}Th/^{232}Th$ activity ratio was higher than 40.

Results

Khsheifa Cave

The study was performed mainly in Khsheifa Cave, a 920 m long lava tube system (Fig. 5), which was first mentioned by Helms (1981, p.138). Lava tubes are well shielded against surface processes, so they can serve as potential repositories for preserving paleoenvironmental records (Greeley and Hyde, 1972; Halliday, 2004; Waters et al., 1990; Witter and Harris, 2007). Lava tubes are common in the volcanic fields of Saudi Arabia (Pint, 2006), and have been previously observed in Jordan (Helms, 1981; Kempe and Al-Malabeh, 2005).

The lava flow direction in Khsheifa Cave is eastward and northward, observed through a ~1% downstream gradient and pahoehoe (Waters et al., 1990) flow structure. Increasing vesiculation and turbulence changed the flow from pahoehoe to spiny aa-type, bubble-filled ragged surface downstream (Fig. 4B). Two small entrances lead into the central part of a 920 m long tube, allowing human entry to both the upstream (in terms of lava flow direction) and downstream portions of the cave. Following the formation of the entrances, the cave has been widely used by Striped Hyaena (*Hyaena hyaena syriaca*), indicated by bones, coprolites and dens.

Fluvio-eolian deposits are currently swept into the cave during storm-runoff events, covering partially the bottom of both the upstream and downstream parts of the lava tube. On February 2006 we observed the aftermath of a runoff flood event which entered the western entrance, reaching 100 m in the downstream portion, and 70 m in the upstream portion, along the modern gradient of the washed-in sediments covering the cave bottom. The flood water gradually infiltrated along these two routes, eventually disappearing into the cave bottom. Disappearing flood water flow is a common feature of desert caves with ephemeral streams (Frumkin, 1994). We found no indication that the cave was ever used for artificial water storage, a possibility raised by Helms (1981, p.138).

Speleothems and dating

Infiltration of rainfall from the surface is observed in various seepage points along the cave ceiling. Long term seepage has deposited calcite speleothems at the upstream portion of the cave (Fig. 6A). Calcite speleothems in lava tubes are rare, even if the seeping water contains high amounts of CO_2, mainly because the concentration of calcium ions in seeping water is sparse. Such karstic speleothems are best developed under humid conditions where carbonate sediments cover the basalt (Kashima and Suh, 1984; Kashima et al., 1989; Kyung-Sik et al., 2004; Woo et al., 2000). Due to preservation issues, and because speleothems are not common in the cave and the region, only parts of two broken stalactites were dated: JK-17 and JK-18 (Figs. 6B, C). The thickness of the stalactites is 1–3 cm (Fig. 6). The stalactites are composed of columnar low-magnesium calcite crystals (less than 1.4% Mg, Supplemental material table) with laminated texture. Thin white laminae cutting through the brownish crystals are composed of dark, opaque, slightly corroded and porous calcite crystals, sometimes rich with detritus, indicating hiatuses.

The outer surface is slightly weathered, indicating a recent long period of non-deposition with some condensation of aggressive humidity (Fig. 6A). Condensation is indeed observed today on the cool rock surfaces of the cave. ^{230}Th–U dating was performed on three laminae of stalactite JK-17 and on three laminae of stalactite JK-18. The ^{230}Th–U ages (Table 1) show three main depositional events: (1) between ~250 and 240 ka; (2) between ~230 and and 220 ka; (3) between ~80 and 70 ka. The youngest lamina (A) of JK-17 was too rich in detritus ($^{230}Th/^{232}Th$ is 3.4) to yield an indicative age (Table 1 and Supplemental material table). None of the individual speleothems grew throughout the entire time span. No Holocene deposition was observed.

Calcrete layers covering the basalt surface have been sampled at the north edge of Jawa flow. The attempt to date two samples (JK-1-1 and JK-1-2) was unsuccessful, due to high detrital content, demonstrated by $^{230}Th/^{232}Th$ values of 1.2 and 1.3 respectively (Supplemental data table and Table 1).

