Arid hypogene karst in a multi-aquifer system: hydrogeology and speleogenesis of Ashalim Cave, Negev Desert, Israel

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Abstract: Ashalim maze cave, and neighbouring caves in the NW Negev Desert, Israel demonstrate hypogene karst features. These features are shown to have developed as a result of the mixing of two types of groundwater flowing in opposite directions within two tiers of Cretaceous rock aquifers. The stable isotope composition indicates that the lower Kurnub sandstone aquifer was recharged over far-field Nubian Sandstone outcrops in the vicinity of the Precambrian basement outcrops of the Sinai Desert, which belongs to the Afro-Arabian dome. The water flows northward and rises into the Judea carbonate aquifer through deep faults. A similar hydrogeological system is inferred for the speleogenetic period of Ashalim Cave. Dewatering of the cave occurred in the Pliocene due to regional uplift. This is indicated by the first vadose speleothems, dated to the late Pliocene (3.1 Ma). This was followed by surface denudation, which breached the cave and formed the present entrance.

Water scarcity is the main constraint on karstification in arid regions. The study of relict hypogene karst within desert regions will lead to a better understanding of the palaeohydrology and palaeoclimate of such regions. The present study tackles this issue, addressing the effects of converging tiered aquifers which are recharged in remote outcrops.

The Negev and Sinai deserts are part of the Saharo-Arabian Desert, the largest desert on Earth. Several hypogene features have been observed by our team in the Negev Desert, among which is Ashalim Cave, the largest known cave in the NW Negev (Fig. 1). The Cretaceous rock sequence in the Negev consists of Lower Cretaceous sandstones, carbonates and marls (Kurnub Group), Cenomanian–Turonian carbonates and marls (Judea Group) and Senonian chalk, chert and marls (Mount Scopus Group). Most of the Negev caves are within late Cretaceous, Cenomanian–Turonian carbonates. Eocene limestones (Avedat Group) contain additional karst features, such as unconfined chamber caves.

Ashalim Cave is located on the flank of Boqer Ridge, a moderate limestone hill 370 m above sea-level, drained through Nahal (wadi) Besor to the Mediterranean. This region of the Negev is relatively rich in small caves located within Turonian limestone of the upper Judea Group. The regional structure is marked by NE-trending anticlines, forming topographic ridges separated by synclinal valleys (Fig. 2).

Some of these structures are associated with faults, most of which are buried (Weinberger & Rosenthal 1994) (Fig. 2). In addition, the Zin transverse fault (Bartov *et al.* 1976), which is the northernmost east–west-trending fault of the Negev Desert, apparently runs in the subsurface not far from the cave.

Rainfall is highly variable, with a mean annual amount of *c.* 110 mm; the rainy period is October to May. The vegetation is concentrated mainly along ephemeral stream beds and consists of sparse steppe and desert plants of C3 and C4 photosynthesis pathways. Few ligneous perennial shrubs are scattered on the limestone hill above the cave (Fig. 3), but annual plants are abundant after rain storms.

Cave morphology

Ashalim Cave is a three-dimensional maze of interconnected passages and chambers with a total length of 570 m and a depth of 31 m. The cave's single entrance opens subvertically at a mild limestone slope without evidence of water flowing intensively into the cave, except for tiny flows from the immediate surroundings. Colluvial sediments have accumulated through the shaft-like entrance in recent times (Holocene?).

The cave entrance shows no genetic connection with the surface. It was apparently opened when subaerial denudation breached the ceiling of chamber A. This must have occurred >6000 years ago, because at this time the cave was already used by humans as a burial site (Cohen 1971; Yalalom-Mack *et al.* 2015). The entrance chamber (A) is the largest in the cave (Fig. 4). At its bottom, a smaller

