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Distribution, evolution, and morphology of caves in southwestern Samaria, Israel

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ABSTRACT

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Karst has a significant role in the morphology of the Judean–Samarian mountains and may be associated with potential risk to groundwater pollution. Despite this, there is little knowledge of the pattern of karst in Samaria and its origin. The purpose of this research is to characterize the karst distribution and origin within southern Samaria. A karst survey was performed in a 25 km^2 area, in which all the cavities above a volume of 5 m^3 were mapped. In most formations in the Judea Group cavities appear in clusters. Each cluster consists of a big cavity and several other smaller ones. The distribution and intensity of cavities is partially explained by the percentage of insoluble residue in the different formations. Most cavities are small, isolated chambers characterized by limited vertical and horizontal development. The morphology of most cavities indicates that they were formed under shallow phreatic conditions, likely before the last major uplift of the backbone of central Israel.

INTRODUCTION

The mountain aquifer of Israel consists of karstic carbonates and shales of the Cretaceous Judea Group. Karst has significant impact on the potential for groundwater pollution and rain water infiltration in the Judea Group (Boyko et al.,1993; Gvirtzman et al., 1994). Pollution is known to infiltrate faster through karstic rock, which often has significantly higher hydraulic conductivity than unkarstified rock (Ford and Williams, 2007). For example, in the Weradim Formation, following rain events there is an immediate rise in discharge of springs draining the karst (e.g., Even et al., 1986).

Nowadays, this issue is becoming more critical due to the fact that the recharge area of the mountain aquifer in central Israel is under intensive urban and industrial development. The development is usually unaccompanied by facilities for sewage treatment near the source of the pollution, often located in the West Bank (Boyko et al., 1993; Fischhendler, 2007; Cohen et al., 2008). Consequently, the quality of the groundwater aquifer is threatened. This raises an immediate need for land use planning and water pollution risk assessment. In order to do so, there is a necessity to evaluate the distribution and origin of the karst in Samaria. Despite this requirement, knowledge of the karst pattern in Samaria is very limited.

Some caves in western Samaria have been surveyed and studied by the Cave Research Center for the last

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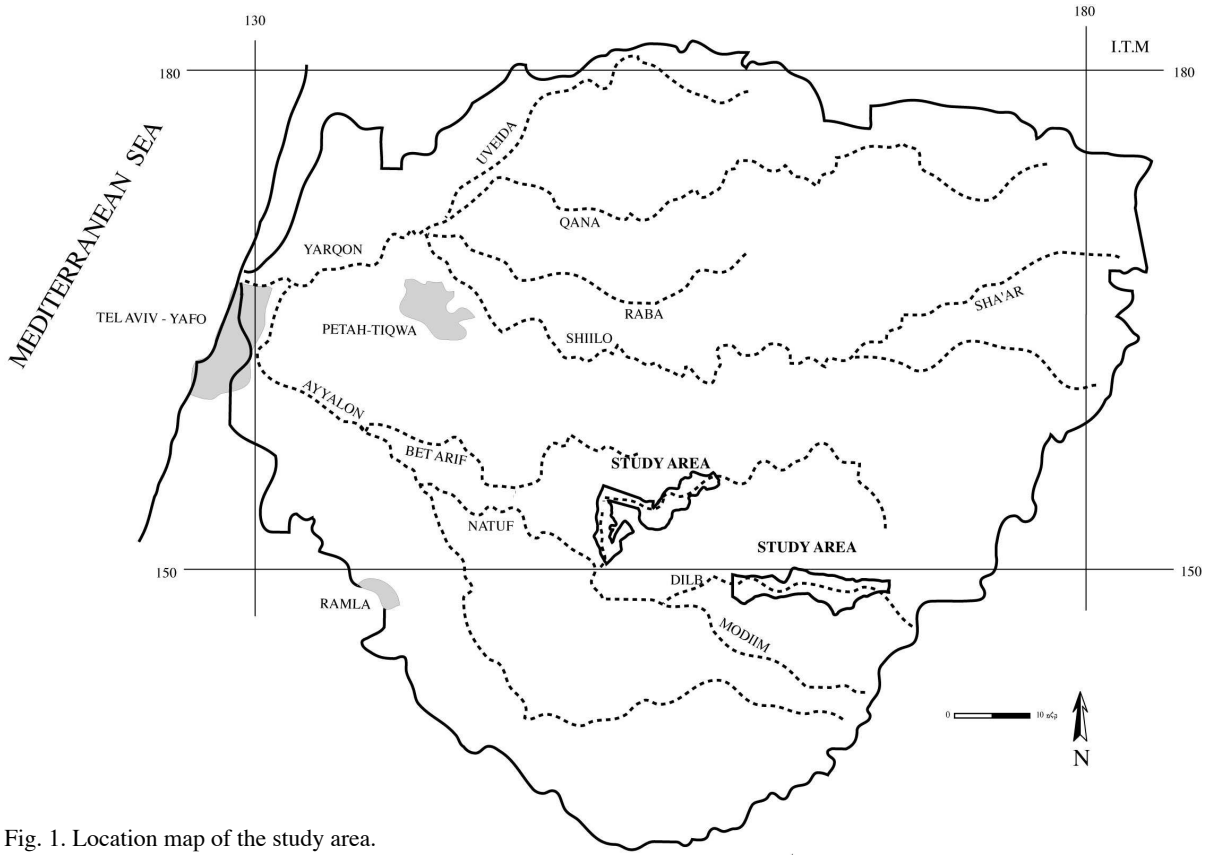


