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MORPHOLOGY AND DEVELOPMENT OF SALT CAVES

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Morphology and origin of salt caves are discussed, based on a study of 105 caves in Mount Sedom salt diapir, Israel. High solubility of rock salt has favoured the development of allogenic caves under arid climate. Caves along the margins of the mountains are integrated systems with open outlets at base level. Central caves lack such an outlet, discharging slowly through narrow fissures to a regional aquifer. Cave profiles are adjusted to base level, allowing reconstruction of the evolutionary history of the region.

INTRODUCTION

Rock Salt, composed mainly of halite (NaCl), is extremely soluble, three orders of magnitude more than limestone. However, salt caves were scarcely studied until recently, and their very existence has been doubted in some scientific literature (e.g. Bögli, 1980, p. 3). The first modern review discussing salt caves is by White (1988, p. 337).

Because of its solubility, rock salt outcrops are rare. Salt layers (which are not uncommon in the subsurface), usually dissolve completely by meteoric water down to depths of several hundred meters. This process, termed interstratal (or intrastratal) karstification is often accompanied by salt aquifers, breccias, subsidence dolines and bedrock collapse structures (DeMille et al., 1964). Such features may originate at depths of more than 1000 meters below surface. However, few true caves in salt were known until recently. Cave explorers have found one example in the Persian Gulf (Shaw, 1979), 31 caves in Rumania (Ponta, 1986), five in former USSR, two in Spain, and eight in Algeria (Chabert, 1989). For a detailed bibliography see Choppy, (1988). No accessible salt caves in the American continent are known to the author, but interstratal salt karst is common (Quinlan et al., 1986).

The largest known assemblage of salt caves is found in Mount Sedom, Israel. During the last decade 105 caves have been surveyed in this rock salt mountain (Frumkin, 1982; Donini et al., 1985; Frumkin, 1986). The range of salt cave types of Mount Sedom seems to include the common morphological types found elsewhere, as well as types unknown from other localities. Each type is represented by enough specimens to allow classification and generalized discussion.

The purpose of this paper is to discuss the morphology and genesis of the major types of salt caves, based on a detailed study of Mount Sedom caves (Frumkin, 1992).

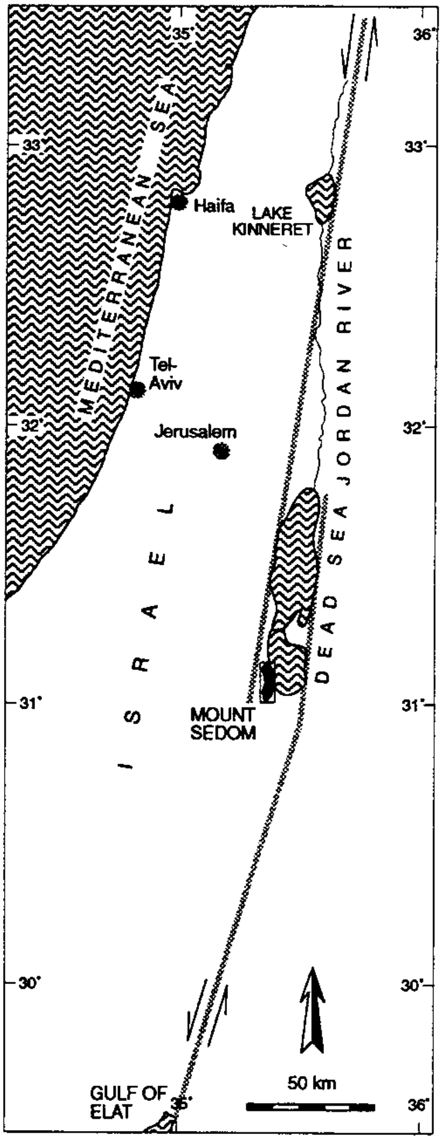
REGIONAL SETTING AND GEOLOGY

Mount Sedom is the exposed head of a salt diapir, forming an elongated ridge 11 by 1.5 km, rising up to 250 m above the 1993 Dead Sea level (Fig. 1) in the sinistral transform fault zone of the Levant (e.g. Garfunkel et al., 1981). In 1993, the elevation of the Dead Sea surface, being the regional base level, was 410 m below MSL (Frumkin, in press, b). The Dead Sea basin is filled by a thick sequence of detrital sediments and evaporites which give rise to subsurface salt diapirs (Neev and Hall, 1979). Of these, Mount Sedom, on the southwestern shore of the lake, is the only one to have broken the surface. It consists of Plio-Pleistocene(?) beds of rock salt, of marine origin, piercing through tilted strata of younger lake evaporites and clastics.

As the diapir rises, lithostatic pressure is released and fissures tend to open in the upper parts of the rock mass, especially near its margins. These are important for initial groundwater flow, since the primary porosity of rock salt is negligible. Borehole evidence indicates that below base level, fissures are annealed (closed) under pressure, due to the plastic properties of salt (Yossi Charrash, Dead Sea Works, personal communication, 1992). Bedding planes are vertical or steeply inclined. They often yield under the shear stress induced by the rising diapir and become minor fault plains (Zak and Freund, 1980). Horizontal fissures are rarely found in Mount Sedom. Before its subaerial extrusion, the top of the rising diapir suffered dissolution by groundwater. Residual, relatively insoluble anhydrite, shales and dolomite accumulated above the salt, forming a cap rock that is up to 50 m thick (Zak and Bentor, 1968). The flat, near-horizontal contact between the steeply inclined salt layers and the cap rock is referred to as the 'salt table' (Vroman, 1950-1). The cap rock is covered by Late Pleistocene Lisan lake sediments ('Lisan Marls'), consisting of aragonite, clays and gypsum (Begin et al., 1980). The Lisan Marls will be included in the term 'cap rock' for most of the present discussion. The top of Mount Sedom is roughly tabular, with many small catchments up to 0.7 km^2 in area. Karst terrain has developed under arid to extremely arid climate during the Holocene; the oldest cave was dated to ~7000 convention ^{14}C years (Frumkin et al., 1991).

HYDROLOGICAL BACKGROUND

The region is extremely arid today, with an average yearly rainfall of 50 mm. Annual precipitation-evaporation deficit ex-



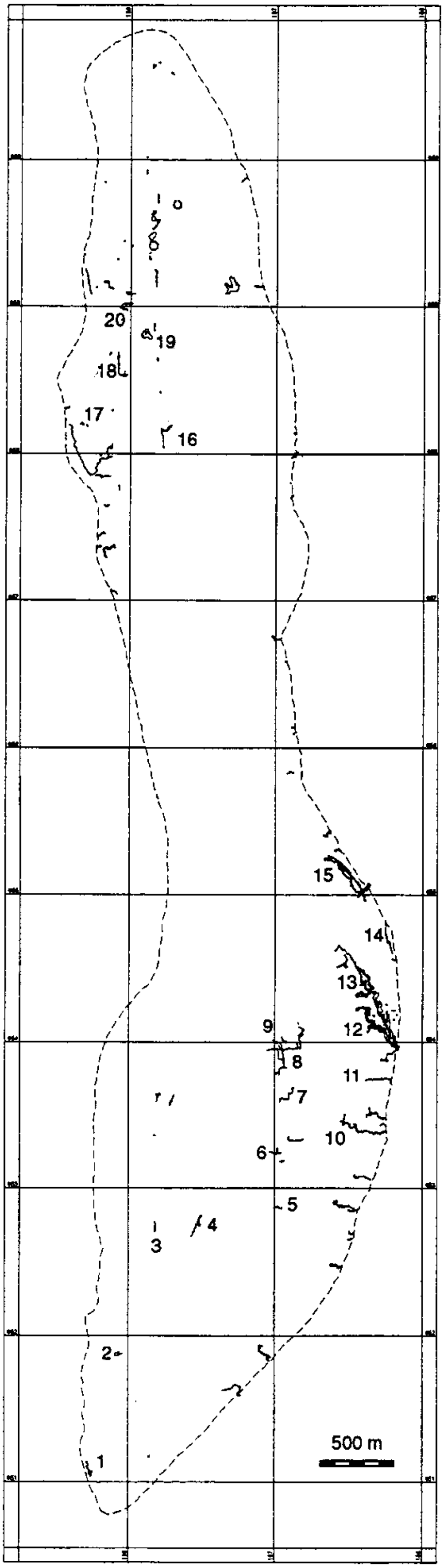


Figure 1. Map showing the location and ground plan of Mount Sedom caves (1) Nahal Melah Cave System, (2) Tupim Cave, (3) Gavish Cave, (4) Karbolot Cave, (5) Prahim Cave, (6) Tsinor Cave, (7) Notsa Cave, (8) Zehuhit Cave, (9) Qupa Cave, (10) Colonel Cave System, (11) Bua Cave System and Karega-Nolda Cave, (12) Malham Cave System, (13) Lashleshet Cave, (14) Lehavim Cave System, (15) Sedom Cave System, (16) Nahash Cave, (17) Sharsheret Cave, (18) Mifrazim Cave, (19) Agam-Yavesh Cave, (20) Mevokhim Cave.