Discussion

Moist episodes in the black desert

Abundant carbonate minerals in fluvio-eolian dust deposits, calcrete and some speleothems indicate that potential dissolution and re-deposition of carbonate minerals can occur in this environment. The limiting factor for speleothem deposition in deserts is precipitation/evaporation ratio (Vaks et al., 2003, 2006, 2007).Water in essential, both directly as the dissolving/depositing agent, and indirectly as the main factor controlling vegetation which supplies the CO_2 necessary for calcium-carbonate dissolution. Excessive water which is not readily evaporated can sustain natural vegetation and agriculture, as well as some infiltration into the vadose zone. The observed speleothem deposition, although being scarce, can serve as preliminary indication of moister periods in the Black Desert.

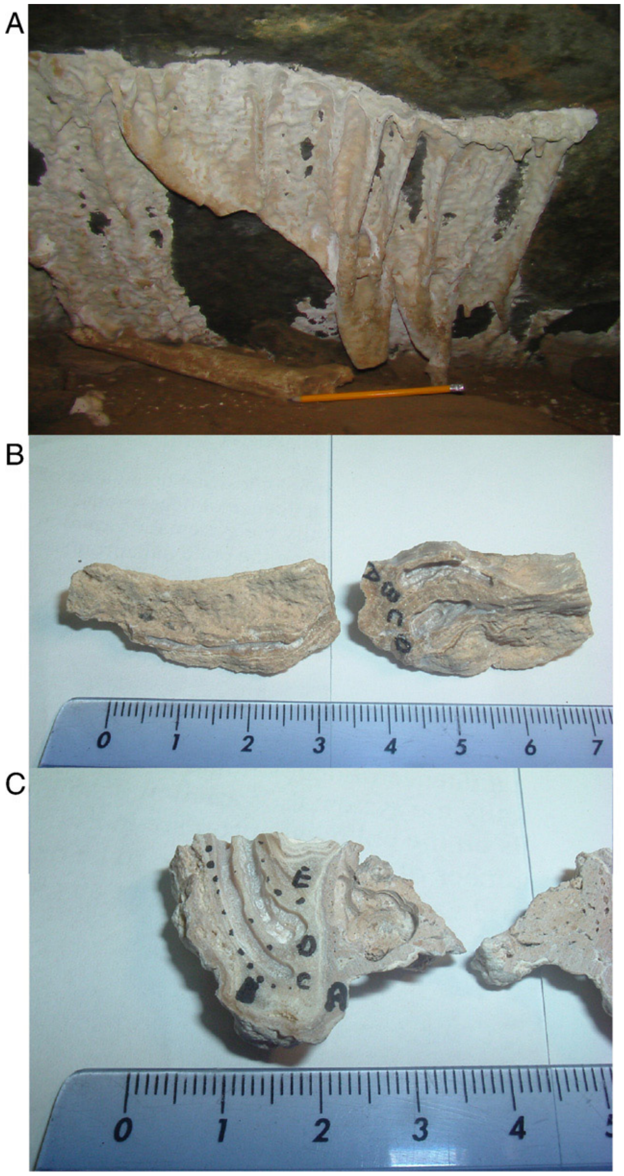

Figure 6. Calcite speleothems of Khsheifa Cave lava tube: (A) General view of speleothems, deposited from a fracture in the basalt roof. Note pencil for scale. (B) K-18 with dated laminae. (C) K-17 with dated laminae.

The recorded moist episodes at Khsheifa Cave occurred during marine oxygen isotope stage 7 (MIS 7) and during the stage 5/4 transition. These episodes seem to fall within pluvial events indicated by sediments of the Azraq basin (Besançon and Sanlaville, 1988; Cane, 1992). However, the Azraq record has yet to be more rigorously studied and precisely dated. The moist period during the MIS 5/4 transition at Khsheifa Cave occurs at the end of the Eemian pluvial stage in Mudawwara depression, southernmost Jordan (Abed et al., 2000; Petit-Maire et al., 2002). No correlation is observed between Khsheifa Cave speleothems and sediments of the Qa' el-Jafr depression in southern Jordan (Davies, 2005; Huckriede and Weisemann, 1968). This indicates that the paleoclimatic history of northern Jordan does not resemble the southern part of the country. A similar north–south contradiction is observed in Israel (Vaks et al., 2007), and it agrees with the present-day north–south climatic gradient which is associated with regional circulation and the location of the south Mediterranean shoreline (Enzel et al., 2008).