Fig. 1. Location map of the study area.

few decades (e.g., Cohen, 1982; Tsuk, 1983; Frumkin, 1996; Frumkin and Fischhendler, 2005; Frumkin et al., 2009). These studies were mostly based on sporadic information or specific finds attracting special interest. The present study is based on the first comprehensive cave study within a given area of western Samaria, thereby allowing a regional analysis. Within its aerial coverage, this study includes outcrops of formations in which no caves were previously known to exist, hence affording a quantitative geological analysis.

This study is an attempt to determine quantitatively and qualitatively the nature, intensity, and distribution of the karst cavities in the research area of southwestern Samaria. Comprehensive research in a limited study area may enable extrapolation from a small scale to a larger scale to other areas with similar geologic, topographic, and climatic conditions.

STUDY AREA

The research area consists of two sites in the west flanks of the central backbone of Israel (Fig. 1). The first site, with a 15 km^2 area, is stretched along the watershed of Wadi Dilb (one of the tributaries of Modi'in stream). The second site (10 km^2) is in the Wadi Natuf watershed. Both are tributaries of the Ayalon–Yarkon stream.

The two wadis have cut through Judea Group beds of Lower Cretaceous to Turonian age. The downcutting has followed a strong uplift of the mountain backbone during the late Cenozoic (Kafri and Arad, 1978; Bar et al., 2008).

The study area was chosen to include the exposed sequence of the four main regional hydrogeological units (Diamant, 1971): (1) an aquiclude that includes Tammun, Ein Qinya, and Qatana formations, comprised manly of marl sand limestone; (2) the lower aquifer, which includes Kefira, Givat Yearim, Soreq, and Kesalon formations—the lithology of those formations is mainly limestone and dolomite; (3) an aquitard unit separating the upper and lower aquifers, which includes Bet Meir and Moza formations, comprised of layers of marl, thin limestone, and dolomite; (4) the upper aquifer of Judea Group, which includes Amminadav, Kefar Shaul, Weradim, and Bina formations; most of these limestone and dolomite formations

are characterized by dissolution features and high hydraulic conductivity.

The surface karst morphology in the region may be defined as fluviokarst (White, 1988), with a developed subaerial drainage system. Karst cavities are usually small, developed under ancient phreatic or confined conditions (Fumkin and Fischhendler, 2005). Along the study area all the Judea Group formations are exposed, from the Tammun Formation up to the Bina Formation. The eastern, upper part of the study area is characterized by a mild eastward dip; the central area dips steeply westward, becoming milder towards the western, low part of the research area. The entrenchment of the Wadi Dilb and Natuf streams into the Judea Group exposed many karst features such as cavities and fissures enlarged by dissolution. These karstic phenomena are considered to be partly a result of previous phreatic dissolution of groundwater in periods when the sea level and the associated groundwater levels were higher (Frumkin and Fischhendler, 2005). Other phenomena result from vadose dissolution, activated after the drop in the regional base level and water table following the uplift of the mountain backbone in the late Cenozoic. Today, the study area is characterized by a Mediterranean climate with an average precipitation of 500–600 mm per year, mainly in the winter. It is estimated that 25–35% of the annual rainfall over the recharge area infiltrates into the Western Mountain Aquifer (Baida and Burstein, 1970; Guttman and Zuckerman, 1995).

The paleoclimate of the region during the Mid-Late Pleistocene was commonly wetter and cooler than today during most glacial periods (Frumkin et al., 1999, 2000; Vaks et al., 2003; Enzel et al., 2008). Dust contribution from the regional deserts to local soils has also been high, mostly during glacial periods (Frumkin and Stein, 2004). However, the caves were mostly formed in earlier periods, the paleoclimate of which is not well known. Yet, hypogenic cave formation is hardly dependent on local climate (Klimchouk, 2007).

METHODS

A systematic survey of karst phenomena was performed in the study area. The karst features were identified in two main ways. First, by a sequence of air photos. Second, by a field survey of the north and south slopes of the wadis in the study area. The field survey also included a study of road sections along which most of the formations are exposed, including karstic phenomena. The survey's purpose was to search subaerial features of karst, such as dolines, as well as underground cavities. However, since the cavity survey was based on 2D exposure rather than 3D sampling, the number of identified cavities represents a minimum. The actual number of cavities in the research area is expected to be higher.