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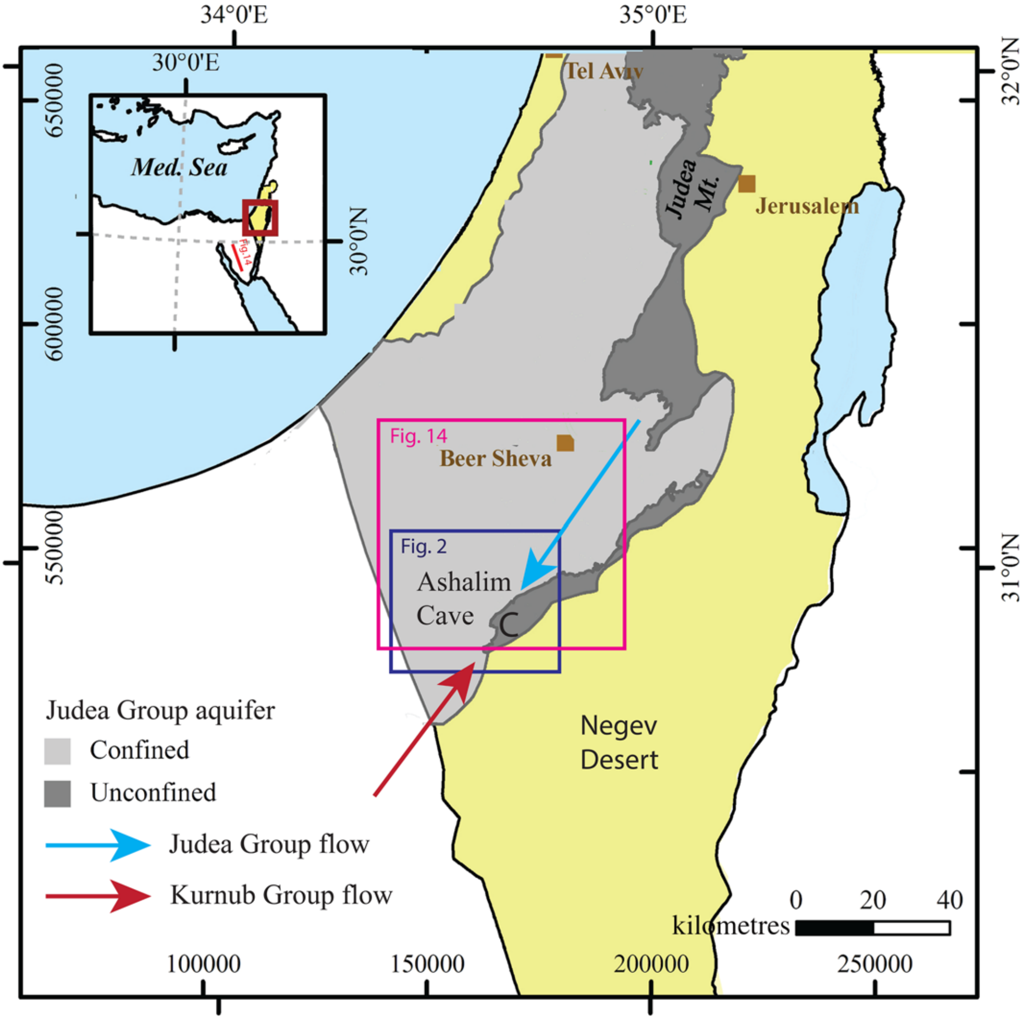

Fig. 1. Location map showing Ashalim Cave in the NW Negev Desert, Israel, at the confluence of the aquifers of the Judea Group and Kurnub Group. For stratigraphic sections see Figures 14 and 16.

passage (B) leads towards a speleothem-rich chamber (C), followed by narrow passages leading downwards to the lowermost level of the cave, where the main 110 m long lower passage (D–E–F) extends to the NW and SE (Fig. 5).

The inner parts of the cave can be reached from point Dc of this passage and include several medium-sized chambers (E, H, I, J, K and L) connected by narrow passages. The lower passage, D–F, developed along the bottom of a NW-trending oblique fracture that possibly acted as a fault. This fracture is the backbone of the three-dimensional maze of the cave.