ceeds 2 m. During the infrequent rainstorms, runoff collects on the relatively impervious cap rock and flows into fissures, leading to large cavities in the underlying rock salt. Such a setting may be classified as allogenic karst (Jakucs, 1977), even though the cave catchments are within the boundaries of Mount Sedom.

The eroded cap rocks contribute large amounts of clastic load to flood water, ranging from 10% to 80% by weight (Gerson and Inbar, 1974). Flood flow velocities range from 0.5 to 2m/sec, allowing bedload cobbles to be carried along cave passages. Extreme suspended load concentrations may render the flow dense and highly viscous. Suspended load scarcely changes while the water is flowing through the caves. On the other hand, TDS (total dissolved solids) in flood flow increases dramatically within the caves, from ~10 g/l (gram/liter) at stream sinks up to 200-300 g/l. This consists mainly of halite (Frumkin, in press, a). Most flood waters remain chemically aggressive while flowing rapidly within cave passages. However, if the flow is stopped or slowed down considerably, saturation is approached after few hours or days.

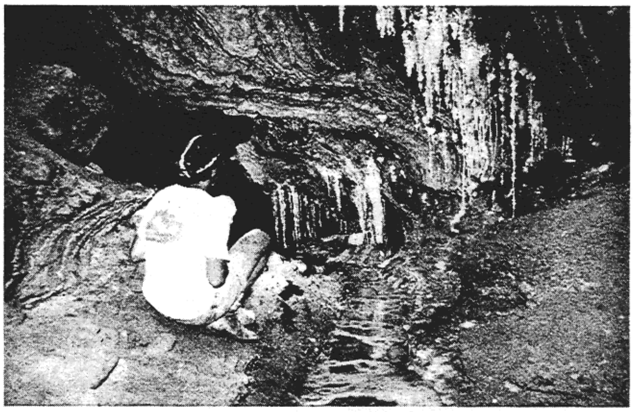


Figure 2. Rock salt passage in Malham Cave. Vertical salt beds are seen in the upper right corner. A saturated brine seeps from the alluviated bottom, forming (salt) rimstone pools. Vadose seepage forms halite stalactites.

Two types of resurgences are known along Mount Sedom margins, differing from one another chemically and hydrologically (Frumkin, in press, a): (1) Cave outlets where sinking streams reappear. (2) Alluviated resurgences discharging diffuse continuous flows of brine ("exurgences" of Sweeting, 1972). The brine emerges along the foot of the eastern escarpment and in some eastern caves (Fig. 2), apparently discharging from a aquifer (Figs. 3, 4) encountered in boreholes (Petroleum Services, 1979). It is saturated in salts, with high concentrations of Mg^{++}, K^+ and Br^-, in addition to Cl^- and Na^+ (Frumkin, in press, a).

METHODS

Some 20 km of cave passages have been surveyed by compass, tape and clinometer. Higher precision elevations with maximum of ±5 mm were measured by a tripod-mounted automatic Wild surveyors' level, for comparing cave levels to one another and to the water table level.The time scale for cave development was obtained by direct measurement of downcutting from 1986 to 1991 (Frumkin and Ford, in press) and by ^{14}C dating of driftwood carried by floods into the caves (Frumkin et al., 1991). This dating method, applicable in caves younger than ~40,000 years, provides the actual age of speleogenesis with error margins of only a few hundred years, compared to carbonate speleothem dating which provides the minimum age of the cave passage with larger error margins.

Hydrological, chemical and isotopic data being published elsewhere (Frumkin, in press, a) are also used to facilitate the present discussion.

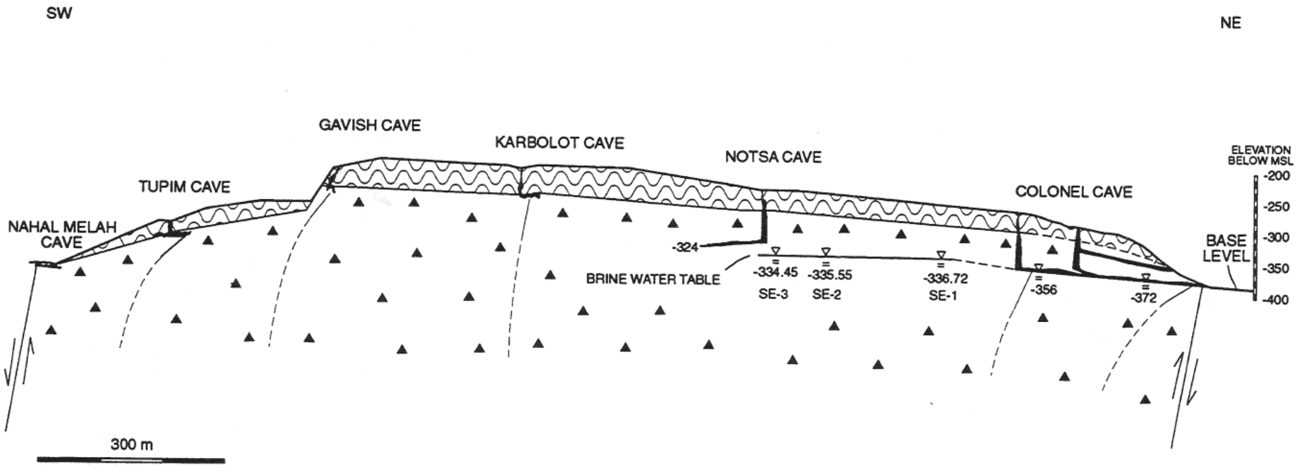


Figure 3. Cross section of southern Mount Sedom. Curly lines indicate cap rocks and black triangles are rock salt. Upper level of Colonel Cave is reconstructed from segments between breakdowns. Salt layers in caves dip subvertically westward.