Karst cavities larger than 5 m^3 were studied by collecting for each cavity the following data:

- x, y, z coordinates;
- Polygon-based survey with a compass, tape, and inclinometer (Frumkin, 1984b);
- The formation in which the cavity appears;
- Volume (in 1000 m^3/km^2), length, and depth (in km^2/km); and number of cavities per km^2. In addition, we measured the average volume of cavities and the standard deviation in the different formations. The cave data were normalized to the outcrop area surveyed in each formation. However, quantitative characterization of the cavities involves some bias: (1) Some isolated cavities were probably larger in the past, before being truncated by fluvial erosion. As a result, the measured parameters are considered to be minimal values, which are good only for relative rating of the karst in the different formations. (2) Areas of the exposed formations were measured on a horizontal map projection. The steep topography and the river meanders increase the actual survey area. (3) The areal size of each surveyed formation outcrop is not constant. In smaller areas, the reliability of the results is also smaller;
- The field lithology of the cavity walls and ceiling. In some cases, it was difficult to differentiate in the field between calcrete (locally termed "nari") crust ceilings and chalk-marl walls. For differentiation we used the porosity, which is up to four times lower in nari than in chalk (Yaalon and Singer, 1974). Using a Schmidt hammer enabled measurement of the compressive strength under field conditions. The Schmidt hammer is a device to measure the elastic properties or strength of concrete or rock, which has been adopted by geomorphologists for a variety of uses, including relative dating, the study of weathering phenomena, and the effects of rock strength on landforms (Day and Goudie, 1977; Goudie, 2006). In our case, since elastic recovery is mainly influenced by the porosity of the rock, the Schmidt hammer indicates the density differences between nari and chalk-marl;
- Each cavity was classified according to its morphology to one of three categories: (1) phreatic/

confined cavity formed below the water table with morphology unrelated to recent conditions; (2) vadose cavity formed above the water table with morphology influenced by recent conditions; (3) cavity formed under phreatic/confined conditions with morphology influenced by a later vadose phase; and (4) cavity formed by weathering of soft rocks;

- The amount of insoluble residue. Rock samples were taken from each cavity whose volume could be reconstructed. In order to avoid a bias in favor of cavities formed in cohesive strata, samples were taken only from cave chambers smaller than 370 m^3. This arbitrary volume was chosen as representative of the approximate mechanical upper limit border of non-cohesive cavities developing in the research area. For each sample, 2 g of ground dried powder were dissolved in 100 ml 8% HCL. The residue was washed, dried, and weighed.

CAVE DISTRIBUTION IN DIFFERENT FORMATIONS

Most studied cavities are small, isolated chamber caves (Frumkin and Fischhendler, 2005). A basic assumption was that the geological formations have a major influence on nature, intensity, and distribution of cavities. This assumption was based on the fact that the different formations have unique lithologic, stratigraphic, and tectonic features. The cavities in each formation were divided into 4 volume categories and projected on a map of the study area (Figs. 2 and 3).

The results of the analysis are: (1) cavities are not scattered homogeneously but often appear in clusters. This distribution is noticeable in Ein Qinya, Qatana, Kesalon, Kefar Shaul, and Bina formations. In contrast, Givat Yearim and Weradim formations demonstrate a homogeneous distribution of cavities. A typical example of a cavity cluster is found in Ein Qinya Formation (Fig. 2); (2) each cluster usually consists of one large cavity and a few small ones; (3) the volume of the cavities varies according to formations. Larger cavities developed in Kesalon, Amminadav, Weradim, and Bina formations, in contrast to Ein Qinya, Givat Yearim, and Beit Meir formations, where only small cavities have developed; (4) the volume variability of cavities in the different formations is significant. This diversity is especially noticeable in formations with large cavities; and (5) many cavities appear in chalk (Kefar Shaul) and marl (Qatana) lithologies.

MORPHOMETRIC ANALYSIS

Table 1 illustrates the quantitative characterization of the cavities for the different formations.

The Kesalon and Weradim formations are characterized by relatively large cavity volume per area. In the Weradim Formation, the volume is associated with a few exceptionally large cavities; in the Kesalon Formation, the large volume comprises a large number of cavities per area and one exceptionally large cavity. In contrast, Tammun, Givat Yearim, Soreq, Moza, and Bet Meir formations are characterized by small cavity volume per area. Figure 4 depicts the number of cavities in each formation according to volume (four categories) and height (three categories), and