The solutional micromorphology of the cave includes smooth walls, elliptical cross-sections of passages, cupolas (Fig. 6) and solution pockets in the walls and ceilings (Fig. 7). Corroded bubble trails are observed at some points along overhanging walls (Fig. 8). No evidence was found for fast-flowing water (such as scallops or clastic fluvial sediments).

The morphology of the cave indicates that water intruded the cave during speleogenesis through a fracture, which is hardly accessible at the bottom of the cave (bottom of passage D–F). From there the cave developed upwards through the oblique fracture, forming a sloping three-dimensional maze, divided to several tiers of sub-horizontal passages. The cross-section of the main passages is often elliptic or asymmetrical, reflecting the sloping guiding fracture (Fig. 9). The various levels of the

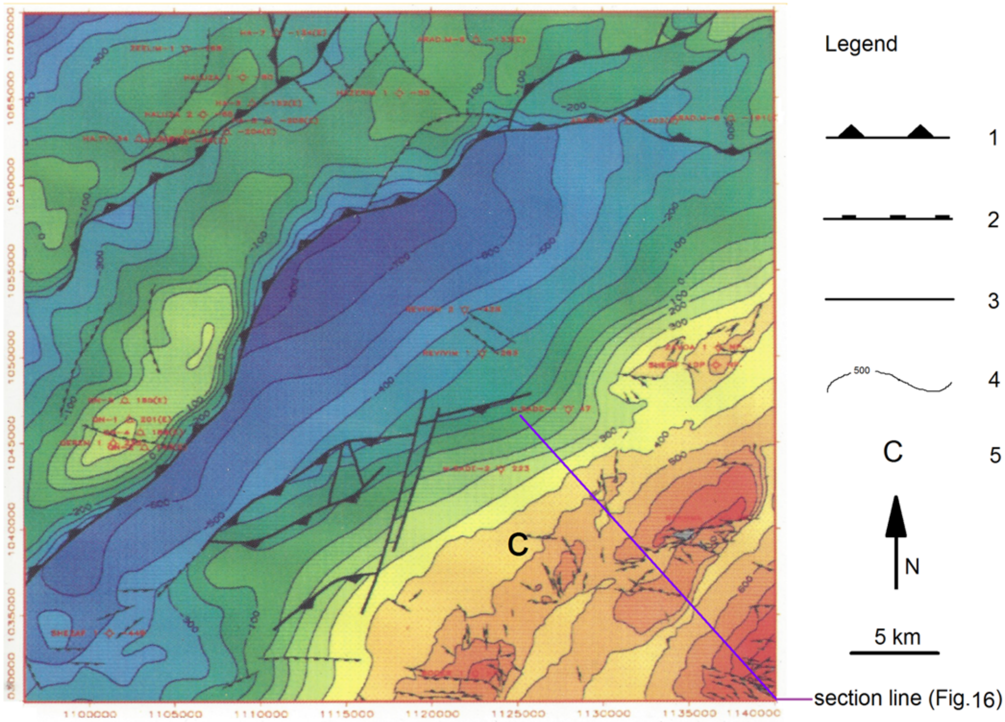

Fig. 2. Structural map (top Judea Group) showing the main regional Syrian Arc anticlines and faults in the vicinity of Ashalim Cave. Modified after map by Ofer Siman Tov, the Geophysical Institute of Israel. For location, see Figure 1. 1, Major fault; 2, medium fault; 3, small fault; 4, structural contour; and 5, Ashalim Cave.

cave are interconnected by smooth-walled shafts, either vertical or sloping (Fig. 10), which, having no vadose dissolution features, appear to have formed as rising conduits or feeders (Klimchouk 2013). Above the lowermost passages, the cave bifurcates in a fan-like fashion. Some of the passages interconnect in a complex three-dimensional fashion, forming a 'boneyard' and boulder-divided intricate voids. Water circulating through the cave can escape horizontally through tight outlets, or upwards through passage A.

Vadose speleothems (mainly flowstone) are observed at the entrance of the cave, half a metre below the present surface, indicating a previously thicker bedrock ceiling that has been eventually denuded. The walls and ceiling of the lowermost passage (Da) are covered by a thin gypsum crust (Fig. 11). Salt and gypsum 'flowers' are also common here. During the vadose stage of the cave, some of the rising shafts have served as downward routes for saturated vadose flow, which deposited calcite dripstones (Fig. 12).

