CHAPTER 5

CLIMATE AND HYDROLOGY

As there is no meteorological station in the study area, climatic data of the nearest stations were correlated. These are the stations in Bir al Ghanam to the north and in Yafrin to the south, both being about 12 km from the geographical center of the karst area. The Bir al Ghanam Station is located on the Jeffara Plain, the one in Yafrin on the top of the Jabal Nefusa. Based on sporadic observations and incomplete records the main long term average climatic data are shown in the table:

	Yafrin	Bir al Ghanam	Abu an Niran
Elevation (m)	680	143	340
Min. temp. (°C)	9,1	11,5	10,0
Max. temp. (°C)	27,5	32,0	30,0
Mean temp. (°C)	18,5	21,9	20,0
Rainfall (mm)	260,8	134,5	200,0
Number of rainy days	55+	no info	no info

+ information only in 1971-72

According to its geographical position, the normal values in Abu an Niran were considered to be the averages of the data in the two stations.

The climate of the Bir al Ghanam Karst is pre-desert according to its Martonne aridity index:

$$i = \frac{\text{rainfall}}{average\ temp. + 10} = 6.7$$

or arid by its Emberger index:

$$i = \frac{2000\ x\ \text{rainfall}}{T_{\max^2} - T_{\min^2}} = 34.13$$

(T = temperature)

Using more common words, the area is desert or semidesert.

Two kinds of runoff occur in the outcrop of the Bir al Ghanam Formation:

1 Transit runoff forms the sort of streams that originate either on the top, or on the slopes, of the Jabal Nefusa on other than gypsum terrain. These streams have very high hydraulic gradients. The gradient of the hydrological system of the Wadi at Tall is 4%. The effect of erosion is very strong, and the exposure of weakly resistant gypsum has completely vanished in the stream profiles.

2 The precipitation which falls on the surface of the gypsum outcrop will run off in two different ways:

a. Sheet flow, of which the weathering effect is surface solution since the primary porosity of the gypsum is almost nil.

b. Stream flow which concentrates the waters of the sheet flow. Because of the great solubility of the rocks the streams will be deeply cut. The streams flow on the surface until they meet the "planes of weaknesses" and infiltrate in quantities increasing with time. As the dissolution of the rock along the "weaknesses" advances in time, swallets develop. The "weaknesses" are joints and bedding planes (secondary porosity). At favorable places the secondary porosity becomes underground conduits and later caves of a size large enough to take in the entire surface runoff of a wadi, which then becomes underground-runoff. The valley beyond the swallet becomes a dry valley.

Underground runoff develops only in relatively short stream beds since, in the case of too large quantities of runoff, the effect of the erosion is stronger than infiltration/solution. The underground streams emerge to the surface in resurgences – karstic springs.

The fifty five rainy days recorded in Yafrin caused only sixteen floods in the Wadi at Tall in the 1971-72 hydrological year, all occurring between September and May. The Wadi at Tall is the recipient of a large hydrological basin, it receives the runoff of what are generally short duration, high intensity rains and receives a relatively large number of floods. This cannot be expected of its tributaries that may or may not contribute to any particular flood.

The caves did not flood in the period of the field work (25th March - 6th June, 1981) in spite of some heavy rainfall. Floods, or their effects, however, were observed in the preceding period. The preliminary study of the Abu an Niran Karst was started in November, 1978 which was, coincidentally, a rainy period following a completely dry summer. In spite of the heavy rains and floods in the wadi at Tall the caves remained dry. There were pools in the deeper reaches of the caves, thin gypsum crusts floating on their surface proving that the water was of no recent origin. Weekly observation revealed that until the end of the rainy period (end of April), the caves flooded only two or three times. No rainfall and runoff records have ever been made in the area under study, and thus it is not easy to correlate the hydrological factors.

By luck, one of the floods (February, 1979) was observed directly. The flood was preceded by 12 hours of light rain which varied in intensity. Then there followed a 15 minute shower of extreme intensity and within five minutes surface runoff started instantly flooding the cave. The flood lasted about two hours. It was observed where it occurred in the AN-3 cave system.

Photograph 46: Flood in the Hyena cave's AN-1-6 swallet (pic46.jpg) (see Photograph 25 too)

The value of this observation was that it can now be stated under what conditions and for what duration the runoff occurs in the gypsum area. Thus for any runoff exceptional conditions are necessary, the valleys that originate within the gypsum hills do not flood more than several hours annually in the rainy winter season. Indirect observations gave some more information regarding the cave floods. The 1980-81 winter was very wet. The rains started at the end of September with such intensity that the caves flooded immediately. The effect was that the caves were polluted by quantities of sheep dung washed in from the surface. Deposition of the material which had been washed in and the temporary lake formed (the area it covered was observed the next day) in AN-1-6 swallet showed that the caves could not cope with the large amounts of runoff, and the flood had been temporarily dammed. Later observations (Spring 1981) showed that the dung had gone, proving the occurrence of successive floods. In spite of all uncertainties the quantity of runoff per km^2 can be estimated. The number of rainy days registered in the rainy season of the 1971-72 hydrological year at the Yafrin station was fifty five. According to observations rainfall of less than 10 mm/day has no hydrological effect. The precipitation was less than that for 42 rainy days at Yafrin, leaving only 13 days during which runoff could start in the area of the station which delivered water to the Wadi at Tall. (Other floods in the Wadi at Tall are due to rainfall in other parts of its hydrological basin). The 13 rainy days supplied 74% of the annual rainfall at Yafrin (371,8 mm in 1971-72). Expecting the same proportions in the Bir al Ghanam Karst the effective normal rainfall would be 148,0 mm, that is, 148,000 m^3/km^2 of runoff. As the estimation of this number is very indirect it must be treated with caution. The precipitation at the foot of the escarpment will be less.

The floods in the wadis and consequently in the cave are the typical devastating *flash floods*, a desert phenomenon, happening in a matter of minutes ruining bridges and carrying heavy trucks away, very dangerous in caves. The author and company were hit by one in the Hyena cave in the relatively spacious spring passage.

Quantities of runoff – proportional to the catchment areas of the swallets in the gypsum karst – will sink and re-emerge in the karst springs. The waters join one of the main recipients to be lost to infiltration in the Jeffara Plain. As a result the area has no water resources, it has been abandoned and is uninhabited. The idea of surface water reservoirs in valleys was considered and then rejected because of the lack of sufficient dam sites.

The catchment and storage of the underground runoff in the caves seems to be a strikingly simple possibility for the development of reservoirs. Details of the feasibility and practicality of water storage in the caves will be discussed in Chapter Eight raising the problems of environmental nature .

Any mention of stagnant waters and water filled passages applies only to the summer of 1981. In other drier or wetter years the situation may be different.

CHAPTER 6

ANALYSES OF ROCK AND WATER SAMPLES, SOLUBILITY

6.1 Rock Analyses

Over 50 soil and rock samples were taken from the study area. The sampling was concentrated on the cave-areas. The analyses of the rock samples were made in the X-ray and DTA (derivatograph) laboratories of the Hungarian Geological Institute.

List of samples

1 yellow clayey marl, Bu an Niran Member, Abu an Niran

2 red clay, Bu an Niran Member, Abu an Niran

3 light-gray gypsum, cave, near AN-1-5 swallet

4 white gypsum, cave, between AN-1-,4 and -5 swallets

5 white gypsum, cave, at AN-1-4 swallet

6 light gray gypsum, cave near AN-1 spring

7 yellowish white gypsum, cave at AN-1-1 swallet

8 light gray gypsum, cave, AN-4 spring

9 light gray gypsum, cave, AN-4-1 swallet

10 dark gray gypsum, cave, at ZG-1-10 swallet

11 yellowish gray gypsum, cave, near ZG-1-6 swallet

12 white gypsum, cave, near ZG-1-6 swallet

13 anhydrite, ZG-1 cave, at the 800 m section

14 yellowish gray gypsum, cave, north of ZG-1-1 swallet

15 light gray gypsum, cave at WF-4-1 swallet

16 yellowish gray gypsum, cave at WF-1 spring

17 white gypsum, cave, at WF-1-6 swallet

18 porphyric gypsum, cave, BA-1 swallet

Results of the X-ray diffraction analyses: (%)

No. of sample	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*
Mineral																		
montmorrilonite		6																
illite-montmorillonite	2	6																
illite	9																	
kaolinite	4	12																
quartz	8	34																
gypsum	1		100	97	99	98	100	99	100	100	99	100	1	100	99	100	98	99
anhydrite			tr	tr	tr	1	tr	tr	tr			tr	99		1	tr	1	tr
potash feldspar	6																	
calcite	10																	

dolomite	66	29																
hematite		7																
celestite				3	1	1		1			1						1	1

tr = traces

List of samples analysed by DTA (derivatograph):