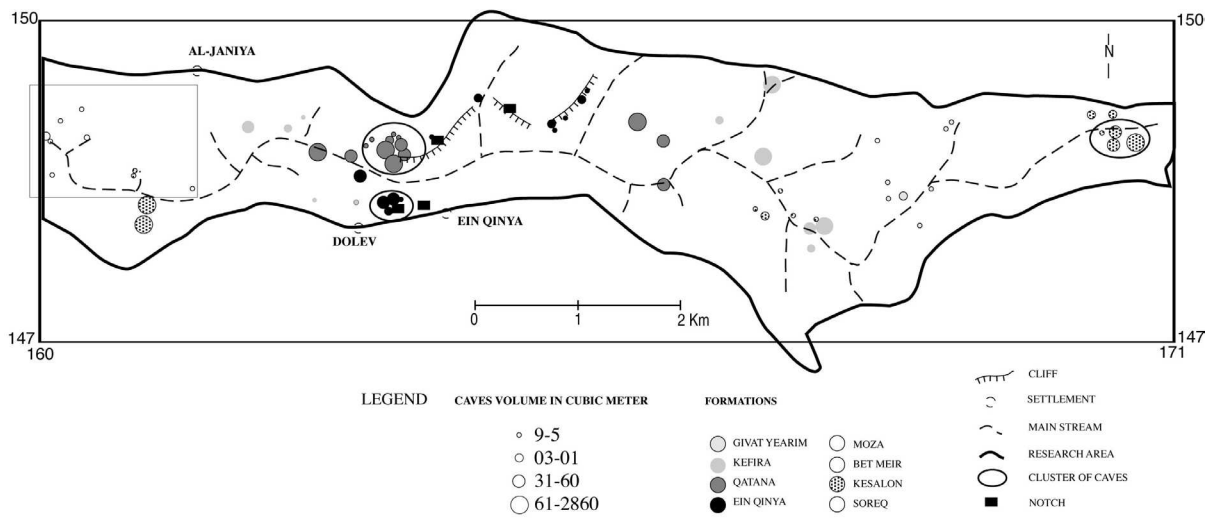


Fig. 2. Cavity distribution in Wadi Dilb according to volume and formation.

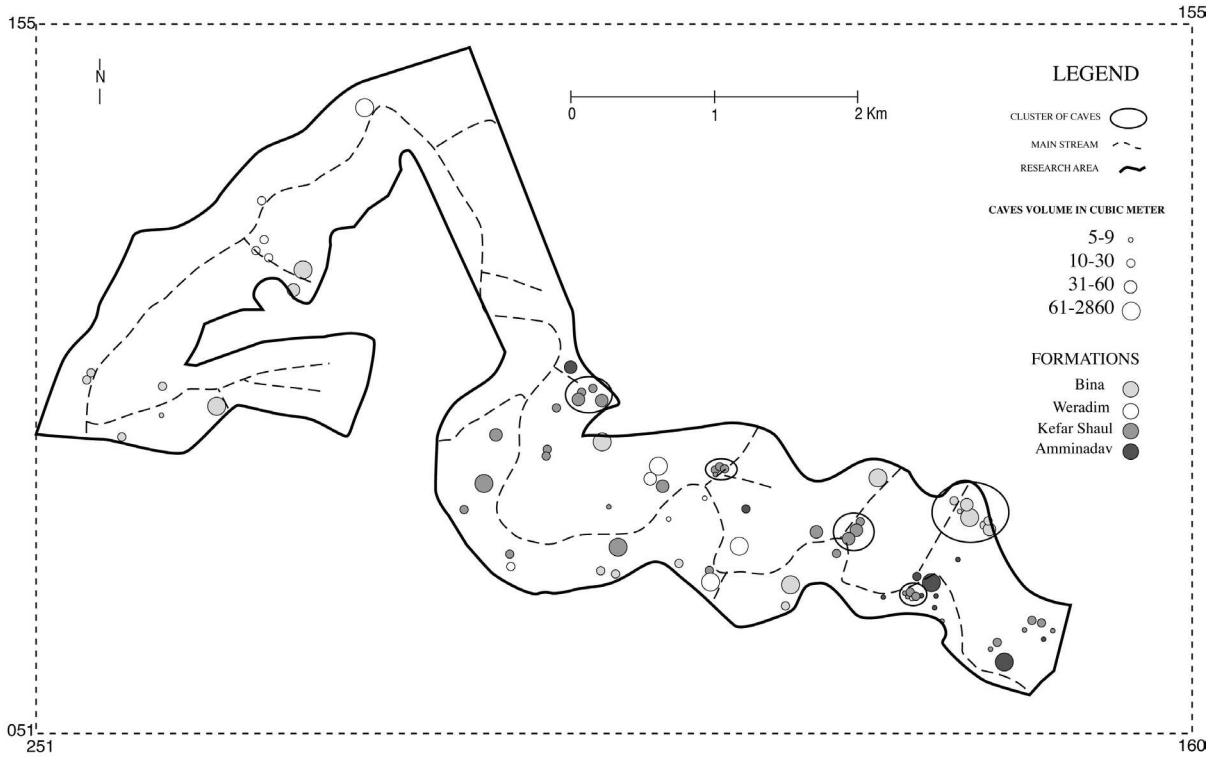


Fig. 3. Cavity distribution in Wadi Natuf according to volume and formation.

also indicates that cavity frequency decreases in most formations as the volume and height of the cavities increase.

Eighty-five percent of the cavities have volumes smaller than 60 m^3. Large cavities were found in the Qatana, Kefira, Kesalon, Amminadav, Weradim, and Bina formations, but exceptionally large cavities were found only in the Kesalon and Weradim formations. In Kefar Shaul and Kesalon formations, the number of cavities per area is much larger than in other formations. In comparison, Tammun, Soreq, and Bet Meir formations are characterized by a small number of cavities per area (Fig. 5).