The general morphology indicates that the cave initially formed in a confined, hypogene setting (e.g. Klimchouk 2013; Audra & Palmer 2015; De Waele *et al.* 2016 and references cited therein). Three gypsum samples have $\delta^{34}S_{SO_4}$ values of 14.4, 14.8 and 15 (std up to 0.5), indicating evaporative origin. The isotopic composition of the gypsum crust does not indicate the corrosion of limestone by sulphuric acid (e.g. Galdenzi & Maruoka 2003; Hose 2013; Palmer 2013; Naaman *et al.* 2014 and references cited therein). The voids started forming by the action of aggressive water; this aggressiveness could result from mixing corrosion or the cooling of thermal water. This process is no longer active in the cave and there are insufficient data on the composition of the groundwater currently present below the cave.

U–Pb and U–Th age dating of the vadose calcite speleothems show that they have been deposited on the bedrock wall and ceiling of the cave intermittently since the late Pliocene (3.1 Ma) (Vaks *et al.* 2013). The Pliocene age of initial deposition under vadose conditions suggests that late Neogene regional uplift, possibly associated with the deepening of the Dead Sea Rift (Guralnik *et al.* 2010; Matmon *et al.* 2014), caused the dewatering of groundwater from the cave, a process followed by the deposition of speleothems under vadose conditions.

Fig. 3. Ashalim Cave entrance. Photograph by Amos Frumkin.

Speleothem deposition lasted intermittently until the early–late Pleistocene (115 ka) (Vaks *et al.* 2010). There is no sign of speleothem deposition during the last 115 ka. The speleothems indicate increasing aridity since the relatively mild climate of the Pliocene, with ever-shortening moist episodes, ending at MIS 5.

Condensation corrosion by convective air flow has partly truncated some of the speleothems, exposing their internal stratification (Fig. 13). Ceiling collapse is common and its products are piled on the floors of most chambers and some passages. The chamber's ceilings and collapsed blocks are commonly smoothly corroded.

These types of maze cave, formed by hypogene dissolution, possibly assisted by the cooling of thermal water (Dublyansky 2013; Klimchouk 2013 and references cited therein), were typically formed in the Negev and Judean deserts under confined conditions during the Oligocene–early Miocene within Late Cretaceous massive limestones of the Shivta Formation (Frumkin & Fischhendler 2005; Frumkin *et al.* 2017*a*, *b*).

Groundwater flow

Two major aquifers are known in Cretaceous rocks of the NW Negev Desert: the Judea Group freshwater aquifer and the Kurnub Group brackish aquifer. Both aquifers are capped by poorly permeable layers of chalk and marls, resulting in

Fig. 4. Plan of Ashalim Cave. Surveyed by B. Langford, M. Ullman, N, Fishbein, L. Buchman, Israel Cave Research Center (2011).

confinement and artesian conditions mainly within synclines. These aquifers are clearly distinguished from each other by their hydrochemical properties (Kronfeld *et al.* 1993).

The Judea Group, composed of carbonate rocks, is recharged mainly in the western-central mountain range of Israel (Fig. 1) (e.g. Weinberger *et al.* 1994; Sheffer *et al.* 2010). The east Mediterranean precipitation that replenishes the Judea Group aquifer has a unique stable isotope signature, following the east Mediterranean meteoric water line, with d-excess values of *c.* 22‰ (Gat & Dansgaard 1972).

Conversely, most of the lower Cretaceous sandstone groundwater of the NE Negev Desert has d-excess values of *c.* 10‰, as well as low values of $\delta^{18}O_w$ and δD, similar to correlative aquifers in Egypt–Sinai (Gat & Issar 1974; Thorweihe & Heinl 2002). This is in agreement with the assumption that the Kurnub aquifer contains palaeowater recharged at the Nubian Sandstone outcrops of the Sinai Desert, downstream from the Precambrian basement outcrops (Fig. 14), which form part of the Afro-Arabian dome, south of the Negev Desert (Issar 1981; Rosenthal *et al.* 1998; Vengosh *et al.* 2007).