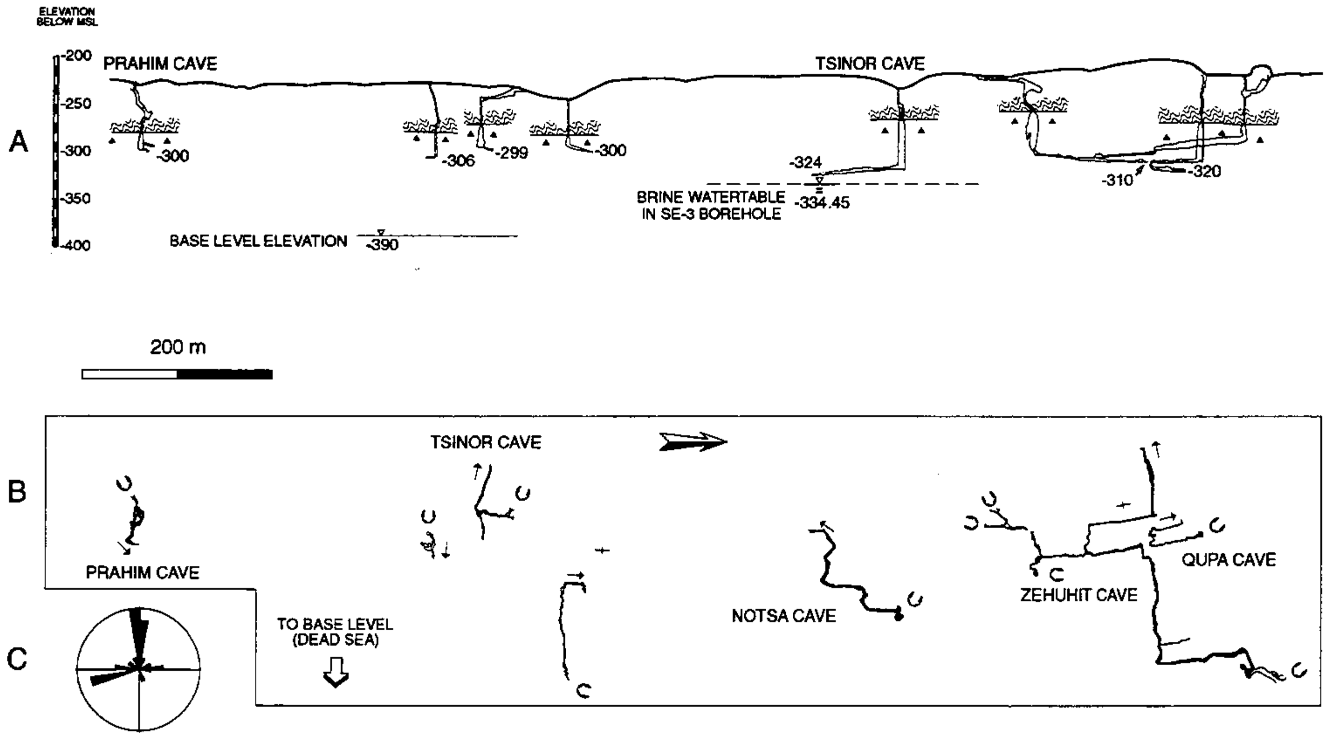


Figure 4. Inlet caves in the central part of southern Mount Sedom. (A) North-south section. (B) Ground plan; arrows indicate sinks and flow direction at the cave bottom. Bedding is vertical, shown by crosses. (C) Rose diagram shows preferred flow directions in salt cave passages. Most conduits developed westwards along joints and southward along bedding plains, although Dead Sea base level is in the east.

COMMON CAVE MORPHOLOGY IN MOUNT SEDOM

Each cave is fed by one or more sinks with a distinct catchment area. Often several conduits join underground to form a branchwork cave (e.g. Zehuhit Cave, Fig. 4). Most of the older caves are multi-phase, possessing inactive conduits above or beside the modern channels. Relocation of inputs (e.g. Bua-Karega-Nolda caves, Fig. 5) and outputs (e.g. Colonel Cave, Fig. 3) is common over time.

After a short initiation period, salt caves develop mainly by open-channel flow, unlike limestone caves where pipe-full conditions may prevail for a long period across a major portion of the cave. A salt cave must retain a downstream slope, developing by gravitational flow along the available openings.

An active cave typically consists of the following sections: A stream sink, a conduit in cap rocks (including Lisan Marls), a vertical shaft crossing the salt table and a rock salt passage. These components are discussed below in downstream order.

UPSTREAM SECTIONS

Subaerial channels are captured into subsurface routes through fissures in the cap rock (Fig. 6) that offer higher gradient flow routes. The sink dimensions vary from impenetrable (few cm), up to 2 m. Some sinks drain directly downwards to shafts crossing the salt table, while others lead first to sub-horizontal passages in cap rock. Most cap rock flow routes are narrow, up to several tens of cm in width. Both piping and dissolution enlarge the channels within these relatively insoluble rocks. Close to the salt table the cap rock channel usually becomes vertical, forming the upper, narrow part of a shaft which crosses the salt table (Fig. 4). This morphology is comparable to invasion vadose caves in limestone (Ford and Ewers, 1978).

A cap rock fissure usually does not extend across the salt table into the rock salt. However, the shaft drops vertically into the salt, regardless of fissures or bedrock dip. Its cross section enlarges downwards below the salt table, having a bell-like shape. The rock salt part of the shaft may reach 15 m diameter and 60 m depth. In most shafts the floor is covered by alluvial sediments. The lower, vertical part of shaft walls are either smooth or fluted. Some younger shafts are spindle shaped in vertical section (e.g. southern shaft of Zehuhit Cave, Fig. 4).

ROCK SALT PASSAGES

The shafts in most of the studied caves are drained by subhorizontal conduits, typically vadose canyons with incised me-

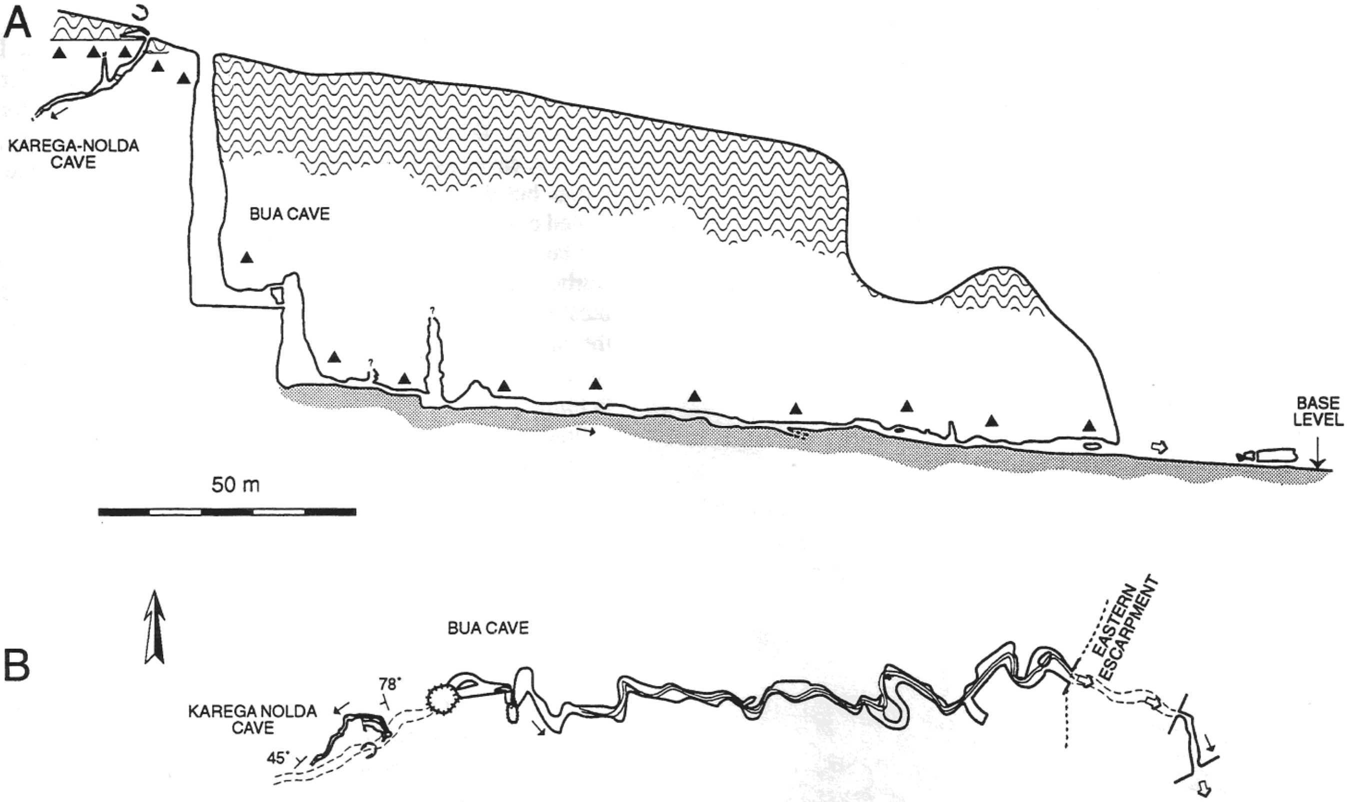


Figure 5. (A) Profile (B) map of Bua Cave system (surveyed by Anan Zeidner) and Karega-Nolda Cave. The catchment of Bua Cave was recently captured upstream, forming the embryonic Karega-Nolda Cave.