Only in a few formations was a correlation found

Table 1
Quantitative parameters: Summary for the different formations

	A	N	AV	S	D	L	V
Bina	2.16	10.10	46.60	6.90	20	100	0.47
Weradim	1.95	4.60	374.00	30.50	20	70	1.72
Kefar Shaul	1.65	23.63	24.20	2.80	30	200	0.57
Amminadav	1.30	8.46	56.48	10.20	20	90	0.47
Moza	0.23	8.77	6.40	0.57	10	50	0.06
Bet Meir	1.47	2.72	9.05	6.14	0	20	0.02
Kesalon	0.50	19.84	211.62	23.55	40	200	4.20
Soreq	2.18	0.91	3.58	0.77	0	0	0.00
Givat Yearim	1.64	4.02	6.04	1.60	10	30	0.03
Kefira	4.60	3.69	27.00	6.20	10	30	0.10
Qatana	1.62	8.02	41.18	6.10	20	100	0.33
Ein Qinya	1.18	11.01	19.50	4.00	30	70	0.21
Tammun	0.93	0.00	0.00	0.00	0	0	0.00

A—Size of survey area (km^2); N—number of cavities per area (km^{-2}); AV—average volume of cavity (m^3); S—standard deviation of cavity volume; D—cumulative cavity depth (m km^{-2}); L—cavity length (m km^{-2}); V—cavity volume (10^3 m^3 km^{-2}); N, D, L, and V are normalized by survey area.

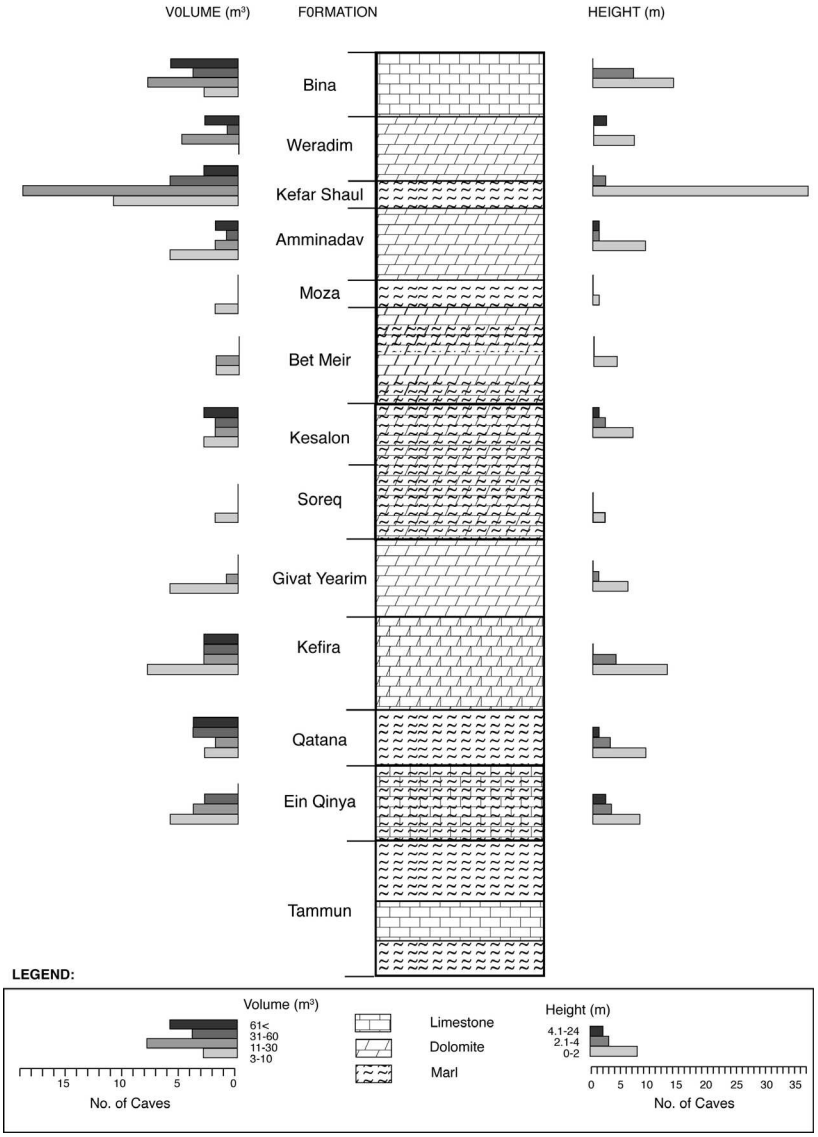


Fig. 4. Frequency of cavity's volume and height for the different formations.

between the number of cavities per area and their mean volume. These include Tammun, Moza, and Kesalon, showing a positive relationship. This suggests that the volume of cavities and the number of cavities per area are not influenced by the same factors.

The tendency of cavities to appear in clusters suggests two possibilities. First, there are preferable foci, where the development of karst is encouraged. The second is that the existence of one cavity promotes the development of additional nearby cavities with a positive feedback mechanism. The lack of physical connection between individual caves in most of the studied cave clusters does not support the latter process.

As shown above, many of the cavities developed in massive to well-bedded formations such as Kesalon, Amminadav, Weradim, and Bina. Bedding planes were often found to serve as initial flow routes for aggressive water (White, 1960; Ford and Williams, 2007). Indeed, the slope of many small cavities tends to follow the bedding plane dip (Fig. 6). In addition, those cavities are often located between two bedding planes. The control of bedding planes is less apparent in large cavities where chambers stretch beyond and transcend the bedding planes. In addition, the lack of water table morphology (such as horizontal notches) renders it difficult to identify whether the cavities developed before or after the regional tilting of the strata.