The above-mentioned studies suggest that the water of the sandstone aquifers flows gravitationally northward along the general regional dip, becoming confined under younger strata. The flow northward from Nubian Sandstone outcrops has been extensive since the rising and truncation of the Afro-Arabian dome during the Oligocene (Almond 1986; Avni *et al.* 2012; Bar *et al.* 2016).

The present water table in the Ashalim region is *c.* 400 m below the cave entrance. A groundwater anomaly was observed in this region, where the Nizana 1, Revivim, Mashabim and Ashalim wells, drilled into the Judea Group aquifer, encountered water with Kurnub Group aquifer properties, reaching up to 83% of this water type at Ashalim well (Fig. 15) (Rosenthal *et al.* 1998). The Kurnub-type

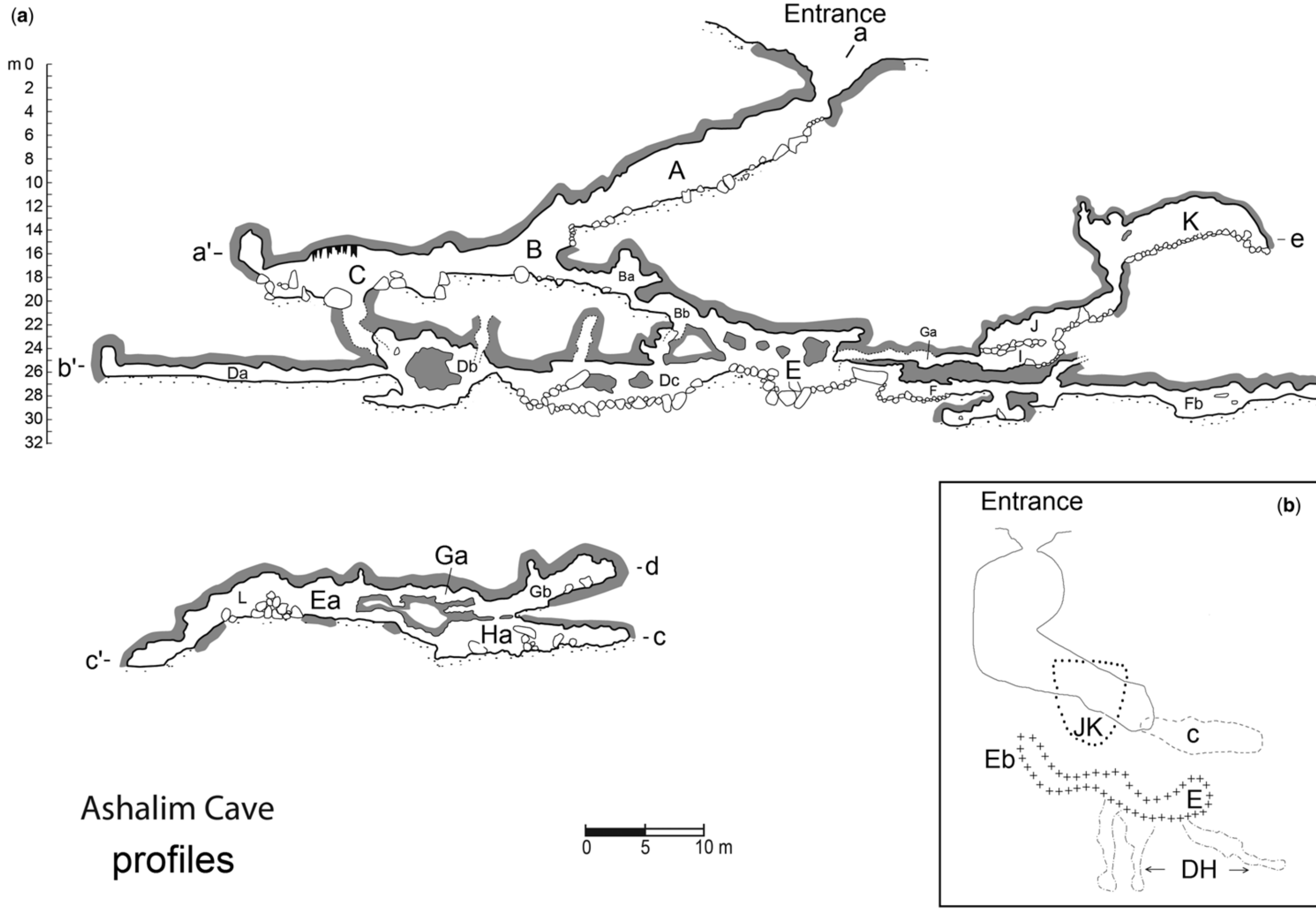

Fig. 5. Ashalim Cave profile. Surveyed by B. Langford, M. Ullman, N, Fishbein, L. Buchman, Israel Cave Research Center (2011). (**a**) Profiles along the main cave axis; (**b**) vertical projection of the cave perpendicular to its axis, view to azimuth 155°.

Fig. 6. Cupola at Ashalim Cave. Photograph by Amos Frumkin.

water gradually mixes with Judea-type water flowing in the Judea Group to the SW (Fig. 1). The contrasting water with intermediate mixing is best observed between Nizana 1 well, SW of Ashalim Cave, and Tel Shoqet 4 Well, NE of Ashalim Cave (Fig. 15).

Fig. 7. Solution pockets at Ashalim Cave. Locally resembling scallops, these are isolated and variable in size. Photograph by Amos Frumkin.

Fig. 8. Morphology indicating possible bubble trail at Ashalim Cave. Photograph by Amos Frumkin.

Fig. 9. Lower passage of Ashalim Cave. Cross-section determined by a sloping fracture. Photograph by Lihi Buchman.