The Khsheifa record can be better compared with paleoclimatic records on a west–east transect, the main direction of cyclonic activity bringing rain from the Mediterranean. A comparison along this line with the Dead Sea catchment is relatively robust, because hundreds of radiometric dates and detailed paleoclimatic records have been published for the Israeli side of the transform.

During the MIS 5/4 transition a major wet phase initiated in the Dead Sea catchment, demonstrated by the initial rising of Lake Lisan (Bartov et al., 2002; Lisker, 2007; Haase-Schramm et al., 2004) and the initiation of speleothem deposition after a long hiatus in the rain-shadow desert of Israel (Vaks, 2007; Vaks et al., 2003). The situation during MIS 7 is less clear due to smaller sampling and larger error margins, but MIS 7 depositional periods also seem to be coeval at the rain-shadow desert of Israel and Khsheifa Cave.

The observed depositional episodes in Jawa during the last 300 ka are compared in Figure 7 with speleothem depositional periods at Ma'ale-Efrayim and Kanaim caves at the rain-shadow desert in Israel (Vaks, 2007; Vaks et al., 2003). The rain-shadow sites represent periods of increased moisture from the Mediterranean source in the west. The depositional periods in Khsheifa Cave fall within (or very close to) these of the rain-shadow desert, indicating a similar moisture source.

Situated closer to the precipitation sources, the Israeli caves demonstrate more intensive speleothem deposition, albeit intermittent. The relatively short duration of the Khsheifa episodes,

Table 1
U–Th dating of calcite from the Jawa Region

Sample number	Type of sample	^{238}U (ppm)	±1σ	^{234}U/^{238}U	±1σ	^{230}Th/^{234}U	±1σ	^{230}Th (ppb)	^{232}Th (ppb)	^{230}Th/^{232}Th	Age (ka)	±2σ
JK-17-A	Stalactite lamina	2.7001	0.0026	1.1590	0.0017	0.5944	0.0022	0.0303	1676.80	3.39	Too high detrital Th	
JK-17-C	Stalactite lamina	1.3782	0.0013	1.0811	0.0019	0.8911	0.0031	0.0216	16.88	240.88	225.3	5.6
JK-17-D	Stalactite lamina	1.0962	0.0008	1.0744	0.0014	0.9101	0.0039	0.0175	14.04	233.91	243.2	7.9
JK-18-A	Stalactite lamina	0.3722	0.0002	1.1522	0.0017	0.5178	0.0023	0.0036	16.21	42.15	77.8	1.0
JK-18-B	Stalactite lamina	0.5516	0.0004	1.1605	0.0015	0.4927	0.0027	0.0051	12.73	76.24	72.4	1.1
JK-18-D	Stalactite lamina	0.9666	0.0007	1.1346	0.0010	0.5207	0.0022	0.0093	17.26	101.44	78.5	1.0
JK-1-1	Calcrete	0.7885	0.0005	1.0973	0.0007	0.6335	0.0019	0.0089	1290.70	1.30	Too high detrital Th	
JK-1-2	Calcrete	0.7683	0.0004	1.0802	0.0009	0.7403	0.0031	0.0100	1594.79	1.18	Too high detrital Th	

compared with speleothem deposition periods of the rain-shadow desert caves of Israel, is in agreement with the rare penetration of precipitation into the north Arabian Desert today.