Figure 6. The sink of Sharsheret Cave; a typical cave input developed on a cap rock fissure crossing a subaerial channel.

anders. They can usually be found to have initiated along a fissure—joint, bedding plane or fault.

Average downcutting along the young salt canyon channel shown in Figure 7 was 44 mm during 5 years of measurement (Frumkin and Ford, in press). It took place mainly in the course of two major floods. Salt bedrock is exposed along the passage bottom and its mean gradient is 40%. Gradients from 2 to 10% are more common in most active passages, in which case the bed will be alluviated. Alluvial clastic deposits are fine grained to pebbly, including anhydrite, dolomite and quartz, all locally derived from Mount Sedom. The uppermost inactive storey (or 'level') of a cave is typically steeper than the modern channel (e.g. Colonel Cave, Fig. 3). In Sedom Cave, gradients of 27-32% were measured in the uppermost level above a modern channel of only 5%. Downstream, closer to the outlet, upper level storeys are more moderate, becoming either sub-parallel to modern channels or converging with them.

Steep passages follow the initial fissure closely (Figs. 8, 9A), while sub-horizontal passages with aluvial fill are more sinuous (Figs. 5, 9B). Some wide passages with meander notches and 'shelves' indicate long periods of flow without downcutting, when lateral migration of meanders caused destruction of earlier canyon walls (Fig. 10). The older caves in Mount Sedom have several distinct wide levels above the modern channel. The development of a cave profile and morphological features such as meanders, shelves and notches are sometimes constrained by hardly soluble layers, such as dolomite, shales and anhydrite, interbedded within the salt (Fig. 9C).

Figure 7. A young passage in Sedom Cave, one day after 9 Feb. 1987 flood. Using the white plastic pegs as benchmarks, 2 cm of downcutting was measured to have occurred during this flood. The film box for scale is 6 cm high.

Solid load may settle on the cave bottom, shielding the floor and favouring upward dissolution of the roof—a form of paragenesis (Renault, 1967). Corrosion bevels—flat roofs regardless of geologic structure (Ford and Williams, 1989, p. 307) develop where flood water touches the ceiling (Fig. 9E). Any salt protruding from the ceiling into the passage is truncated by the water, and upward solution proceeds with the same rate across all the bevel. The resulting flat ceiling is an imprint of the water surface forming it. A vadose canyon is often entrenched in the alluvium under a bevel (Fig. 9F, 11).

Salt caves may be classified into two groups according to the way they terminate: (1) integrated cave systems, having a distinct open outlet; (2) inlet caves, lacking such an outlet.

INTEGRATED CAVE SYSTEMS

In terms of exploration limits, thirty eight of the studied caves are 'through caves' (as classified by Jennings, 1985, p. 137)—they can be traversed along the full distance from sink to outlet (e.g. Colonel Cave, Fig. 3; Bua Cave, Fig. 5). These caves are located along the margins of Mount Sedom (Fig. 1). Twenty-seven cave outlets drain directly to the south basin of the Dead Sea, the hydrologic base level of the region; the remainder discharge westwards into wadis that flow around Mount Sedom towards the Dead Sea. In terms of hydrological function, the through caves as well as caves which include inaccessible segments but drain freely to base level, may be classified as integrated cave systems as defined by Ford and Ewers (1978)—they are large enough to allow turbulent flow from input to output. Turbulent floods flowing through integrated cave systems carry most silt and clay fractions of the suspended load and most of the dissolved load through the outlets towards the Dead Sea. Residence time of flood water in these caves is short, measured in minutes.

Integrated cave systems are developed along the margins of the rising diapir, where conditions are favourable: hydraulic gradients are high and fissures are long, open and abundant because of lithostatic stress release.

INLET CAVES

Caves in the central portions of the mountain, accessed through their sinks, appear to have no distinct outlet but terminate several m or tens of m above the apparent water table (Figs. 3, 4). These are termed here 'inlet' caves. The direction of conduits in the caves does not depend on the direction to base level or the water table gradient. Rather, they develop in orientations dictated only by available open fissures. Some inlet caves such as Zehuhut, Tsinor and Notsa seem to flow away from the Dead Sea base level (Fig. 4B, C). Some inlet caves develop close to one another but do not meet (e.g. Zehuhit Cave and Qupa Cave, Fig. 4).

The downstream parts of Inlet caves often contain steep silt and clay banks with surge marks, similar to those described by Bull (1976) in limestone caves. They indicate occurrence of low energy water pondings with variable residence times (see below), in which sediment load could settle. This further suggests that the limit of exploration is also a hydraulic limit between two sequential modes of water flow: rapid turbulent floods prevailing from input to cave bottom, and diffuse infiltration below the bottom of the explorable passage, down to the output boundary of Mount Sedom. The water infiltrating from inlet caves may recharge the brine aquifer known from boreholes SE1, SE2 and SE3 (Figs. 3, 4). However, chemical and isotopic differences between the ponded water and the aquifer indicates an additional source and a complex origin of the aquifer (Frumkin, in press, a).

A transition between slow and rapid kinetics, known in limestone to coincide approximately with the laminar-turbulent transition (White, 1977), is not known in salt dissolution. Therefore salt fissures are not believed to enlarge in a uniform rate over long distances downstream under phreatic conditions. Rather, dissolution seems to act mainly close to the inputs, forming inlet caves; infiltrating water probably approaches saturation rapidly