Rosenthal *et al.* (1992), Kronfeld *et al.* (1993), Weinberger *et al.* (1994) and Weinberger & Rosenthal (1994) suggested that the anomalous properties of the groundwater, particularly the elevated temperatures, indicate transverse rising flow from the Kurnub Group into the overlying Judea Group, where the waters of the two aquifers mix. The upward flow is facilitated by the confined higher pressure heads measured in the Kurnub Group aquifer and the deep reverse faults revealed by lithological and structural analysis of the subsurface (Fig. 16) (Weinberger & Rosenthal 1998).

An increase in transmissivity was observed in the Judea Group aquifer between Revivim and Mashabim wells in the vicinity of Ashalim Cave (Fig. 15) (Weinberger & Rosenthal 1998). A geophysical study of wells across the aquifer, using resistivity, gamma ray, caliper and acoustic logs,

Fig. 10. A smooth-walled shaft at Ashalim Cave, probably formed by rising water. Photograph by Boaz Langford.

Fig. 11. Gypsum crust and evaporitic ‘flowers’ at the lower passage of Ashalim Cave. Note horizontal bottom line of flowers, indicating air stratification. Photograph by Lihi Buchman.

indicated that the Ashalim vicinity has more permeable fractured zones than most of the wells of the NW Negev Desert towards the Mediterranean coast (Laskow *et al.* 2011).

Discussion and conclusions

This paper presents evidence for past rising water along the presently known area of rising water, forming hypogene karst. This water must have been aggressive during cave formation. Analysis of the present hydrogeology suggests that the most probable palaeohydrological scenario during speleogenesis was similar to the present configuration: rising water from the Kurnub Group invaded the Judea Group under confined conditions, developing hypogene karst, as demonstrated by Ashalim Cave.

The palaeohydrogeological setting is assumed to have been generally similar to the present setting:

Fig. 12. Solutional v. depositional morphology at Ashalim Cave. Top-left: smooth walls and pockets with solutional morphology. Bottom-right: calcite speleothems deposited from down-flowing vadose water. Photograph by Lihi Buchman.

Fig. 13. Speleothems truncated by condensation corrosion. Photograph by Amos Frumkin.