1 yellow clayey marl, Bu an Niran Member, near BA-1 cave

2 brownish-red clay, Bu an Niran Member, near BA-1 cave

3 red gypsum concretion, Bu an Niran Member, near BA-1 cave

4 light gray gypsum, cave, north of AN-1-5 swallet

5 white gypsum, cave, branch from AN-1-4 to AN-1

6 light gray gypsum, cave, near AN-4 spring

7 clayey marl, cave, near AN-4-1 swallet

8 gray gypsum, cave, in ZG-1-10 swallet

9 yellowish white gypsum, cave, ZG-1-6 swallet

10 white gypsum, cave west of ZG-1-6 swallet

11 yellowish gray gypsum, cave west of ZG-1-1 swallet

12 loessy soil, west of Qasr Abu an Niran, from O-5 cm depth

13 loessy soil, west of Qasr Abu an Niran, from 5-40 cm depth

14 loessy soil, west of Qasr Abu an Niran, from 40-60 cm depth

15 concretion from loessy soil near Takbal

Results of the DTA (derivatograph) analyses:

No. of sample	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
Mineral															
gypsum %	3	tr	98	92	95	95	tr	97	91	98	98				55
dolomite %	50	11		7	4	2	7		4	tr	2				55
calcite %	10		0.4									27	44	55	9
other %(clay minerals and quartz	30	30										72	56	33	

6.2 Water Analyses

Samples of water were collected from the locations listed below:

1 WF-1 spring cave

2 stream in the Wadi Fasat near WF-1

3 cistern near WF-7 cave 4 WF-7 cave

5 stream at the palm grove downstream of WF-7 spring 6 AN-1 spring cave

AN-4 spring cave ZG-1-6 swallet

ZG-1-1 swallet

ZG-1 spring cave

Ain al Mizraq (southeast of Mizdah, see in Chapter 9)

Results of water analyses in mg/l:

No. of sample	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
Dissolved solids											
TDS	3327	3521	167	3624	4026	3367	3431	2965	3248	3315	1614
Chlorides	293	248	9	195	346	230	319	213	248	257	124
Sulphates	1779	1895	trace	1792	2093	1746	1742	1576	1730	1730	719
Calcium	728	700	40	620	910	620	620	660	660	656	310
Magnesium	32	73	4	114	31	122	120	50	80	84	34
Sodium	141	153	6	129	225	145	180	107	137	141	115
Potassium	10	7	5	9	7	6	12	10	6	6	8

The analyses were made in the Industrial Research Center, Tripoli, X5.1981. No. of analysis 81/26)

6.3 Solubility Tests

Samples for the solubility test of the gypsum rock were collected from:

1 cave passage west of ZG-1-6 swallet

2 cave passage between the ZG1-6 and -9 swallets

3 cave passage east of ZG-1-1 swallet

4 cave passage near AN-1-5 swallet

5 cave passage in AN-4 spring

The size of the samples was approximately 4x4x4 cm cubes cut from irregular shaped samples. The solvent was distilled water of pH 6.6 instead of 7 thus resembling rain water.

The first phase of the test was simple gravimetry. The samples were weighed then treated in 500 ml of 18 °C distilled water stirred for 72 hours. After 24 hours the sample was taken out of the water, dried, then weighed. The weighing was repeated after a lapse of 48- and 72 hours but considerable decrease of weight compared to the value measured after 24 hours was not detectable. Consequently the saturation of the solution took place within the first 24 hours. It must be noted that the solvent of one of the samples was not stirred, it was moved only at the daily weighing. In this case saturation did not taken place until the end of the 72 hours showing that the dynamic state of water plays an important role in the solution of the gypsum rock.

The results of the test:

No. of sample	*1*	*2*	*3*	*4*	*5*
original weight(g)	161.67	129.70	161.62	138.09	125.77
after 72 hrs (g)	150.63	128.37	160.61	137.24	125.51
dissolved material (mg/l)	2,080	2,146	2,020	1,700	2,080

It must be noted that some samples contained considerable amounts of insoluble impurities, and some sediment was always found at the end of the test.

The amount of this sediment was weighed in the case of sample No.2, where it appeared to be more. The value was 257 mg. The result in the table was corrected with this value. Possibly carbonates went into the solution too, but their value should have been no more than 20-30 mg/l.

A second test was made measuring the electrical conductivity of the solutions by resistoscope. The result converted to mg/1 was as follows:

No. of sample	1	2	3	4	5
gypsum (mg/l)	1900	1860	1800	1700	1960

The result relates favourably to the gravimetric test. The values are somewhat smaller as conductivity does not show impurities missing from the dissolved rock sample.

The solubility test gave important information about the rate of solution but the values seem to be less than those found in the natural water samples (see this chapter) and in the references (2,550 mg/l at 18^{o}C).

CHAPTER 7

KARST MORPHOLOGY AND SPELEO-GENESIS

7.1 Surface Morphology

The relief of the Bir al Ghanam Karst is a product of its geological position and structure as well as a result of the prevailing hydrological-hydrogeological factors. The gypsum member is a part of the sequence of formations that build up the Jabal Nefusa and as such its outcropping depends on the recession of the escarpment. Active points of this recession are at the rim of the scarp where streambeds cross it. Owing to the high gradient, erosion is very energetic, and streams cut through the outcropping gypsum beds. In the elongation of the promontories, between the deeply incised major wadis, the gypsum outcrop remains intact in spite of the intensive erosion in strips up to a 25 km length. Local hydrological systems develop on the gypsum surface during the runoff of local rainfall.

The typical surface forms of the Bir al Ghanam Karst, the cone hills, are ubiquitous in the outcrop. The cone-hills develop in both the Bir al Ghanam- and Abregh Gypsum. The development takes place initially in the upper Abregh Member descending to the dolomite plateau of the Bu an Niran dolomite and continuing again in the Bir al Ghanam Gypsum. Thus the cone hills develop twice in every particular place of the outcrop during its weathering process first on the top and then under the Bu an Niran Member. Thinner intercalations of dolomite also play local roles similar to, but much less important than, the dolomite of the Bu an Niran Member.

The Bir al Ghanam Gypsum Karst resembles a type of tropical limestone karst formation (cone karsts, kegel karsts) in appearance and origin. In spite of the likeness the tropical karst formation and that found in desert conditions they are far from being equal. The morphology of the Bir al Ghanam Karst is not tropical but a desert phenomenon where favorable climatic conditions, and scant rainfall, is balanced against the petrographic factor of the high solubility of gypsum to produce the same forms as in the less soluble limestone areas of the tropics where there is a high-rainfall.

The question must be asked as to whether cone-polygonal karsts can exist in substantially different climates other than the tropics? The answer is yes. This karst area at Bir al Ghanam is complete with cone hills, cockpits, border plain, and towers. Estimated annual rainfall does not exceed 130 mm. This amount is only about 10% of a tropical area with a low rainfall. The climate is desert type. The karstified rock is gypsum. Since the solubility of gypsum is higher than that of limestone, no wonder that with so much less rain tropical landforms still develop. Similarities occur where there is high rainfall intensity in wet tropical regions as in desert climates. (Kósa, 1986) We can consider the connection with "Gunung Sewu" type cone karst in Indonesia described by Balázs, 1970. Similar forms are observable in southern Tunisia, where the continuation of the Bir al Ghanam formation is to be found, and in Spain west of Barcelona at the township of Pina.

The Bir al Ghanam Member contains three distinctive sections. The lower Bir al Ghanam Gypsum Member (same name as that of the whole Formation), the non sulfatic Bu an Niran Member and the uppermost Abregh Gypsum Member. As the Bu an Niran Member is constructed of a lower 2-3 m thick dolomite and an upper approximately 20 m thick clay layer, the Abregh and the Bir al Ghanam Members do not have any karst hydrological relationship. Moreover, the karstification of the Bir al Ghanam gypsum can not begin until the total denudation of the clay layer of the Bu an Niran Member has taken place. Thus, the Bir al Ghanam Gypsum karst is a curious two in one, two overlaying karst areas can be observed, one in the upper Abregh Member and the other in the lower Bir al Ghanam Member. Both karsts are of the same recent age, they continuously develop and break down as newer masses of gypsum are exposed to karstic denudation by the retreat of the escarpment.

7.2 Karst phenomena on the surface.

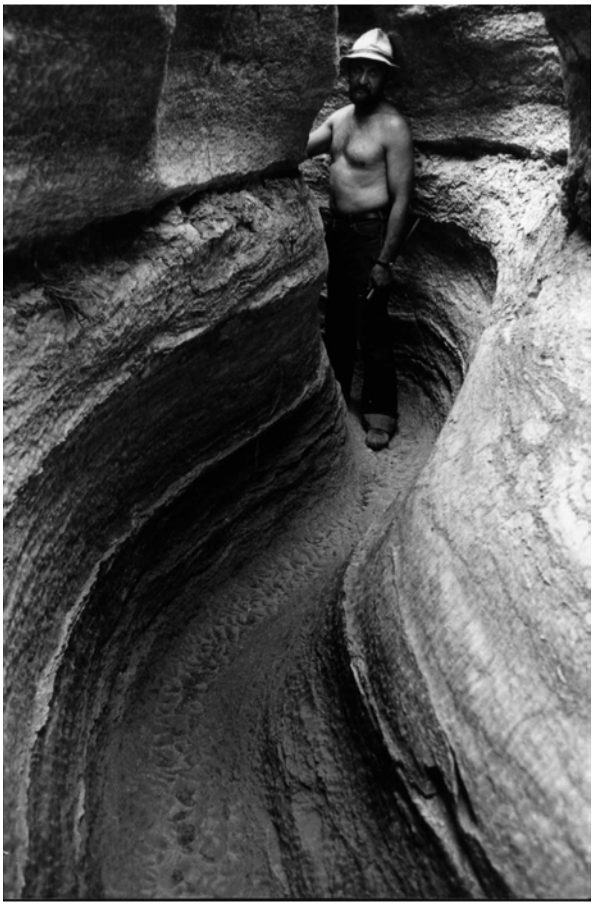
The typical *macro forms* of the Bir al Ghanam karst surface are the aforementioned cone hills, that belong to the moderately sloping and flatter areas of the outcrop. In the flatter areas the cone hills can be seen, but the gypsum surface cannot as it is covered by insoluble debris. There are accumulations of loess in wadis and depressions in different states of erosion.