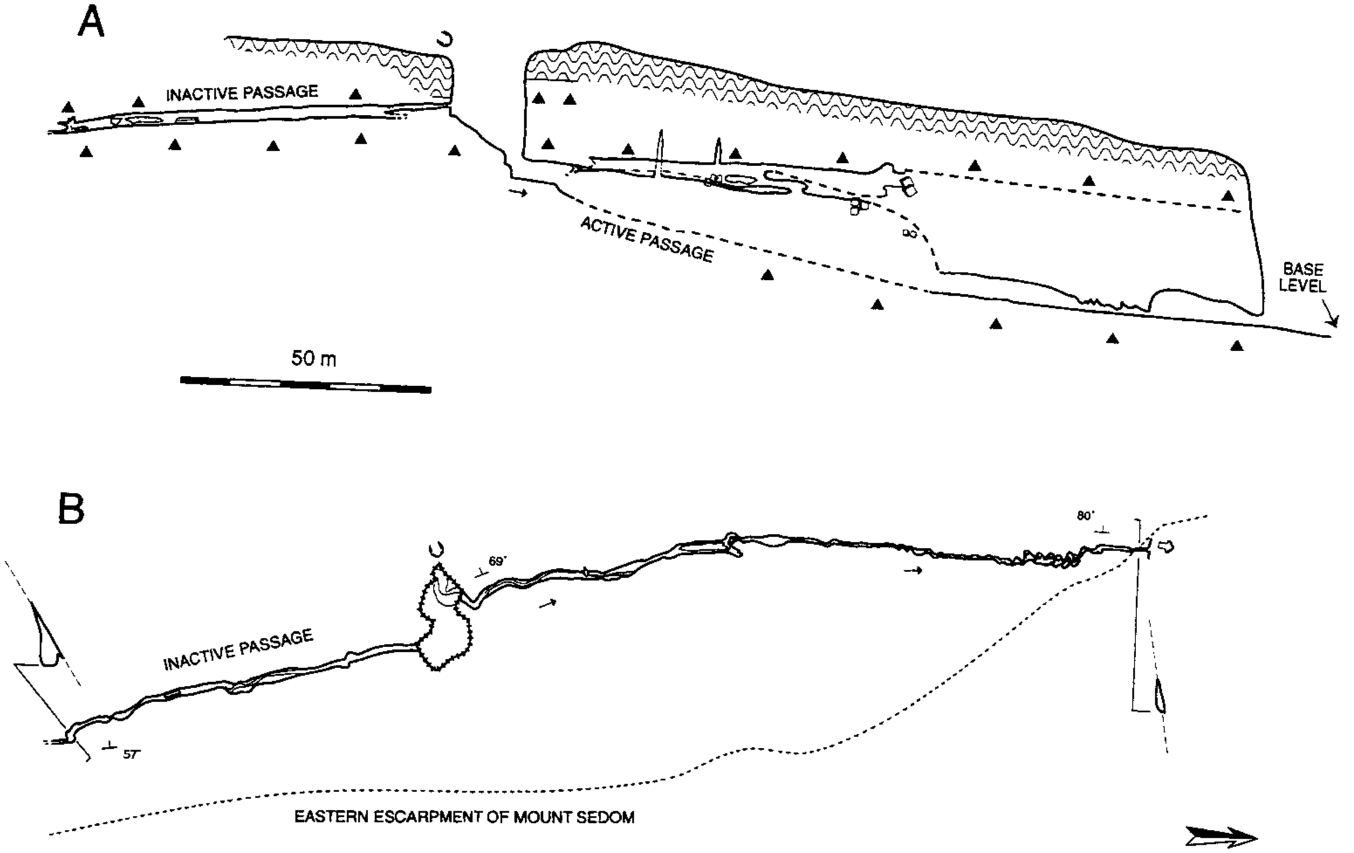


Figure 8. (A) Profile (B) map of Levahim Cave. The passages follow the initial partings, meandering slightly. The inactive southern passage, being sub-parallel to the escarpment, failed to connect to base level. The receding shaft cut across another parting, diverting the flow northward, to the present outlet. The modern channel is steep with no alluvium, indicating active downcutting. Note the initial lenticular cross section (enlarged x2.5), developed along the inclined parting.

below the bottom of the cave. This partly explains why true phreatic conduits are not known in Mount Sedom, apart from paragenetic passages developed under full pipe conditions in the vadose zone. Other arguments discouraging development of salt phreatic caves are: (1) Open fissures are not available below base level. (2) Mixing corrosion (Bögli, 1980, p. 35) is absent. (3) The abundant sediment load settles down in phreatic conditions of low water energies, blocking fissures and conduits. (4) Deep cavities formed in environments sustaining deep ground water circulation tend to collapse or anneal rapidly under lithostatic pressure.

FLOOD WATER PONDS

Silt and clay sediments settling at the bottoms of inlet caves impede infiltration, extending the residence time of pond water. Three of the studied caves in northern Mount Sedom had perennial ponds throughout the study period of 1984-1991. They are perched, without any lithologic control, tens of meters above the nearest potential outlet at the foot of the mountain. Water level in each lake also differs from the others by tens of meters.

Pond waters are highly concentrated with solutes, up to 324 g/l, consisting mainly of halite. This is compatible with flood water chemistry, but not with the brine aquifer mentioned above (Frumkin, in press, a). Both dissolution and precipitation features are observed on walls bordering ponds, as well as on cave walls where ponds have dried out.

Horizontal notches indicate levels of aggressive water temporarily diluting the pond during floods. A horizontal notch is typically 10-20 cm deep (Figs. 12, 13D), consisting of a flat corrosion bevel above a sloping sidewall (facet of Kempe et al., 1975). These features are formed where pond waters develop density gradient stratification. The upper aggressive water layer, originating from the latest flood, dissolves the cave wall. A thin film of heavy, saturated water descends gravitationally along the wall, initiating convection currents in the water. The saturated water is replaced by aggressive water moving from the center of the pond surface towards the walls (Farkas et al., 1951). Densi-

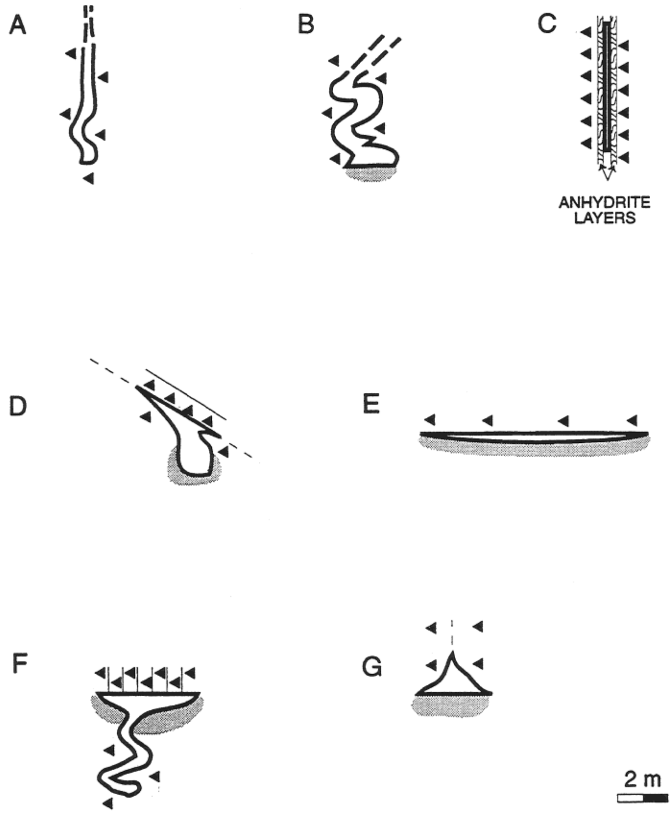


Figure 9. Cross sections of salt cave passages: (A) Young steep canyon, Lehavim Cave. (B) Mature canyon with developed meanders and alluviated channel, Zehuhit Cave. (C) Canyon constrained by anhydrite layers, Malham Cave. (D) Initial fissure widened by full pipe flow, followed by vadose downcutting, alluviation and further downcutting, Lehavim Cave. (E) Corrosion bevel formed by paragenesis is in steeply inclined salt beds, Mevokhim Cave. (F) Paragenetic passage with later vadose entrenchment, Prahim Cave. (G) Triangular cross section tapering upwards, formed under full pipe flow with high hydraulic head in a maze passage, Karbolot Cave.

ty stratification in salt water was also observed in the Dead Sea Works evaporation ponds after floods discharged fresh water into them. Similar notches with bevels and facets are observed in German gypsum caves (Pfeiffer and Hahn, 1972). Notches with bevels appear more rarely in limestone caves, e.g. in water table caves in Australia (Jennings, 1985, p. 148) and in China (Ford and Williams, 1989, p. 307). The density gradient between aggressive and saturated waters may reach ~30% in salt, ~0.2% in gypsum but only ~0.03% in limestone. It favours the development of beveled notches in the more soluble rocks, where water is more likely to reach stable stratification, rather than in limestone.

Figure 10. Meander notches and dissolution 'shelves' formed by lateral migration of meanders; upper level canyon of Lashleshet Cave.

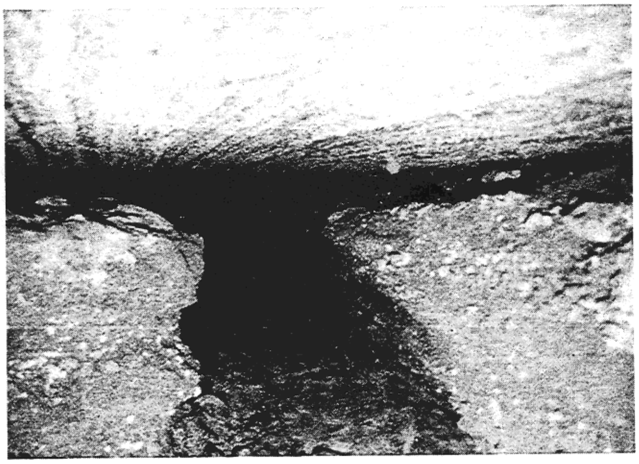


Figure 11. Corrosion bevel and alluvial sediment formed by paragensis, with later vadose entrenchment.

Large secondary halite crystals on some cave's walls indicate supersaturation of the water between successive floods (Fig. 12). The increasing solute concentration is attributed mainly to direct dissolution of rock salt. However, evaporation which is indicated by stable isotope enrichment of ponded water (Frumkin, in press, a) also increases the total dissolved solids. Temperature decrease after summer is a less important factor which may cause supersaturation and precipitation (Cigna, 1986).