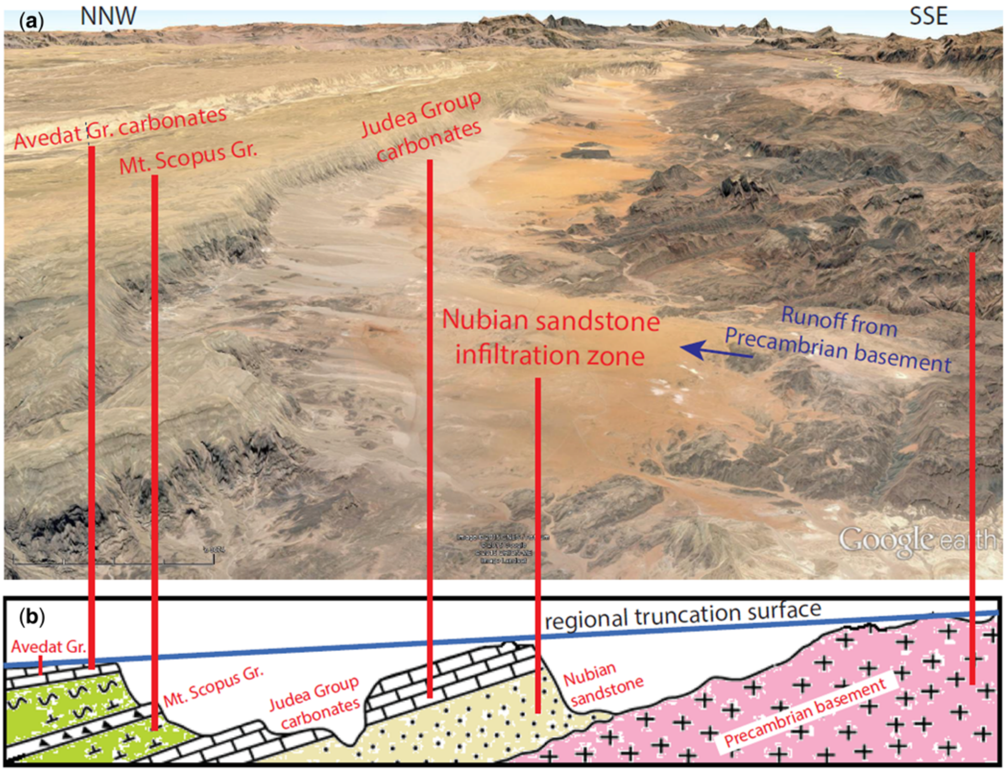

Fig. 14. Hydrogeological setting of central Sinai, *c.* 250 km SW of Ashalim Cave, as a possible recharge zone for the hypogenic water at Ashalim. Ashalim and most Negev caves are in the Judea Group, and some are in the Avedat Group. (**a**) Google Earth view of central Sinai showing an example of runoff from Precambrian basement flowing to Nubian Sandstone outcrops, where recharge of the aquifer takes place. Background courtesy of Google. (**b**) Schematic geological section of the area shown in part (a). Section length *c.* 200 km. Modified after Avni *et al.* (2012). For location, see inset in Figure 1.

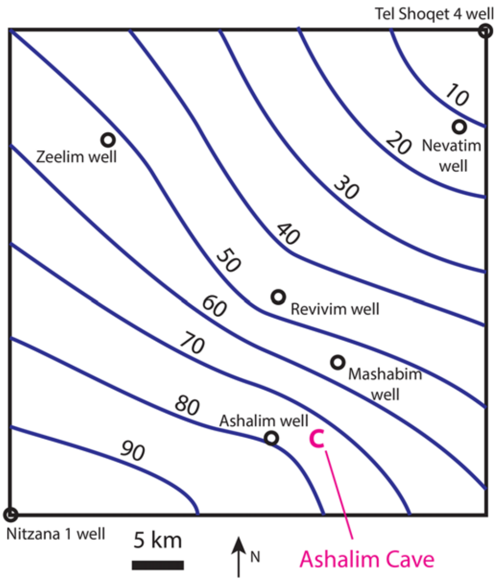

Fig. 15. Percentage of deep groundwater rising from the Nubian Sandstone into the modern Judea Group aquifer near Ashalim. The deep water rising near Nitzana 1 well is diluted towards the NE, where Judea Group groundwater dominates. Modified after Rosenthal *et al.* (1998). For location, see Figure 1.