In the caverniferous and adjoining areas the coverings described exist, and the free gypsum surface is exposed in most localities. Depending on the gradients of the water courses, gypsum may be completely eroded away and the loessy surface prevails in the wadi bottoms. Where there are gentle slopes, cliff-sided canyons develop that may be the vestiges of old caves, as some still preserve some cave remnants or the cliffs clearly show the cross sections of former ancient swallets and solution conduits.

Photograph 47: Wadi, possibly the remnant of a destroyed cave. Remnants of bisected swallets show on the sides (pic47.jpg)

Photograph 49: Side cavities made by lateral erosion in canyon wall (pic49.jpg)

Some wadis develop into box canyons, that look like meandering caves in every respect but which are without a roof. Other canyons develop little side cavities at favorable locations.



Photograph 48: Box canyon (pic48.jpg)

Photograph 50: Fluting (rillenkarren) on gypsum surface (pic50.jpg)

Photograph 51: Fluting (rillenkarren) with dolomite caps on gypsum surface (pic51.jpg)

Photograph 52: "Dog teeth" karren on gypsum surface (pic52.jpg)

The *micro forms* are a surface karren development made by rainfall and sheet flow that occur on exposed gypsum rock. These include "dog teeth", fluting (rillenkarren), and micro-meandering (Szablyár, 1981) etc.

7.3 Origin and Development of Caves

The study related to the caves of the Bir al Ghanam Karst that developed in various petrographic conditions and represent different stages of development. It included the exploration of swallets and resurgences, and a survey of these phenomena yielded a new portrayal of subsurface drainage which had developed in unusual conditions: a dry desert climate with gypsum as soluble rock. All the caves discovered and explored are vadose stream caves.

The landscape reflects the stratigraphic conditions. The multitude of cone hills is interrupted by the dolomite plains of the Bu an Niran Member. Thus the area can be divided into gypsum and dolomite surface terrain. Swallet – cave – resurgence systems develop where there are both types of surface conditions. The swallets studied can be specified as

A. swallets on gypsum surfaces

B. sinkholes and swallets on dolomite surfaces

The origin and development of the different type of swallets can be described as follows. The exposed surface of the gypsum formation gradually flattens out towards the north and where the slopes are more gentle a very unique type of gypsum karst develops.

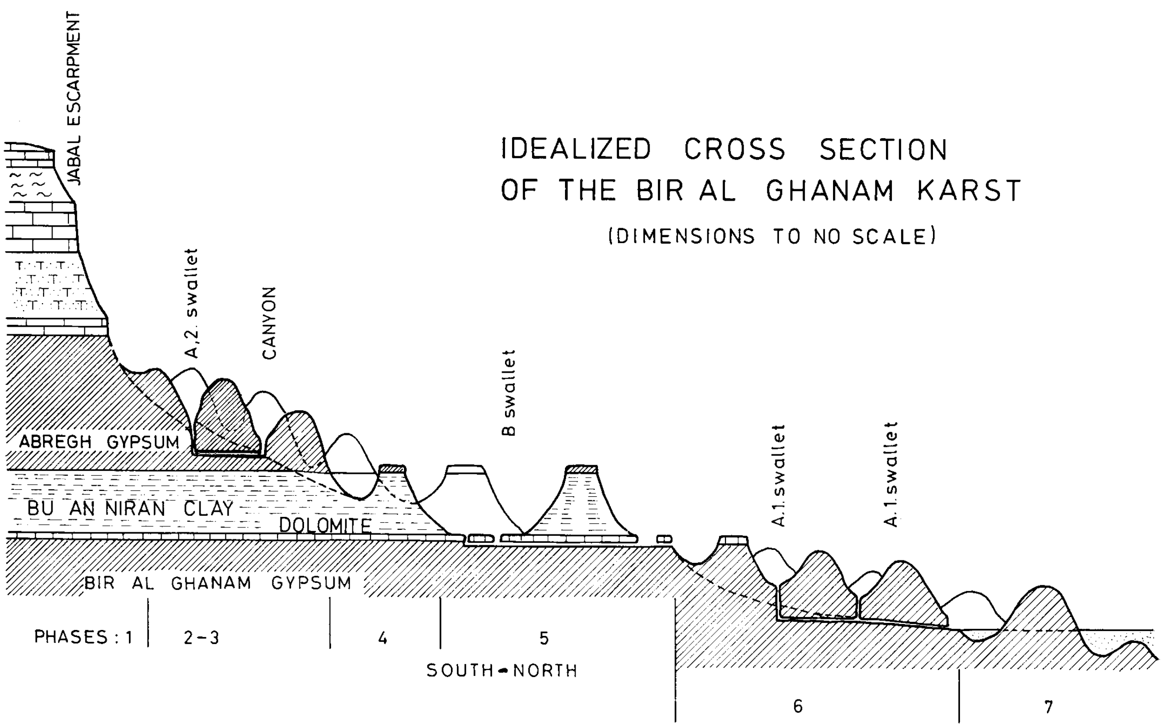


Figure 3: Stratigraphic section of the Jabal Nafusa (Fig03.tif)

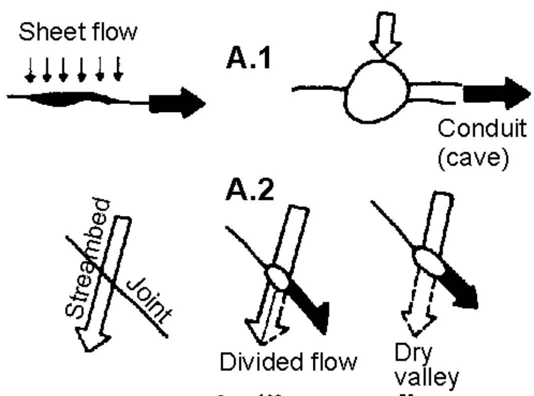
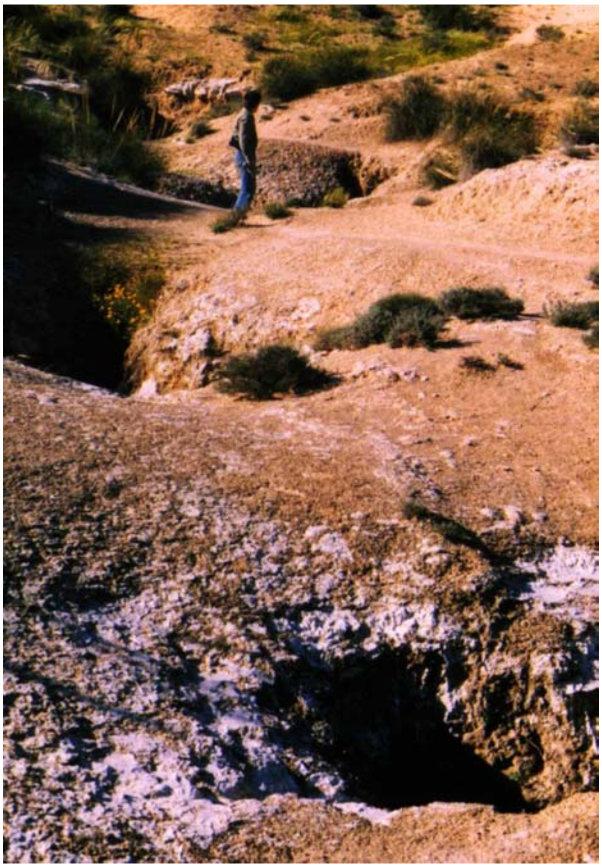


Figure 4: Development of "A" type swallets (Fig04.tif)

1. The newly exposed gypsum is vertically dissected by runoff at the foot of the overlying formation. As the hydraulic gradient decreases along the steep runnels, transverse flows develop which dissect the rock into virtually diagonal blocks. Rainfall rounds these blocks into conical hills that resemble the Gunung Sewu (Java) type tropical cone karst. The surface of the cones is covered by insoluble material previously interbedded in the gypsum.
2. The runnels deeply cut into the gypsum and meandering, deep, and sometimes canyons with a cave like appearance – box canyons – develop. On occasion, tectonics and stratigraphy permitting,

subsurface drainage develops and stream-caves connect neighboring wadis, with one or more of them becoming blind valleys (A.2 type swallets).