Most parameters used for karst intensity indicate

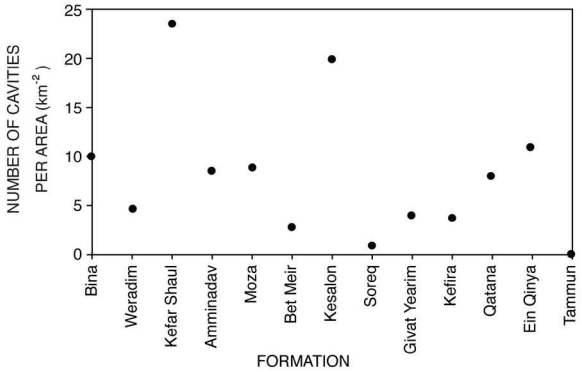


Fig. 5. Number of cavities per area for the different formations.

that karst is intensive in Kesalon, Amminadav, Weradim, and Bina formations, while in Tammun, Soreq, Kefira, Givat Yearim, Moza, and Bet Meir formations, karst is depressed. These differences suggest that in some formations there are "favorable" conditions for karst development. These findings are in line with previous studies (Israeli, 1973; Keshet and Mimran, 1979; Frumkin and Fischhendler, 2005; Frumkin and Gvirtzman, 2006) reporting a major influence of Judea Group formations on the distribution of karst.

Limestone and dolomite are not always more karstified than chalk and marl. This result suggests that other factors, besides lithology, influence cavity development. The geological history of the region will be hereafter considered.

KARST MORPHOLOGY AND ORIGIN

The mountain backbone of Judea–Samaria experienced a major uplift during the late Cenozoic (Bar et al., 2008). Consequently, the water table dropped below parts of the Judea Group that were formerly under saturated conditions. As a result, the studied cavities are presently above the water table. This change in the water table may cause uncertainty of cave origin associated with multiphase cave morphologies. In addition, the Judea Group carbonates are intercalated by many marl beds, and the Judea Group was capped in the past by the impermeable Mount Scopus Group. These stratigraphic conditions may have induced confined flow conditions. This change in the regional hydrologic regime causes uncertainty whether the karst was formed under phreatic or under confined conditions. Where possible, the morphology of the cavities is used as an indicator for the speleogenetic process (e.g., White, 1977).

Phreatic and confined zone cavities

Most of the cavities in the research area are characterized by "phreatic" morphology, such as wide and low elliptical cross sections of the cave passage (Fig. 7). This section reflects the low-pressure regime of shallow depth in which the cavities were formed (Davis, 1960; Frumkin and Fischhendler, 2005). In addition, cavities formed near the water table are characterized by a small vertical dimension (White, 1988). The cavities frequently have one main chamber with a few secondary narrow passages diverging in straight lines from the main room. Clear, gravitational, vadose flow routes are not observed. Other criteria which we used to identify phreatic morphology in cavities were smooth and rounded walls and ceilings and solution pockets. However, this morphology may be associated

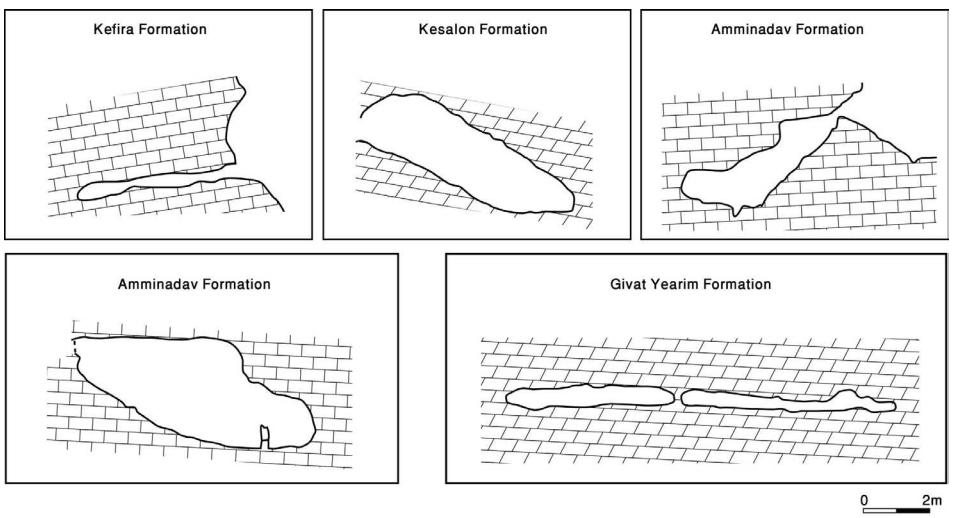


Fig. 6. Bedding plans and several of the cavities' identities.

at times with partial confinement and/or hypogenic flow, although upward flow trails are not observed (Klimchouk, 2007).