Horizontal notches and secondary salt are absent in many inlet caves, indicating that residence time of the ponded water there is too short to produce these features.

Cross sections of some inlet cave passages become smaller downstream, tapering to an impenetrable point (Fig. 14). There is no lithological constraint. The flowing water is still aggressive at the end of the passage, indicating that the taper results from a

Figure 12. A dry pond at the bottom of Agam-Yavesh Cave. Horizontal notches indicate previous pond level immediately after a flood event. Salt crystals covering the wall suggest long residence time of the water in the cave.

downstream decrease of flood discharge caused by gradual infiltration along the alluviated channel. Ephemeral surface streams in arid environments also display a similar decrease of discharge downstream (Renard and Keppel, 1966). This behavior differs from most caves and fluvial systems in moist envrionments, where discharge and cross section stays constant or increases downstream (e.g. White and Deike, 1989). Limestone caves may however taper downstream during their initial phase of development because of decreasing aggressiveness (Palmer, 1991).

Tapering inlet salt caves which terminate with no signs of water ponding, indicate that all flood water infiltrates along the channel. On the other hand, there are sharp responses where only a fraction of the flood can infiltrate along the passage. Mifrazim Cave is an example. An abrupt change in passage cross section from a narrow vadose canyon (Fig. 13B-C, sections 1-4) to a wide bevelled passage (Fig. 13C, section 5) indicates the maximum level of the pond water there. This is comparable to the morphological change observed in the vadose-phreatic transition of some limestone caves (Palmer, 1984).

ELONGATED INLET CAVES

The ground plans of inlet caves suggest a range that is contained within three end members: elongated conduit, chamber and maze. Some caves display features of two or three of the end members combined. The most common form is an elongated conduit, however, consisting of one or more segments developed along fissures (Figs. 4, 13, 14). Elongation is favoured in fissured rock with low hydraulic head, under gravitational flow. The morphological features of the conduit are similar to those of integrated cave systems (discussed above), down to the uppermost pond level at the downstream end of the conduit.

CHAMBER CAVES

A homogeneous rock without open fissures gives rise to a chamber cave, whose length and width are roughly equal. Chamber caves are more common in northern Mount Sedom which is less structurally deformed than the southern part (Fig. 1). Agam-Yavesh Cave is a good example (Fig. 15). Horizontal notches and halite crystals developed across the lower walls of the chamber indicate dried up ponds (Fig. 12). Bedrock salt exposed in the walls and ceiling is massive, without insoluble layers and with few tightly closed joints. Three radiocarbon dates of wood (Frumkin et al., 1991, samples # AY1, AY4, AY6) indicate that the chamber began to develop in its upper southeastern corner, gradually expanding downwards and westwards during the last 3000 years. The westward direction of water flow and cave development is preferred because of the bedding dip (Fig. 15A). Long lived ponds occurred in this cave only during the last few hundred years.

Other chamber caves in northern Mount Sedom exhibit more complex shapes, reflecting local structure and lithology. Large collapse dolines in the same area are probably remnants of similar chamber caves.

Chamber caves are comparable to solution-mined artificial cavities. If aggressive water is artificially introduced to a depth where rock salt joints are tight, then a roughly cylindrical chamber of 100,000 m^3 may be excavated in few hundreds days (Saberian, 1983). In the artificial case the resulting salt water is extracted from the cavity by pumping, whereas in natural caves the water escapes by infiltration.

FLOOD WATER NETWORK MAZES

High fissure frequency with a considerable hydraulic head applied by flash floods favour the development of network mazes. Karbolot Cave, having the largest catchment among inlet caves and extensive fissure system is an example (Fig.16). Infrequent large floods have submerged most of the cave for short periods during the recent centuries, as indicated by surge marks, clay deposits and wood twigs, dated to 480 (conventional ^{14}C) years BP (Frumkin et al., 1991, sample #Ka1). The maze passages developed mainly along two interconnected dense fissure systems, perpendicular to each other. The fissures probably originated by pressure release of the rising diapir. Passages scarcely developed along the fault plains as these are sealed by clay. The passage cross section is typically triangular, with a ceiling tapering upwards into a fissure, and a floor covered with alluvium (Fig. 9G). The salt network maze is similar to flood water mazes described in limestone caves (Palmer, 1975).

LONGITUDINAL PROFILE

Thirty-six alluviated salt cave systems slope asymptotically towards base level. Perching on an insoluble bed near the cave

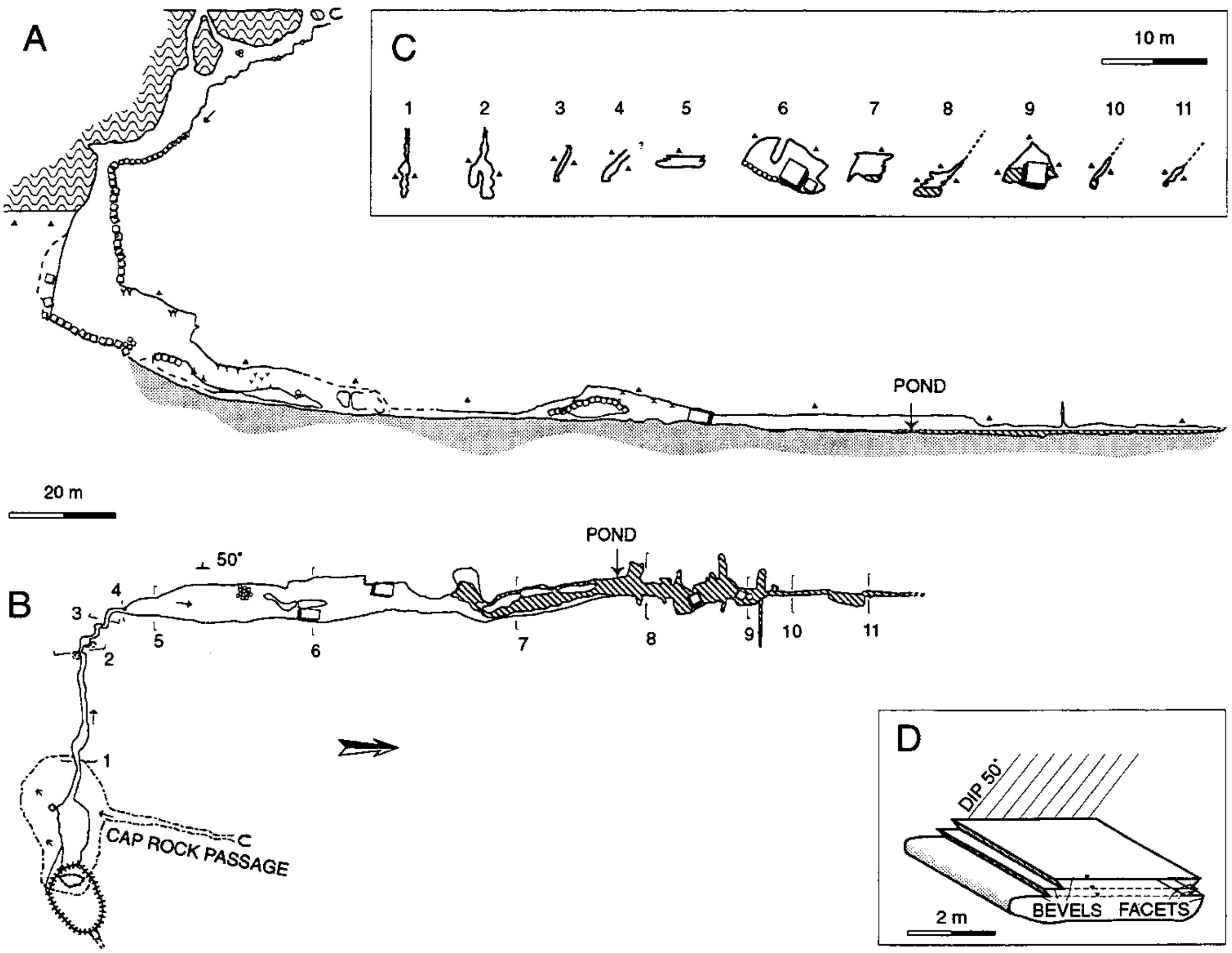


Figure 13. Mifrazim Cave. (A) Profile with 1987 level of flood water pond. (B) Map. (C) Cross sections. (D) Isometric view of the passage at section 5, showing dissolution features with correspondent water levels. The rock salt passage may be divided to three segments: sections 1-4—vadose canyon; sections 5-9—passage widened by pond water; section 10-1—passage tapers where aggressive water hardly arrives.