3. Towards the foot of the Abregh Member cockpit-like swallets develop as a result of the sheet flow from the cone hills (A.1. type swallets). This type of swallet is more frequently found in the Abregh Member but it is the A.2. type swallets that supply the quantity of runoff necessary for the development of the main passages.



Photograph 53: Initial A.1 type swallets (pic53.jpg)

Photograph 54: Initial A.2 type swallet (pic54.jpg)

4. Deep-cutting wadis expose the clay of the Bu an Niran Member which is very quickly eroded away exposing the dolomite layer of the Member. Some gypsum caps on clay cones are the last remnants of the Abregh Member.

5. The hard dolomite layer resists denudation for a long time but runoff infiltrates through its joints (B type swallets) and karsification of the underlying Bir al Ghanam Member begins. Some caves develop which are mostly bedding plane orientated. The dolomite layer does not karstify because of the sparse rainfall (about 120 mm). It is denuded by being "undermined" by caves that are destroyed themselves with the dolomite plateau gone.

6. The karstification that occurred in the Abregh Member repeats itself in the Bir al Ghanam Member with a difference, the latter has a gentler topography. Infiltration is at a greater ratio than in the Abregh Member, thus the A.1. type swallets have played a much greater role here in cave development than A.2. types. Cave development is most intensive in the Bir al Ghanam Member, 79 % of known cave length is located here, 8 % right under the Bu an Niran Member.

7. Denudation flattens out the Gypsum Formation northwards until only some occasional cone hills protrude from the quaternary covering. Cone hill development is a general phenomenon all over the outcrop of gypsum but for cave development the gradient is mostly too steep in the early phase of weathering and too flat in the late phases. Thus topography is an important factor of cave development in the Bir al Ghanam Karst.

The role of stratigraphy and tectonics is also very easily observable once the caves of the area are surveyed. The caves of the Bir al Ghanam Gypsum Karst are principally horizontal stream caves. The cave streams flow generally westwards (82% of all passage length) and only a few (18 %) flow the opposite way. The slope of the cave passages (not counting the vertical A.2. type swallets) that conduct water westwards is 1.5% along the cave axis and 2.3% from swallet to spring as the crow flies. The dip of the easily observable dolomite layer, and thus the gypsum layers, measured on a base line of 7.5 km, is 2.0%. It is quite clear that the caves follow the bedding planes and looking at the cross sections this is more than obvious at many locations.

Caves where the water flows eastwards have axis slopes of 1.7% and 1.2% from swallet to spring. This is less than that of the other "regular" caves as they flow "upwards" to the strike of the layers. In all cases of eastwards flowing caves very deeply cut local wadis seem to be the cause of the irregularity, these being a stronger influence on local hydrogeology than bedding planes. Eastward flowing caves differ in other ways too.

If we introduce a number, a "zig zag ratio" that is the axis length of cave passages over the distance between the swallets and springs, the weighted average for westward flowing caves is 1.42 while it is only 1.12 for eastward flowing caves. It is clear from the ratio, that the latter caves zig zag less than the majority, being more intensely orientated by tectonic lines. It is no surprise, therefore, that the longest straight passage (225 m) can be found in the eastward flowing Abu an Niran (AN-1) cave.

Curiously the tectonic lining of the caves with an opposite flow direction is very much the same. As can be seen on the relevant rose diagrams of the longest westward flowing cave, the Umm al Masabih (ZG-1) and the longest eastward flowing cave, the Abu an Niran (AN-1) both occupy joints orientated in the same main direction, the one a main strike of 295-300 degrees (WNW), and a secondary strike of 240 degrees (WSW). The difference between the two caves can be seen as the straighter, less zig zagging Abu an Niran cave occupies more of the joints in the main strike.

Another difference shows, however, between caves in the Bir al Ghanam Gypsum Member and those in the Abregh Member as the main strike of the latter is 310-315 degrees NW and the secondary strike is variable. This phenomenon remains unexplained but it happens elsewhere in other karst areas of the world (remarks on congresses.) Caves under the dolomite of the Bu an Niran Member understandably show negligible tectonics.

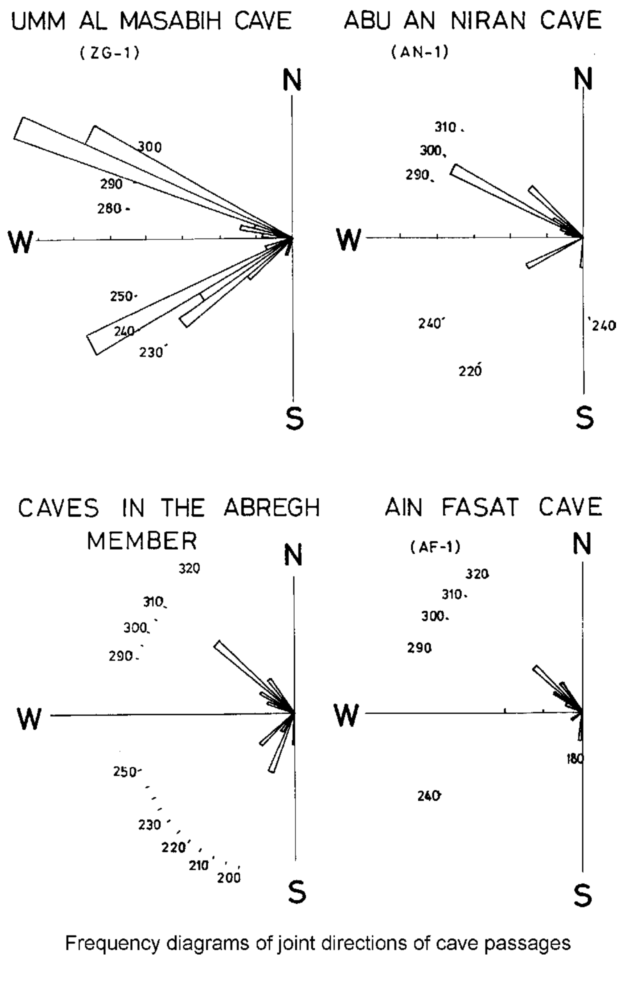


Figure 5: Tectonic diagrams of Bir al Ghanam caves (Fig05.tif)

In spite of the distinctly characteristic tectonics of the Bir al Ghanam caves one can appreciate the dominant role played by the stratigraphy, even in the almost vertical potholes of the A.1. type swallets (deepest 25 m), which resemble tropical cockpits. Concentrated infiltration takes a vertical route along joints until it reaches the "plain of weakness" changing course to horizontal along the bedding planes.

It is difficult to pigeon-hole the Bir al Ghanam Gypsum Karst as it is unique. The karstification of the gypsum layers in substance is nothing more than a phase in the denudation or weathering of a slope however peculiar this may seem. Thus the Bir al Ghanam Gypsum Karst can be classified as a "slope karst" in view of all of its surface and subsurface features.

7.4 Cave features

Swallets

Read about the development of swallets according to Kósa (Kósa, 1981c) in the pervious chapter.

Types of swallets of the Umm al Masabih (ZG-1) cave were specified by Szablyár as well (1981)

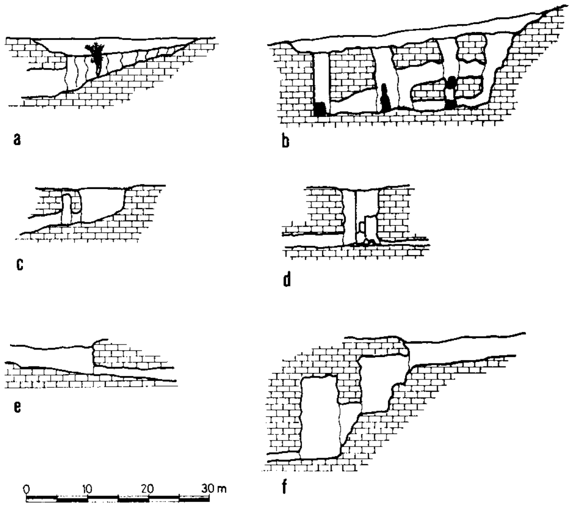


Figure 6: Types of the swallets of the Umm al Masabih (ZG-1) cave (Fig06.tif)

A.1.a Swallets

a. gradually retreating, narrow, canyon-like swallets,

b. gradually developing, retreating rows of swallets connected on one or more levels,

A.1.b Swallets

c. swallets with sizeable funnels and relatively small conduits,

d. Large diameter cylindrical swallets with vertical corrosion marks,

A.2 Swallets

e. Swallets beheading valleys at the valley bottom-level, continuing in cave passage,

f. Swallets beheading valleys at the valley bottom-level, continuing in big steps, then joining the cave passage.