Condensation corrosion forms, such as smooth cupolas, often over-imprint the phreatic/confined morphology, but they are vadose features (Dreybrodt et al., 2005). The observed chamber-like macromorphology is in contrast to many confined/hypogenic caves commonly characterized by intricate systems of maze-like passages (Klimchouk, 2000; Frumkin and Fisch-hendler, 2005; Klimchouk, 2007). This type of cavity, as well as wide voids typical of flank margin caves (Mylroie and Carew, 1988), are infrequently observed in the study area.

Cavities formed under vadose conditions

Vadose caves are formed by gravitational water flow along air-filled voids (White, 1988). Water flowing downwards dissolves the walls of initial fissures. Vertical shaft morphology with dominant vertical dimension is common in vadose caves of the region (Frumkin, 1984a). In order to quantify the vertical dimension, the maximal height difference between the floor and the ceiling of each cavity was measured. The data were divided into three height categories (Fig. 4). High cavities are uncommon. In most of the formations the total vertical extent is limited and does not extend more than a few meters. Also, most of the cavities with large vertical dimensions are concentrated in the Ein Qinya, Amminadav, and Weradim formations. In the Weradim Formation, one of the two cavities with exceptional vertical dimension has phreatic/confined morphology. In the Amminadav Formation, two cavities with exceptionally large vertical dimensions display vadose morphology.

In conclusion, most of the cavities have limited vertical dimensions, which indicates that they were not shaped under vadose conditions; however, the existence of a few exceptional cavities with a considerable vertical dimension indicates intensive vadose potential, especially in the Ein Qinya Formation. Cavities with a relatively large vertical dimension often develop along vertical fractures in their ceiling. These fractures are likely to act as conduits for aggressive water from the surface to the cavities, allowing gradual widening of the cavity. Other evidence of vadose activity in this formation is speleothems found in many cavities. In spite of this, the vertical extent is limited even in the Ein Qinya Formation.

Figure 8 shows a typical vadose cavity located in the Ein Qinya Formation. The cavity is characterized by a significant vertical dimension and seems to follow a vertical joint in its ceiling. In spite of this, the vertical extent is limited, even in this formation.



Fig. 7. A typical phreatic/confined cavity in Amminadav Formation in dolomite rock.

Cavities with calcrete ceiling

Some of the cavities in the Qatana and the Kefar Shaul formations appear in soluble but low cohesive chalk-marl breccia. The cave ceiling did not collapse, mainly because it is comprised of indurated calcrete (nari), having better mechanical strength than chalk-marl (Hazor et al., 1997). The distinction between the nari roof of the cavities and the chalk-marl walls is based on two parameters: (1) the tendency of the nari to follow the gradient of the slope and cover it, unlike the chalk-marl layers; (2) the distinct contact line between nari and chalk-marl.

The morphology of these cavities is similar to the morphology of phreatic/confined cavities, with some modification by recent weathering. The volume is usually limited, but a few relatively large cavities indicate the mechanical ability of nari to support ceilings as wide as 9 m.

The floor of these cavities is partly covered by boulders that disintegrated and collapsed from walls or ceilings. The boulders indicate that weathering and breakdown took part in cave formation. It is difficult to quantify the contribution of mechanical weathering to cavity volume, but the fact that the cavities are not blocked by sediment indicates that some weathered material was likely removed by dissolution.



Fig. 8. A typical vadose cavity in Ein Qinya Formation.

CAVE DISTRIBUTION AND INSOLUBLE RESIDUE

It is assumed that the fraction of insoluble residue in the strata influences the development of karst (Rauch and White, 1970, 1977; White and White, 1989; Ford and Williams, 2007). The insoluble residue, composed mainly of clay and silicate minerals, is released from the rock during the process of dissolution. It accumulates along tight fractures and reduces their permeability. In addition, the clay minerals may coat the carbonate crystals, protecting them from further dissolution (Rauch and White, 1977). It has been argued that as insoluble residue increases above 14%, subsurface karst is depressed, while above 20%, subsurface karst tends not to develop. In the Judea Group there are many shale layers with a high content of insoluble residue. Their influence on karst development is studied by correlating cavity distribution with the percentage of insoluble residue.

Figure 9 indicates that an insoluble residue above 8% tends to depress the development of large cavities. This is likely caused by clogging of initial flow routes by the insoluble residue, preventing them from further enlargement (Ford and Williams, 2007).

Cavities tend to develop in the Bet Meir and Moza formations in spite of their high percentage of insoluble residue (Fig. 10). The Kefar Shaul and Kesalon formations also exhibit a significant insoluble residue and yet tend to show the highest number of cavities per area. Both abnormalities suggest that additional factors control the karst pattern, in particular where insoluble content is lower than 8%. Most of the cavities are characterized by shallow phreatic morphology, suggesting they were formed before the major late Cenozoic uplift of the mountain backbone (Horowitz, 1980). The current steep relief encourages runoff rather than infiltration, and the many marl layers probably inhibit intensive vadose dissolution.

POSSIBLE AGE OF KARSTIFICATION

Some cavities in chalk-marl breccia have phreatic morphology, but the roof of the cavities is composed of

nari. Nari results from a pedogenetic process that occurs only in the soil-epikarst zone (Yaalon and Singer, 1974). Some of these cavities developed in breccia, consisting of limestone boulders supported by chalk-marl matrix. Karstic cavities in breccia often indicate a new dissolution cycle in an ancient paleokarst (Buchbinder et al., 1983; Ford, 1995).