outlet was observed in five caves. It is readily recognized by an abrupt change in gradient because the beds are sub-vertical. Young unequilibrated passages downcut in the salt until they reach the minimal gradient allowing transportation of their coarse sediment load. The active alluviated channels are apparently adjusted to the present base level of erosion with a profile below which the channel cannot degrade and at which neither net erosion nor deposition occurs (Barrel, 1917). The downcutting process prior to reaching equilibrium may take some hundred years up to few thousand years for the measured downcutting rates of ~1cm/year (Frumkin and Ford, in press). The equilibrium profile is a time-independent configuration, maintained as long as boundary conditions do not change. However, Mount Sedom boundary conditions such as base level elevation do change rapidly. The adjustments of cave profiles to such changes result in multi-phase cave systems in which each storey may have reached an equilibrium state while active. The inactive storeys may be used to reconstruct base level changes. Palmer (1987) suggested using limestone cave levels in a similar way for cases where the piezometric limit can be observed. The high modification rate of salt cave systems suggests that they can yield a much higher temporal resolution. Figure 17 presents a model for profile evolution in a multi-phase salt cave system. For simplification, a cap rock passage was omitted and conduits are represented by straight lines instead of exponential lines. Most integrated cave systems originate as inlet caves, created by a capture of subaerial channel into a cap rock fissure (Fig. 17A).

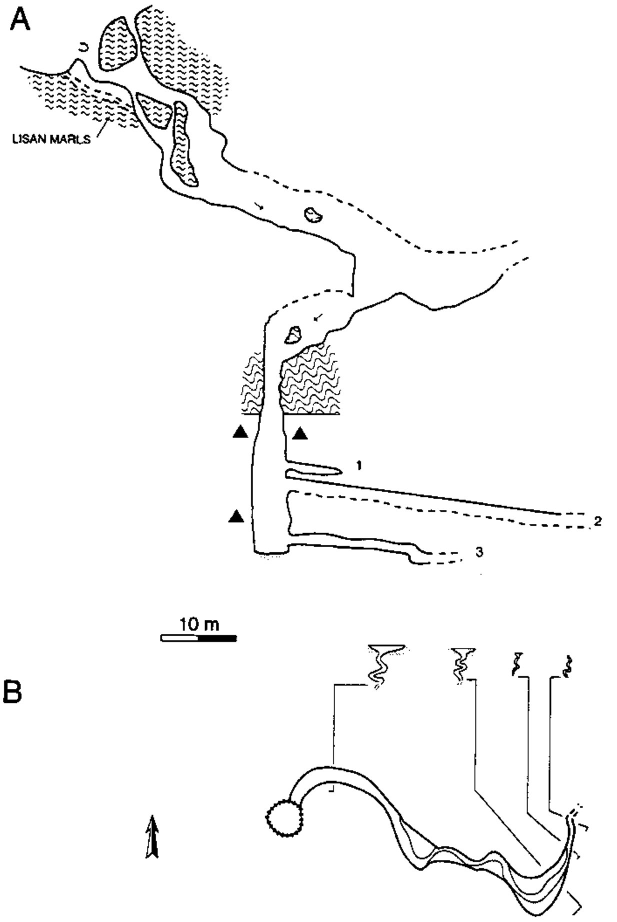


Figure 14. Prahim Cave. (A) Profile showing upper levels in Lisan Marls and cap rock, and three stories of salt passages extending from the shaft. (B) Map and cross sections of salt passage #2.

Diversionary routes are common where earlier conduits are blocked by alluvium, until a conduit connects to an output point and a stable condition is achieved in ground plan (Figs. 8, 17B). If a connection to the output boundary is not established, the cave continues to evolve as an inlet cave. The earliest integrated flow route can be traced along the highest level of some caves in the form of a fissure widened by dissolution (Fig. 9D). Early conduits often follow the shortest route available along the vertical fissure from input to output (Fig. 17C). Consequent downcutting adjusts the profile to base level (Fig. 17D). A change of boundary conditions such as Dead Sea level or diapir uplift is followed by downcutting (Fig. 17E) or paragenesis (Fig. 17F), maintaining grade with the changing base level. This model is comparable to the vadose theories for the development of limestone caves (Warwick, 1953).

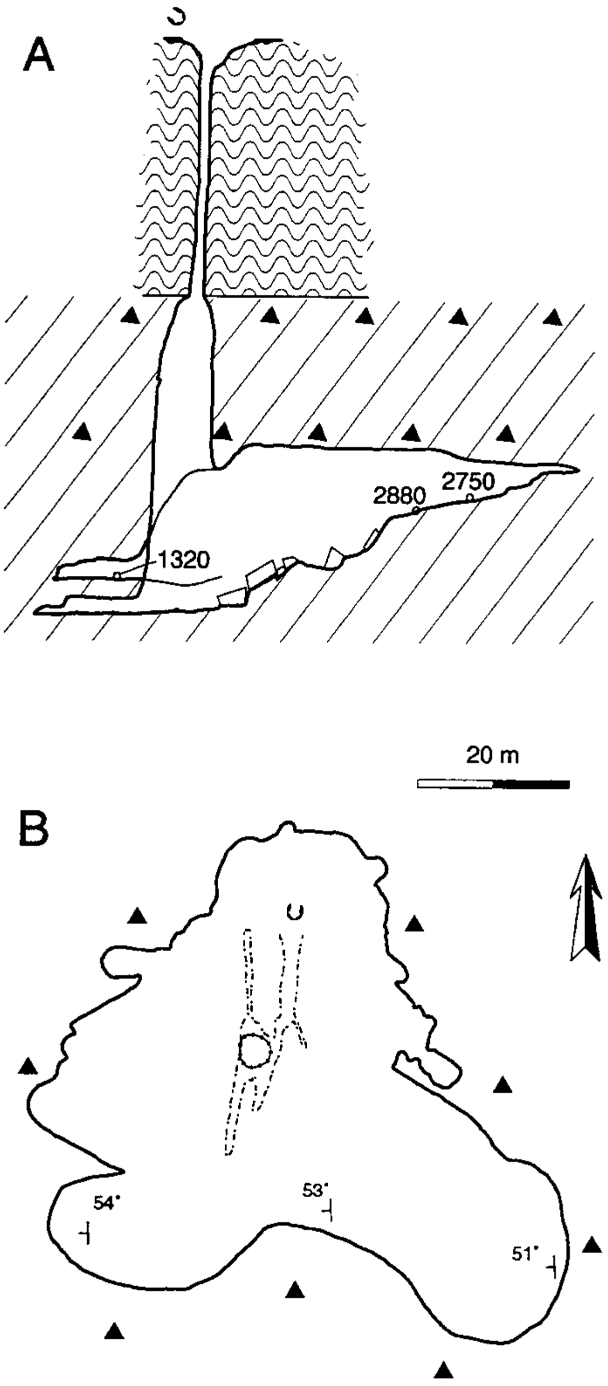


Figure 15. Agam-Yavesh Cave—a typical chamber cave. (A) Vertical section (B) Map. Conventional radiocarbon dates (years BP) of wood fragments are given. The lower western portion contains dry pond features (Fig. 12).