The morphology of the swallets is determined by the

- structural and stratigraphic conditions of the bedrock
- the spatial relations to the catchment areas
- the size of the catchment area, and the conditions of its denudation

7.5 Cave passages

Cave passages were specified by Kósa (1981c)

1. Passages in thick homogeneous gypsum

1.1. Typically joint orientated passages

- high, tight straight passages (a)
- rectangular or rounded off straight passages (b)

1.2. Well developed joint orientated passages

- composite passages, straight, joint orientated at the top, meandering at the bottom (c)
- straight passages meandering within at the bottom (d)

2. Passages in inhomogeneous rock layers

- in inhomogeneously soluble gypsum layers (e)
- "ghost" armed sections. Arms developing at minutely thin clay intercalations (e)
- with thin dolomite intercalations. The dolomite appears as ledges (g)
- with anhydrite intercalation (h)

Cave passages were also specified by Szablyár (1981) from a slightly different viewpoint:

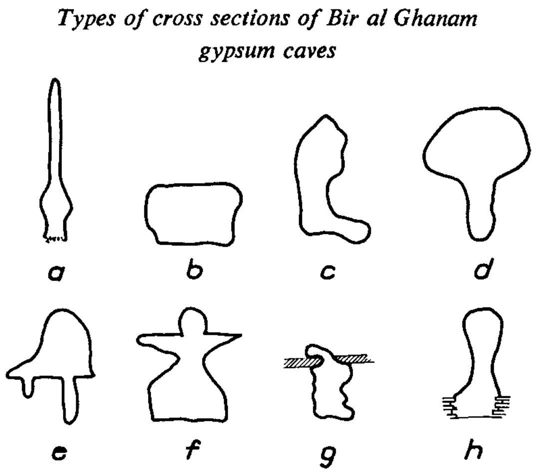


Figure 7: Types of cross sections of Bir al Ghanam caves (by Kósa, 1981c, Fig07.tif)

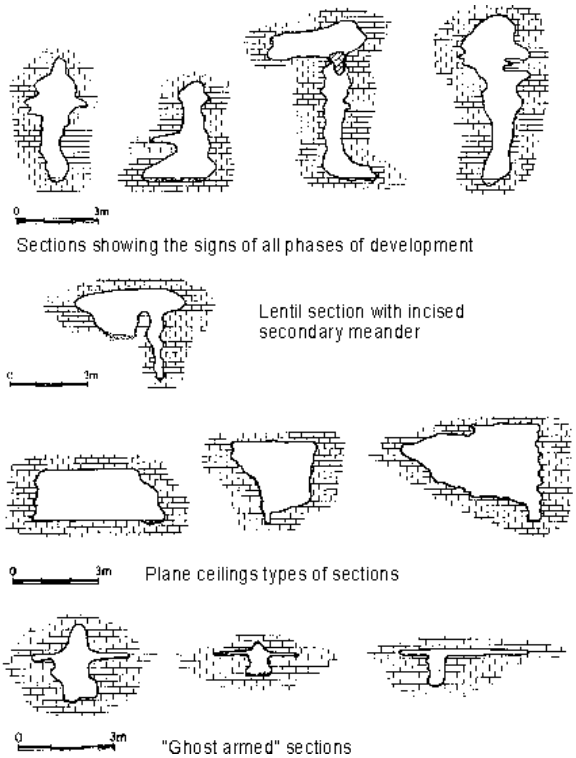


Figure 8: Types of cross sections of Bir al Ghanam caves (by Szablyár, 1981, Fig08.tif)

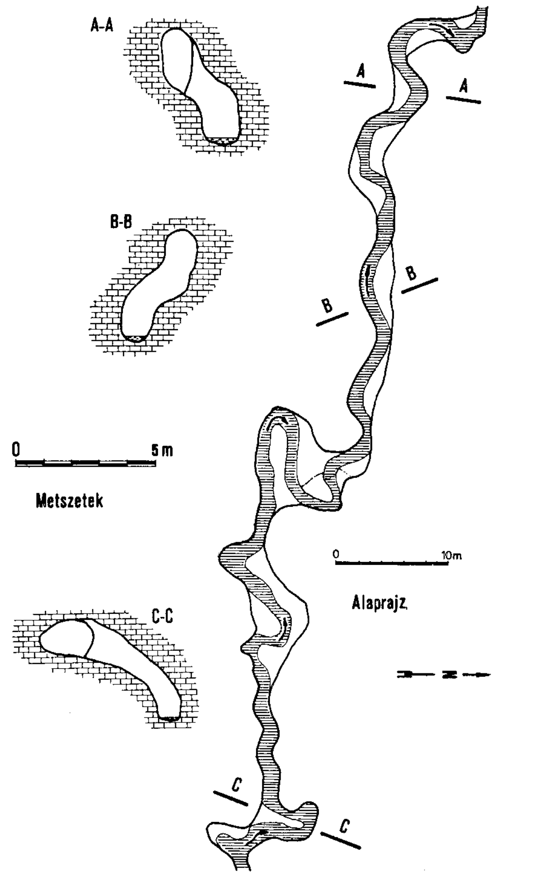
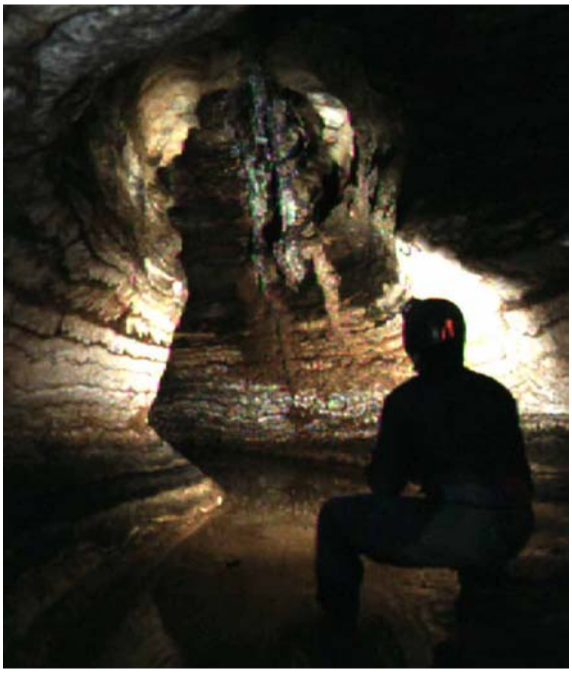


Figure 9: Typical detail of meandering passage in the Umm al Masabih Cave. (by Szablyár, 1981, Fig09.tif)

Meandering bottom channels are very characteristic in the Bir al Ghanam caves. They are the product of smaller floods, or the ebbing phase of large floods. A typical detail of meandering passage is shown on Figure 9 (Szablyár, 1981).

7.6 Cave Decoration

Contrary to the very versatile solution forms, secondary decorations, that is mineral concretions, and stalactites are very rare and restricted to upper dry passages. Small gypsum stalactites and stalagmites, columns, and crystals occur as rarities. The multitude of corroded forms, exposed layers of different color and the texture of gypsum rock offer most of the spectacles of these caves.



Photographs 55, 56: Gypsum stalactites in UMM al Masabih (ZG-1) cave (pic55.jpg, pic56.jpg)

See photographs No. 17 and 21 for stalactite coatings.

The very peculiar corrosion feature, the "bevel" is ubiquitous in the Bir al Ghanam cave systems. Clearly showed on photograph No. 55 (above) at the left side, the corrosion bevel is a more-or less 45 degree slope in the sides of the passages that can be observed on photographs No. 9, 10, 11, 24, 35 etc. The phenomenon is not unique to the Bir al Ghanam caves, it has been seen in Italian, German gypsum caves (korrosion Fasetten) or in New Mexico, Carlsbad Caverns N. P. The corrosion bevel is clearly related to gypsum stratigraphy, the rest about it has been unexplained.

CHAPTER 8

EVALUATION OF STORAGE POSSIBILITIES

The aspects of storage possibilities in the caves of the Bir al Ghanam Gypsum Karst can be evaluated by considering all the facts described in the foregoing chapters. The aspects are both general and specific. General aspects concern the idea of water storage in the gypsum caves asking the question: is it at all possible?

Specific aspects concern the qualities of specific caves, which of them are suitable for the purpose of storage.

General aspects are:

Hydrology

Quality of stored water

Effects of solution in the reservoir – the caves

Sedimentation of the reservoir area

Protection areas and environmental protection

Sedimentation

Protection areas and environmental protection

(See discussion later in 8.2)

8.1 Specific Aspects

1 Completeness of exploration

Caves intended to be developed as reservoirs have been explored and surveyed in their entirety.

2 Volume

There must be a minimum capacity set for the volume of a cave at which storage is uneconomic. In this discussion it will be set at 500 m^3.

3 Storage capacity

It is not the volume but the storage capacity of a cave that makes it suitable to be developed. The storage capacity is almost always less than the cave volume. The structure of the cave, and the locations of the swallets may cause wastage which will not allow the whole volume to be utilized. 500 m^3 of storage capacity is set as the lower limit of suitability.

4 Structure

The structure of a cave must be such that water stored in it cannot escape through breakdown, joints, cracks or other entrances. The structure must be substantial, the stored water should not cause cave-ins in loose roofs or walls.

5 Civil engineering structures

The subsurface reservoir is constructed by the "plugging" of the caves at their spring entrances or at other suitable points. The entrance, or passage, must be solid and small enough to make plugging practical. The shape of the cross section must be such that the construction of the plug is possible without any overflow occurring.