Kurnub Group groundwater flowing northward from far-field recharge areas in the south and mixing with Judea Group groundwater, which flows southward from the Judea Mountains. If we assume that speleogenesis predated the formation of the Dead Sea Rift–Gulf of Aqaba depression, then the Kurnub Group groundwater palaeo-flow at Ashalim region could have been stronger than today due to:

(1) a larger recharge zone of Kurnub Group sandstone outcrops with gradients towards the NW Negev Desert, including regions around the present Gulf of Aqaba and the Red Sea, as well as the central Negev anticlines of Ramon and Hazera; and
(2) the Kurnub Group groundwater presently discharging into the Dead Sea Rift base level (Issar *et al.* 1972) would have flowed towards the Mediterranean, partly through the vicinity of Ashalim Cave.

The following processes may account for the increase in aggressiveness of the water within the Shivta Formation (Frumkin & Gvirtzman 2006; Auler 2013):

(1) mixing of the waters of the two aquifers;
(2) the addition of salt to ‘normal’ bicarbonate water, inducing undersaturation by the ionic strength effect;
(3) hydrogen sulphide degassing and the condensation of sulphuric acid just above the water table;
(4) the aggressiveness of Kurnub Group water flowing without being buffered through sandstone; and
(5) the cooling of hydrothermal waters;

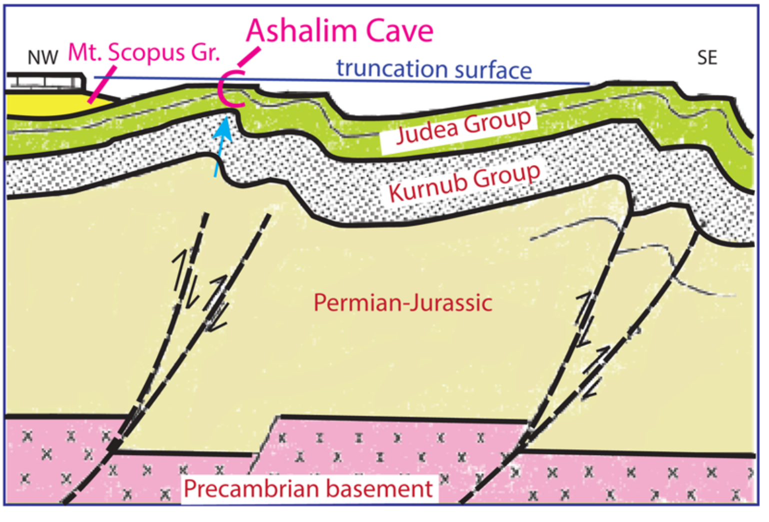

Fig. 16. Schematic cross-section of the Syrian Arc structures near Ashalim Cave and their relation with deep reverse faults, allowing upward flow of deep groundwater. Modified after Flexer *et al.* (2005). Arrow indicates possible palaeo-upwelling flow route to Ashalim Cave. For location, see Figure 2.

The Ashalim Cave therefore acts as a window to understanding past groundwater flow in a desert zone in which the groundwater flow was recharged a long distance away. The general flow in the Ashalim region today seems similar, although the groundwater level has dropped and some of the Kurnub Group waters currently flow eastward to the Dead Sea Rift.

The Ashalim Cave was surveyed by Boaz Langford, Micka Ullman, Vladimir Buslov, Nevo Fishbein and Lihi Buchman of the Israel Cave Research Center, The Hebrew University of Jerusalem. Alon Amrani of the Hebrew University analysed the sulphur isotopes of speleothems. Alexander Klimchouk and an anonymous reviewer considerably improved the manuscript with their remarks.

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