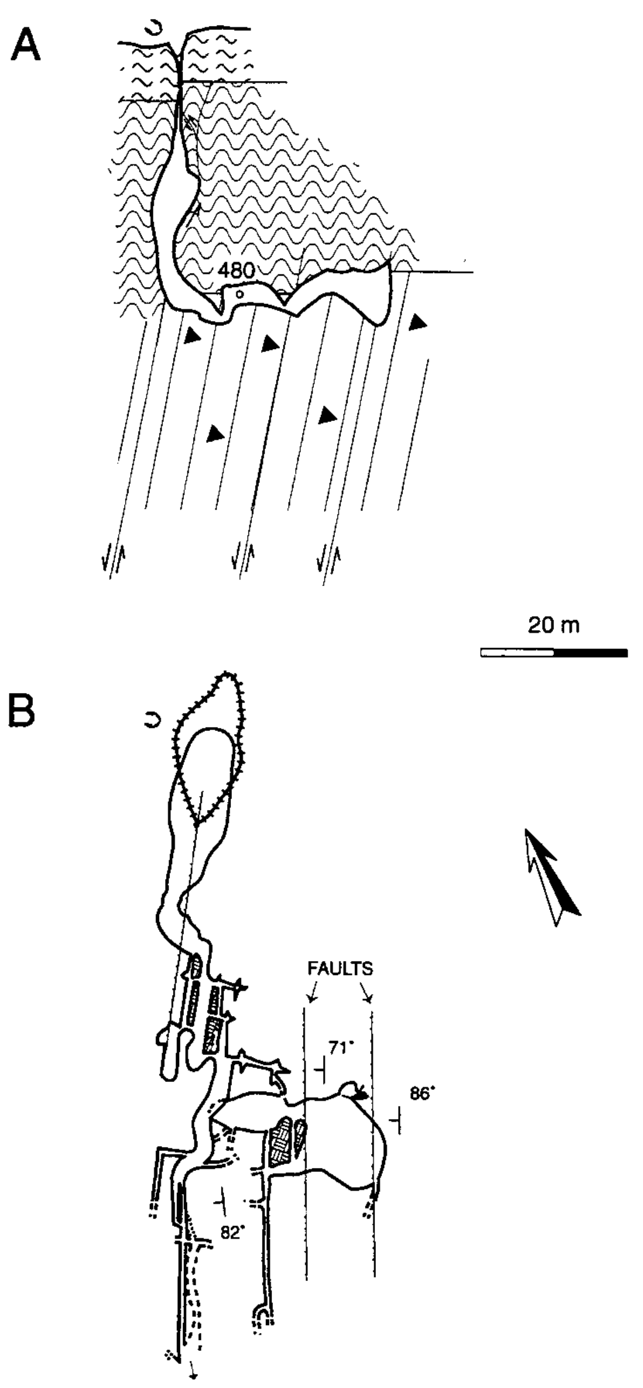


Figure 16. A network maze at the northern end of Karbolot Cave. (A) Vertical section; (B) Map. Radiocarbon dated twig (480 years BP) indicates development during recent centuries.

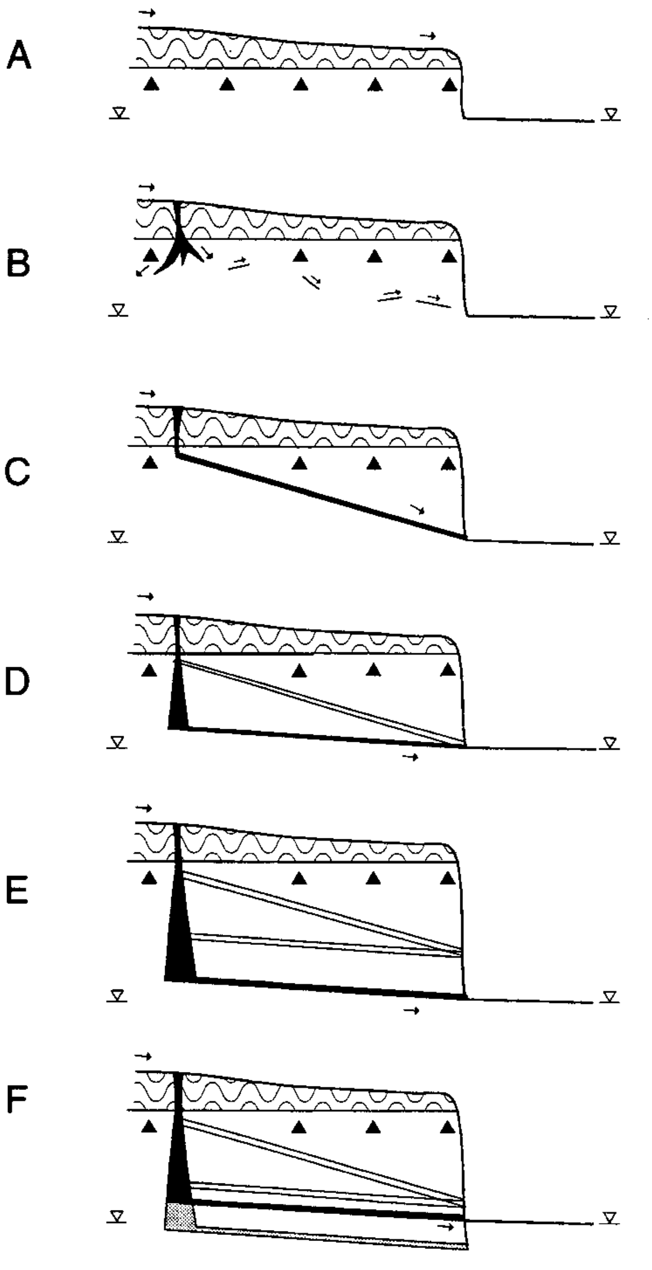


Figure 17. A model for the evolution of a cave system profile. (A) Subaerial channel. (B) A capture into cap rock fissure forms an inlet cave. (C) Input-output connection established. (D) Profile graded to base level. (E) Lowering of base level invokes further downcutting. (F) Base level rising causes paragenesis.

Figure 5 shows a mature cave system whose catchment was captured by a fissure upstream of the sink. The whole evolutionary process starts again in the new cave. Its embryonic conduit is structurally oriented westwards, away from the mature cave. It might either develop into a mature inlet cave or, more probably, connect to the former cave system as has happened in most similar cases. In one case a completely new integrated cave system has developed in this manner.

The subhorizontal passage profile of an inlet cave (Fig. 4) is probably adjusted to fissure width, attaining the lowest level penetrable by the turbulent flow carrying solid load. A later change of the profile is common. Three types of such changes occurred in Prahim Cave (Fig. 14): (1) paragenetic rise of passage #2 caused by alluvial sedimentation; (2) vadose downcutting through the alluvium; (3) diversion to lower storeys.

Downcutting and diversion of inlet cave passages can be attributed either to the rising of the diapir causing fissures to open and gradients to increase, or to gradual dissolution of the cave bottom by infiltrating water, creating a lower cavitiy and increasing gradients locally.

However, many inlet cave channels seem to be relatively stable, probably because the alluvium shields the bottom until conditions change radically.

CONCLUSIONS

The high solubility and physical properites of rock salt, the arid climate and the rapid base level changes of Mount Sedom seem to be unparalleled in other karst terrains. Mount Sedom salt caves share many morphological features with vadose allogenic limestone caves and other features with alluvial streams in arid terrains.

The salt caves of Mount Sedom formed under seemingly contradictory conditions. The arid climate has favoured the rising of a large salt mass above base level without its being dissolved completely. The high solubility and dissolution rate of salt, together with the allogenic nature of recharge and the sporadic intense rains focus an immense dissolution energy along the flood routes. One result is the development of large inlet caves without being integrated to an output. The long interval between successive floods is important, allowing the water enough time to seep slowly to base level. Local rock structure determines the cave patterns, ranging from chamber caves in homogeneous, nonfissured rock, to elongated conduits and mazes in fissured rocks. Hydraulic conductivity and head determine the residence time of flood water in caves and whether interlinked fissures are widened to form a maze. Integrated cave systems are the common end member under high conductivity conditions.

Salt caves appear to be the fastest evolving karst caves (excluding ice cavities). Radiocarbon dates show that a salt cave or a single cave level develops to accessible dimensions in a mere few hundred years (Frumkin and Ford, in press), compared to ≥10,000 years in limestone (Mylroie and Carew, 1987).

Salt cave profiles evolve in a similar way to vadose limestone caves. The rapid rate of evolution and adjustment renders salt cave profiles to be useful for interpreting regional geomorphic evolution.

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