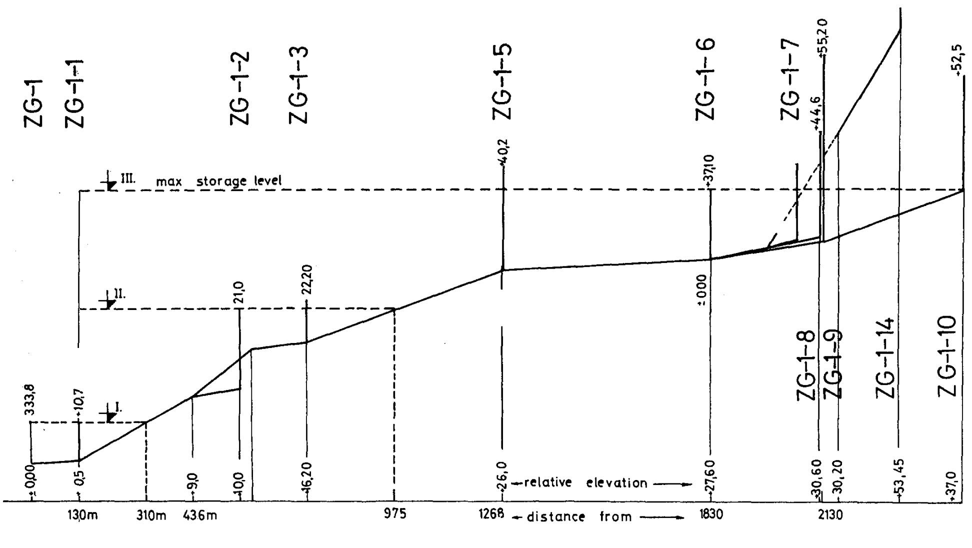
All the caves explored and surveyed have been evaluated in the table below as regards their qualities as described in points 1 to 5 above. See the reasons for the evaluation given: suitable (+) or not suitable (-) later in this chapter.

The evaluation only shows the ZG1 (Umm al Masabih) and the AN-1 caves suitable for the development of subsurface reservoirs. The AN-4 cave system could also be developed although its small storage capacity might rule it out. (See "(+)" sign).

The general aspects of storage will be discussed after the description of the specific caves that are suitable for the purpose.

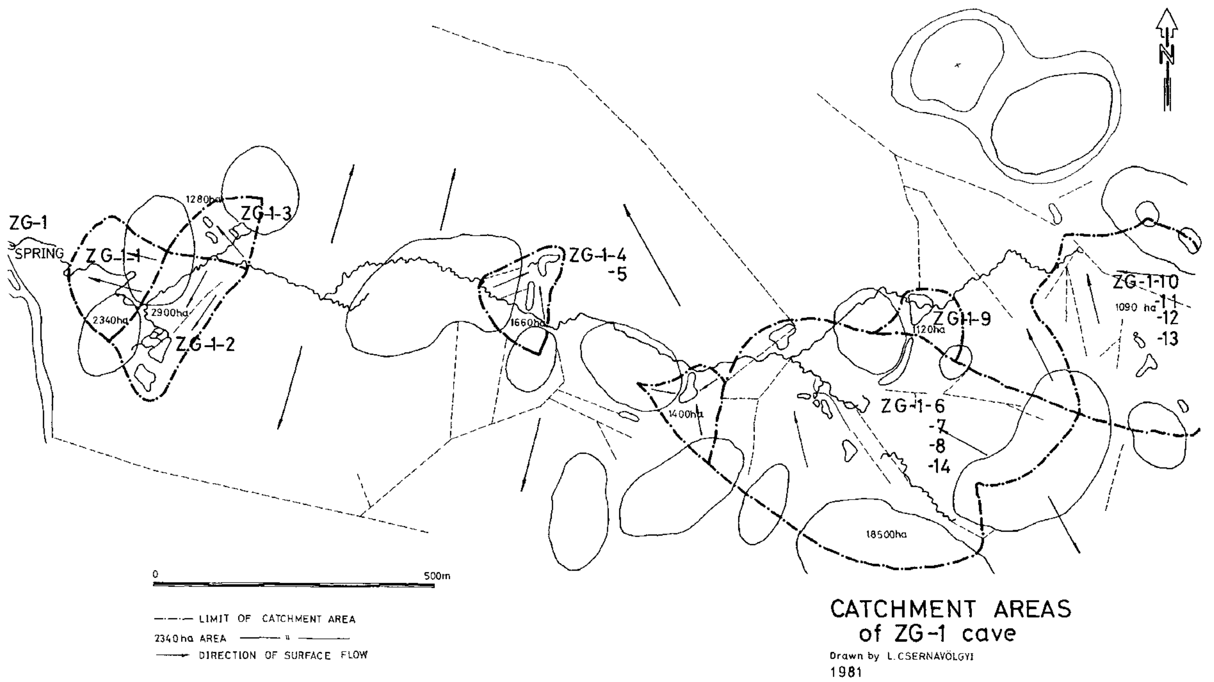
ASPECTS						
Cave	1	2	3	4	5	Suitability
ZG-1	+	+	+	+	+	+
ZG-2	-	-	-	-	-	-
AN-1	+	+	+	+	+	+
AN-2	+	-	-	+	-	-
AN-3	+	+	+	-	+	-
AN-4	+	+	-	+	+	- (+)
WF-1	+	+	+	-	-	-
WF-2	-	-	-	-	-	-
WF-3	+	-	-	-	+	-
WF-4	+	+	+	-	-	-
WF-5	+	-	-	-	-	-
WF-6	+	-	-	-	-	-
WF-7	+	+	-	+	-	-
WF-8	+	-	-	-	-	-
WS-1	+	-	-	-	-	-
BA-1	-	-	-	+	-	-
BA-2	-	-	-	-	-	-
BA-3	-	-	-	-	-	-
BA-4	-	-	-	-	-	-

8.1.1 ZG1 (Umm al Masabih) Cave



HYDROGRAPHIC PROFILE ZG-1 CAVE Drawing No. 35

Drawing 34: Hydrographic profile, ZG-1, Umm al Masabih Cave (Draw35.tif)



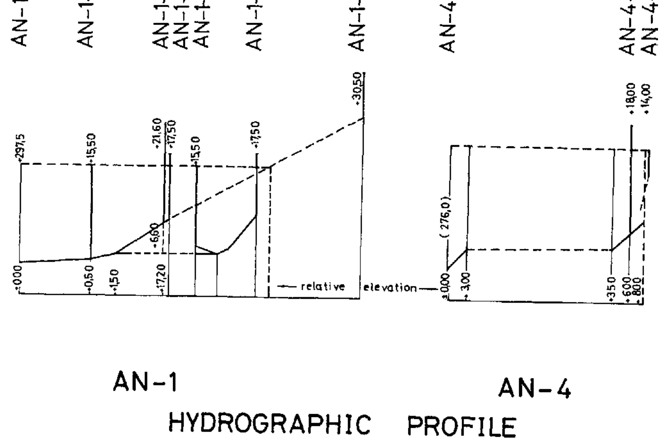
Drawing 35: Catchment areas, ZG-1, Umm al Masabih Cave (Draw36.tif)

Version No. 1. The surveyed volume of the Umm al Masabih cave is 13,350 m^3. A simple plugging of the cave at its spring would cause overflowing through to ZG-1-1 swallet (see figure) and of the total of the 3,593 m length of the cave only 9% would be utilized . Version No. 1 is not suitable.

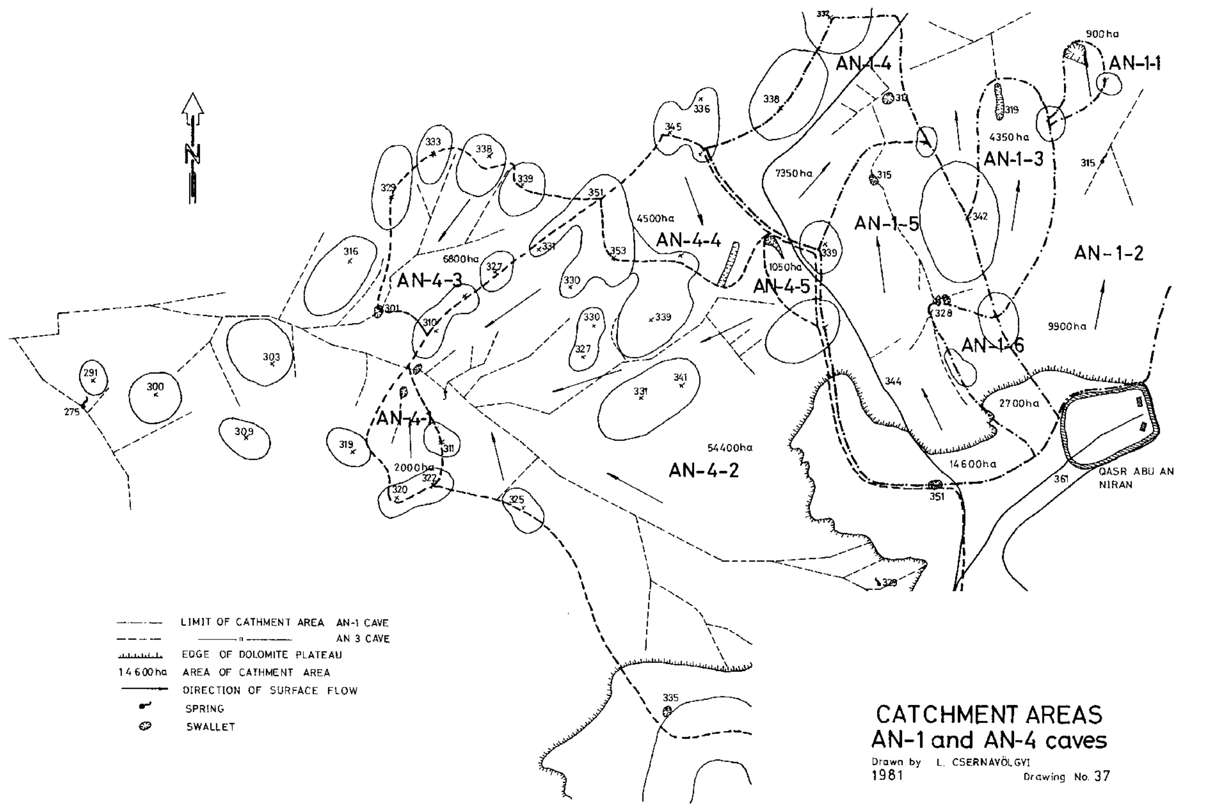
In *version 2* the cave would be dammed upstream of ZG-1-1 swallet. This version dams up the water until it overflows through the lowest of the ZG1-2 group of swallets. In this case 30% of the total cave length would be utilized.