Figure 8 displays a section of speleothem depositional periods across the Middle East, from the Mediterranean to the Indian Ocean. Close to the Mediterranean shore the conditions were relatively wet throughout (at least) the last 250 ka, demonstrated by continuous deposition in Peqi'in Cave (Bar-Matthews et al., 2003). Moving towards the north Arabian Desert, the transgression of precipitation into the desert was increasingly limited in time, as observed by shorter deposition periods towards the south east: deposition periods at the rain-shadow desert are long-lasting, covering the entire two last glacial periods; Khsheifa Cave had only short, rare deposition episodes, while no deposition have been recorded at Star and Broken-Leg caves, north Arabian Desert. This corroborates that the core of the Arabian Desert persisted as an arid belt during (at least) the last 300 ka, although the Arabian caves had significant speleothem deposition earlier than 300 ka (Fleitmann et al., 2004). Nevertheless, Khsheifa Cave always remained close to the north-eastern boundary of the Arabian Desert, so it enjoyed short intermittent invasions of wetter episodes. These were probably associated with Mediterranean cyclone systems which pass over the warm eastern Mediterranean Sea. The warm sea water provides a moisture source for winter rainfall over the Levant, penetrating sometimes into the north Arabian Desert.

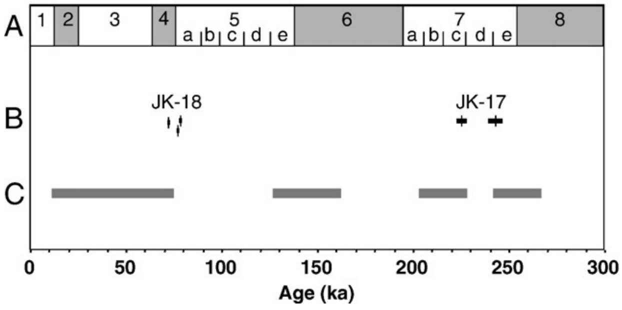

Figure 7. Periods of speleothem deposition determined by U–Th dating. Vertical axis compares three records: (A) Marine Isotopic Stages; (B) Khsheifa Cave dates, present study (JK-17 and JK-18), vertical line with error bars defines each individual age measurement; (C) Bars indicate deposition periods at the rain-shadow desert of Israel, The combined record of Ma'ale-Efrayim (Vaks et al., 2003) and Kanaim caves (Vaks, 2007).