Paleokarst cavities experienced a long phase of inactivity when no dissolution occurred. During that time they likely became filled by rock fragments forming brecciated sediment. The breccia turned them into a new dissolution and weathering target, taking advantage of its high porosity. The extent of the new dissolution cycle is usually limited, forming only small cavities (Ford, 1995).

A Miocene dissolution cycle that followed Turonian paleokarst was noticed in the Bina Formation in Samaria (Buchbinder et al., 1983). The initial karstification became possible due to subaerial exposure about 50 m asl. Dolines formed during the Turonian and were later filled by breccia, which became a focus for a new cycle of dissolution in the Miocene. The cavities in breccia of the Kefira, Qatana, and Kefar Shaul formations cannot be attributed to Turonian regressions because of insufficient relief during that time, as a relief of more than 50 m probably did not occur before the Oligocene (Buchbinder et al., 1983). The paleokarst thus may indicate an initial dissolution cycle during the major Oligocene uplift associated with the first complete exposure of the mountain backbone. The karst features may have developed under phreatic conditions that determined the initial morphology of the voids. The latest vadose dissolution and weathering cycle (after the development of the nari) may have utilized the early phreatic karstic foci.

The morphology of most cavities indicates that they were formed under the water table, most likely Neogene groundwater levels, the remnants of which are presently found at several altitudes, including the 300–400 m contour (Fink, 1963; Picard and Wakshal, 1977; Kafri and Arad, 1978; Arkin, 1980). This argument is based on the assumption that when groundwater levels prevail for a long period of time close to the surface, intensive dissolution occurs and, consequently, karst develops (Davis, 1960). It has been argued that these groundwater levels originated in the fourth transgression, which flooded the foothills of Judea and Samaria (Neev, 1960; Gvirtzman, 1970). This argument requires further examination.

If some of the studied cavities were formed under unconfined conditions, it follows that the major confining unit, the Mount Scopus Group, had already

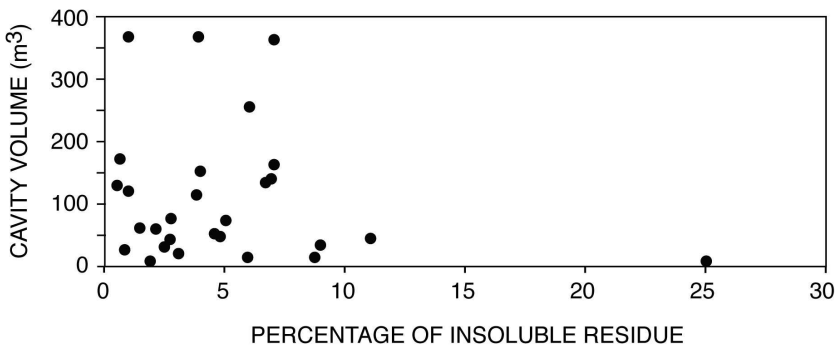


Fig. 9. Percentages of insoluble residue and number of cavities per area.

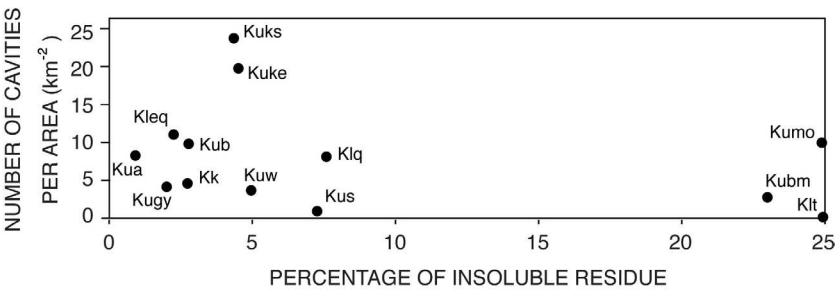


Fig. 10. Percentages of insoluble residue and cavities volume per area.

been eroded, so the aquifer was partly under phreatic conditions. These findings are supported by wide evidence indicating that since the Turonian, the backbone of Israel has been subaerially exposed several times (Buchbinder et al., 1983). Some of the cavities may be attributed to a considerable relief (Gvirtzman, 1970) most likely associated with the extensive erosion that truncated the Mount Scopus Group.

CONCLUSION

In most formations, cavities are scattered inhomogeneously in space, appearing in clusters. The larger the volume of the cavities, the lower their frequency. Eighty-five percent of the cavities have volumes smaller than 60 m^3; the variability of their volume in the different formations is very large. Some formations are favorable for karst development (Kesalon, Amminadav, Weradim, and Bina), while in others the karst is depressed (Ein Qinya, Givat Yearim, Moza, and Bet Meir). The distribution and intensity of cavities is partially explained by the percentage of insoluble residue in the different formations.

Most of the cavities are characterized by a small vertical extent and limited horizontal development. Despite being under prolonged vadose conditions, the morphology of many cavities indicates that they were formed under shallow phreatic conditions, probably before the last major uplift of the backbone of central Israel, but after the truncation of the impermeable Mount Scopus Group.

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