As it is intended to make available for storage the largest possible volume of the cave, the plugging of ZG1-2, and the somewhat higher ZG-1-3 swallets, would give a solution such that the water in the cave would be dammed up to the top level of the ZG1-6 swallet, which is the same as the bottom of the ZG-1-10 swallet. The cave system would be filled apart from the greater part of the passages in the ZG-1-2, -3 and -14 branches and the section between the spring and the plug. *Version 3* would be the only acceptable solution for the development of a reservoir in the ZG-1 system. Therefore, it can be said that the storage capacity of the Umm al Masabih cave would be 81% of its total length which represents approximately 80% of the total volume: 10.680 m^3. The hydraulic head of the reservoir would be 36,5 m.

8.1.2 AN-1 Cave



Drawing 36: Hydrographic profile, AN-1, AN-4 caves (Draw34.tif)



Drawing 37: Catchment areas, AN-1, AN-4 caves (Draw37.tif)

Plugging the AN-1 cave at its spring entrance would provide a reservoir of a size practically equal to the volume of the cave namely 4.500 m^3, the storage capacity would be 100%, the hydraulic head of the reservoir would be 15 m.

Historic sites in the cave would be destroyed by the storage!

8.1.3 AN-4 Cave

This cave was classified as unsuitable for water storage because of its small storage capacity. On the other hand it is its size and simplicity would make it most suitable for experimental storage. For the experiment only the lower (spring) section would be used.

8.2 General Aspects of Subsurface Water Storage

8.2.1 A Hydrology

It was shown in Chapter Five that the effective normal amount of annual rainfall in the study area is 148 mm resulting in 148.000 m^3/km^2 of runoff. The catchment areas of the three caves considered suitable for storage are listed below:

A calculation shows how many times a year the volumes of the caves can theoretically be filled.

ZG-1: 4.43 times

AN-1: 13.16 times

AN-4: 128.70 times

Considering that the caves flood only two to three times a year, and that the total volume of the caves, not the storage capacity has been used in the calculation, the water available would still be enough to fill the caves, even if the number of floods is fewer than expected, or if the runoff is much less.

	Catchment area (km^2)	Total for cave (m^2)
ZG-1-1	0.023	
ZG-1-2	0.029	
ZG-1-3	0.013	
ZG-1-4,	0.017	
ZG-1-5	0.014	
ZG-1-6, -7, -14	0.185	
ZG-1-9	0.011	
ZG-1-10, -11		
ZG-1-12, -13	0.109	0.401
AN-1-1	0.009	
AN-1-2	0.099	
AN-1-3	0.044	
AN-1-4	0.074	
AN-1-5	0.146	
AN-1-6	0.027	0.398
AN-4-1	0.020	
AN-4-2	0.544	
AN-4-3	0.068	
AN-4-4	0.045	
AN-4-5	0.010	0.687

8.2.2, B. Quality of the Stored Water

The analyses of natural water samples of the area collected from caves show an average TDS of 3.272 mg/l. The average gypsum content of the cave waters was 2,280 mg/l, which is 93% of the theoretical maximum at 18°C. Solubility tests showed only an average of 2,082 mg/l after 72 hours of solution in 18°C, pH 6.6 distilled water. This is only 82% of the theoretical maximum. An unstirred solubility test resulted in the dissolution of 1,700 mg/l of gypsum – 67 % of the theoretical maximum. The theoretical maximum was not reached in any sample however long the cave waters were in contact with the gypsum (afterflow) and the sample did not become saturated. Considering this, and the fact that the stored water will not be in dynamic contact with the gypsum rock for long, and also the fact that the contact surface will be relatively small, a significant error can not be made when forecasting the gypsum content of the stored water to be 2,000 mg/l and its TDS 2,800 mg/l. This puts the water quality into the slightly brackish category.

Another factor to consider regarding water quality is organic contamination. This kind of contamination encountered was mainly due to sheep dung carried into the caves and found in different stages of decay. The establishment of protected areas around the sites would be a solution for the problem.

8.2.3, C. Effects of Solution in the Reservoir

The most serious of all the problems discussed is the high solubility of the gypsum rock in direct contact with the stored water. A general calculation using the dimensions of the Umm al Masabih cave shows, however, that this effect is not significant using an initial approximation. The volume of the ZG-1 cave system is 13,350 m^3. The geometry of the cave passages is highly irregular, but it can be represented as a cylinder with a length the same as that of the cave itself, 3.593 m with a radius of the cross section as 1,08752 m. In one filling each liter of water will dissolve 2,000 mg/l of gypsum. This would be a total of 26.4 tons. If the specific gravity of gypsum taken is 2.33 t/m^3 then the dissolved volume is 11.46 m^3. This, added to the surveyed volume, results in a new solution-enlarged volume of: 13,361.46 m^3. The radius of the new representative cross section would be: 1,08799 m. The growth of the radius would be 0.47 mm for one fill of the cave, 0.04%. The growth of the total volume is expected to be 0.086%. Consequently the cave system would double its size during 1,163 fills, that is 388 years counting three fills annually. The above calculation was based on simplified conditions: homogeneously soluble rock, complete filling, regular geometry.

The factors regarding cave enlargement however are not so conveniently consistent. The rock is inhomogeneous, and contains both insoluble material and variably soluble gypsum. The differences in solution are only increased by the fact that the reservoir-caves will not be wholly filled and the water will be present for a longer period in the lower levels. Only by carrying out an experiment will it be possible to tell what the real effects of storage might be.

One of the most dangerous effects of the solution would occur around the "dam" itself. It would be a question of ensuring a sound civil engineering design to guarantee that serious seepage would not occur even in over extended periods.

8.2.4, F. Sedimentation

Sediments of three kinds will accumulate in the subsurface reservoirs. Stream deposits of mineral and organic origin, insoluble material washed out from intercalations in the cave walls (e.g. "ghost arms") and solution residuals.

Mineral stream deposits are carried into the cave from the catchment areas. These are reasonably few in the case of A.1 (primary type) swallets. The runoff is sheet flow on the greater part of the catchment areas, marks of erosion show only very near to the swallet itself, and short gullies cut into gypsum-rock or loessy fill.

Organic stream deposits consist mainly of decaying vegetable matter and animal dung. The first deposit that arrives in the caves is organic as this is the lightest, and even sheet flow carries it to the caves where the soils are stabilized. The organic deposits are carried to the caves by the first flood of a season, successive floods flush it out.

When the cave is plugged the organic deposits would stay and decay in the reservoir creating undesired dangerous water quality.

Insoluble materials create relatively little trouble in comparison to the above listed deposits. According to the solubility tests, an estimated quantity of several tons of insoluble materials will be deposited at each fill of the ZG-1 cave.

The solution to the problems of sedimentation would be civil engineering structures that allow the flushing-out of insoluble deposits. As for organic sedimentation, this must be kept to a minimum.

8.2.5, G. Protection Areas and Environmental Protection

Development of reservoirs in the caves demands a maximum purity of runoff. A protected area must be fenced off encompassing the composite area of the total catchment zone. The purpose of the protected area would be to make sure that no kind of human intervention could change the balance of natural conditions and to ensure that the erosion and reservoir sedimentation would be kept to a minimum. Grazing animals would be kept out of the protected areas for the same reason.

At the same time environmental protection must also be considered. The caves in the Bir al Ghanam Karst and most of its terrain are uniquely undeveloped areas of mostly natural land, both on the surface and underground. The caves explored contain unique forms of dynamic solution, unique mineral deposits and a fauna of troglodytic small animals which may be hitherto unknown species. The sciences of geology, and hydrogeology have been expanded as a result of the exploration of the Bir al Ghanam Karst. The sciences of biology, pedology, and history may also benefit from further systematic study of the area.