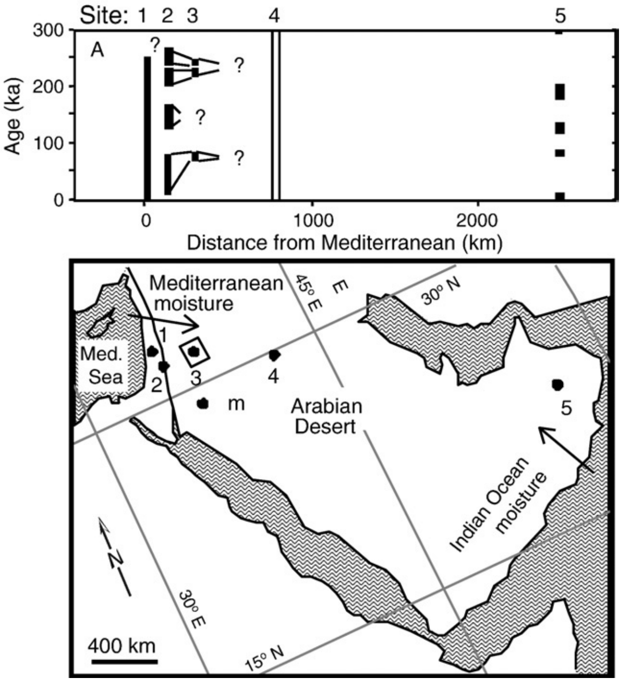

Figure 8. Speleothem deposition at cave sites across the Middle East during the last 300 ka: 1. Peqi'in Cave, northern Israel, (Bar-Matthews et al., 2003); 2. The combined record of Ma'ale-Efrayim (Vaks et al., 2003) and Kanaim caves (Vaks, 2007) (For precise location see Fig. 1); 3. Khsheifa Cave, Jordan, present study (rectangle indicates Fig. 3); 4. Star and Broken-Leg caves, Saudi Arabia, North Arabian Desert, (Fleitmann et al., 2004); 5. Hoti Cave, Oman, south Arabian Desert (Burns et al., 2001; Fleitmann et al., 2003). (A) Periods of deposition at each site, determined by U–Th dating, generalized as black bars. No deposition is observed at site 4. (B) Map showing the cave sites and main moisture sources (arrows). During the last 300 ka both Mediterranean and Indian Ocean precipitation has not invaded the central-north Arabian Desert, as indicated by the lack of recorded speleothem deposition at Star and Broken-Leg caves. Mudawwara depression paleo-lake is also indicated (m).

This penetration is limited, however, due to the desert high-pressure zone and location of the south Mediterranean coastline, juxtaposing Star and Broken-Leg caves within a permanent desert during the last 300 ka.

As the Arabian Desert has been arid during most of the mid-late Quaternary, it could supply the dust that settled on Jawa lava flow, bringing about calcium-carbonate available for dissolution and redeposition in the Khsheifa lava tube.

The depositional periods at Oman, within the south Arabian Desert are almost all chronologically distinct from the wet periods of the north Arabian Desert. This corroborates that the southern Arabian Desert received its moisture from the monsoon system of the Indian Ocean (Burns et al., 2003), unlike the north-west part of the Arabian Desert.

Implications for Jawa

The lack of speleothems during the latest Pleistocene and Holocene allows some general inference on the environmental background of ancient Jawa. The availability of carbonate dust for dissolution and redeposition increases with time. Therefore the cessation of speleothem deposition during the late Pleistocene can be attributed only to deficit of water. During the Holocene the increased heat and associated evaporation must have enhanced the aridity. The Holocene at the north Arabian Desert, including Jawa, must have been generally arid, with probable small periodical fluctuations. Even more important for human settlement, is the fact that desert precipitation fluctuates considerably from year to year, and healthy agriculture depends on an adequate *minimum,* not a seemingly attractive *average.* The rainfall also comes in brief periods and is often torrential, giving insufficient time for it to percolate into the soil. Nevertheless, agriculture is still practiced around (mainly to the west of) Jawa today, without irrigation. The abundance of seed-processing tools in ancient Jawa (Helms, 1981) suggests that agriculture played an important role in the food economy of the city. Dry farming was probably widely practiced, but some irrigation using runoff harvesting and gravity canals cannot be ruled out too, as shown for later periods in the Negev Desert (Evenari et al., 1971; Helms, 1981).

Under the prevailing arid climate, water storage was essential to enable human settlements to subsist in ancient Jawa. Utilizing local water-harvesting from micro-catchments combined with partial deflection of floodwater from Wadi Rajil became the key to successful urbanization, regardless of climate change.

Conclusion

The speleothems reported here are the first ones dated to the last 300 ka from the north Arabian Desert. They were deposited during MIS 7 and the MIS 5/4 transition, and additional dating might add some short depositional periods. However, the scarcity of speleothems indicates that the paleoclimatic framework of the north Arabian Desert is unlikely to change dramatically with additional sampling and dating. The Holocene, as well as most of the late Pleistocene, were too arid for speleothem deposition in Jawa region.

We thus conclude that the late Chalcolithic–Bronze Age urban center of Jawa depended mainly on its elaborate systems of runoff control and water storage. The sophisticated ancient systems that have been found in association with the city (Helms, 1981; Sherratt, 1980) allowed the city to thrive even though the climate was not considerably wetter than today. The ephemeral Wadi Rajil carries more than enough runoff in the aftermath of upstream winter rainstorms. This was supplemented by local runoff water, collected from micro-catchments. The short-lived winter surplus could thus be used to supply both reservoirs and fields and allow Jawa to flourish. The destruction of the city probably had additional causes apart from some climatic deterioration.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.yqres.2008.06.004.

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