When the development of underground reservoirs is contemplated, consideration must be given to the means of protection of a unique land which has a wealth of geological, biological and historical assets.

CHAPTER 9

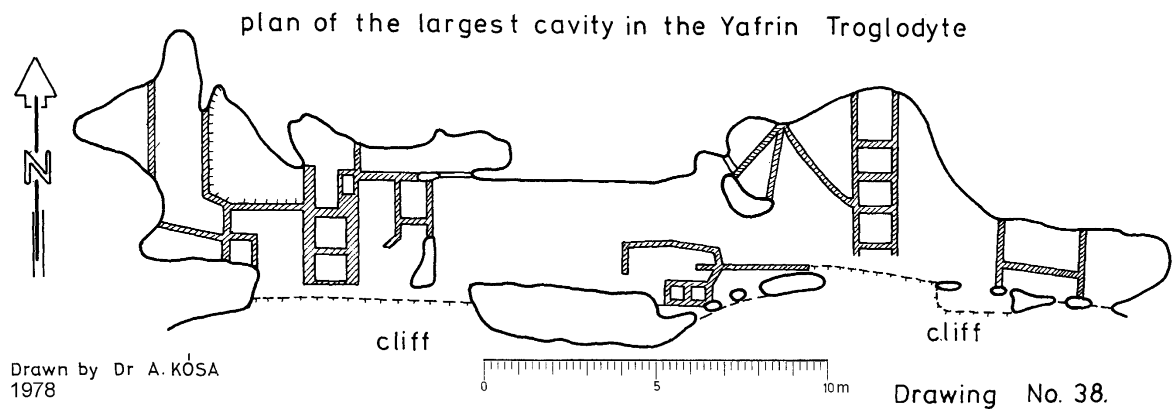
OTHER SPELEOLOGICAL FEATURES IN TRIPOLITANIA

9.1 Cliff Dwellings

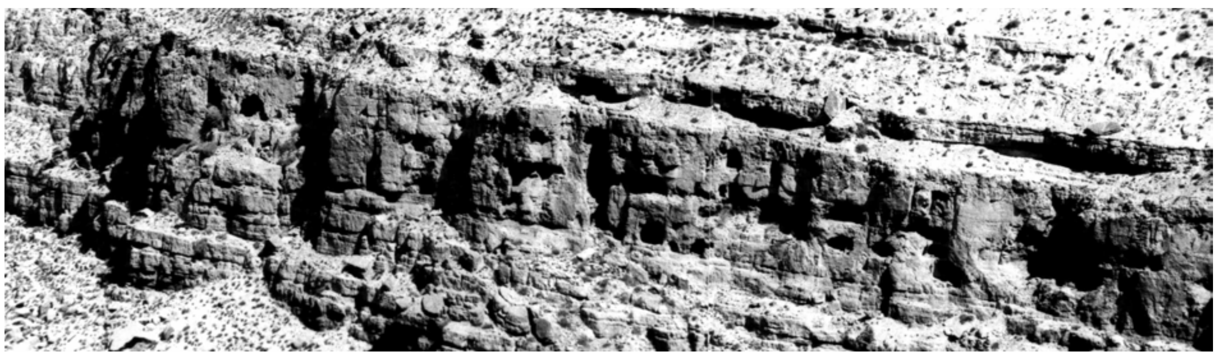
Cliff dwellings are ubiquitous in the sheer cliff of the Ain Tobbi Member of the Sidi as Sid Formation all along the Jabal Nefusa escarpment. They occur both as single cavities and in groups. The biggest cluster is positioned south of Yafrin well visible from the road to ar Rumia. The "Cave-City" comprises of a large group of entrances occupying three levels. Some of the entrances open into individual cavities others into large, interconnected spaces. The cavities inside are almost always bare rock but many places hide the remnants of walls and other structures showing that they have been occupied by people as both temporary and permanent dwelling places – troglodytes. The time period when this occupation took place has not been identified.

The origins of the troglodyte group of dwellings at Yafrin and other places in the vicinity have come about both as a result of natural and artificial intervention. Corrosion has taken place along the joints and bedding planes of the dolomite cliff resulting in shallow, tight cavities. These cavities offer suitable possibilities for enlargement in size, and can be carved out to make trogloditic dwellings. Both the original solution forms (one facing the "Cave City" on the opposite side of the wadi cliff) and the man made trogloditic dwellings were found in large numbers.

The largest known cavity in the Yafrin group was surveyed, and the plan shows the position of the original walls which have now deteriorated.



Drawing 38: Troglodyte at Yafrin (Draw38.tif)



Photograph 57: Panoramic view of the "Cave City" at Yafrin (pic57.jpg)

Photograph 58: Crumbled partition walls in the "Cave City" at Yafrin (pic58.jpg)

Photograph 59: Structure of unknown purpose in the "Cave City" at Yafrin (pic59.jpg)

9.2 Talus caves

The weathering of the Ain Tobbi dolomite take place mainly inside the rock as corrosion along joints parallel to, or at right angles to, the cliff face. The work of corrosion separates huge blocks from the main body of the dolomite bed. The blocks fall or slip down when their support, the rather loose Kiklah sandstone, gives way. In cases of slippage large cavities may result between the fresh rock face and the weathered block, thus creating talus caves. Talus caves can be confusingly similar to some real karstic caves. For many of them debris blocks the way in but for one entrance. There is a cool darkness in talus caves. A higher rate of water seepage facilitates the growth of stalactites and wall coverings to create a real "cave atmosphere".

It is easy to find the talus cave at the Rumia waterfall (intermittent) which lies south of Yafrin along the trail that leads from the top of the fall to the village under the cliff. Through the single opening a cave with vertical walls can be entered. Vertical gear is needed to explore the 30 m deep cave.

Another talus cave opens under the waterfall of Wadi al Uweyniyah. As the water seeps continuously into this cave all year round, the 15 m long tunnel is nicely decorated by colorful stalactites.

Photograph 60: Entrance to a talus cave in the Wadi al Uweyniyah (pic60.jpg)

Photograph 61: Stalactites in a talus cave in the Wadi al Uweyniyah (pic61.jpg)

At both the Rumia and al Uweyniyah waterfalls cave-like alcoves prevail in the north facing big niches behind the falls on the edge of the scarp, gigantic stalactites can be seen hanging there that are exactly the same as tropical tufa curtains.

Photograph 62: The Rumia waterfall as seen from the "Cave City" at Yafrin (pic62.jpg)

Photograph 63: The Rumia waterfall (pic63.jpg)

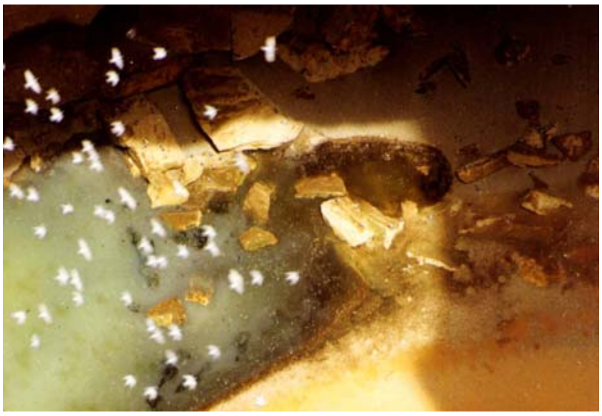
64. The Rumia Waterfall from above (Pic64.jpg)

Photograph 65: Sinter (tufa) stalactites under the Rumia waterfall (pic65.jpg)

9.3 The Ain al Mizraq

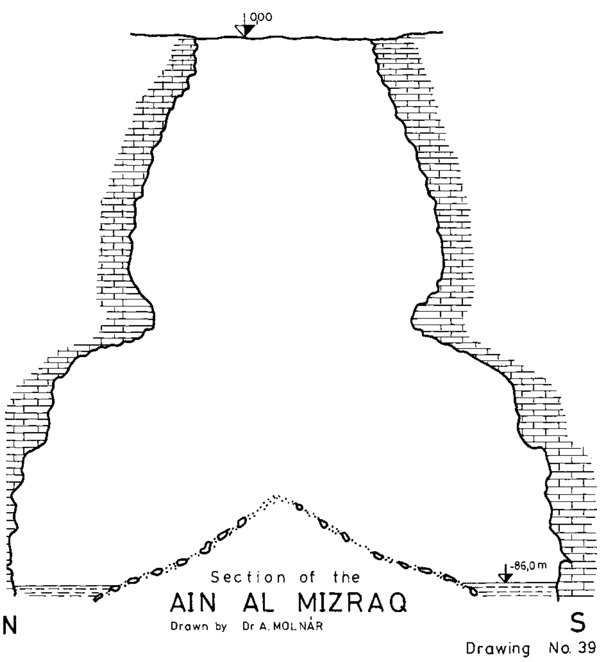
The most important karstic phenomena in carbonate rocks in Tripolitania, the Mizraq "well", is positioned about 30 km southeast of the town of Nasmah on an extensive limestone plateau at an altitude of about 200 m, 250 km south of the Tripoli shoreline of the Mediterranean. The Ain al Mizraq is a huge pothole. Its circular opening is 26 m in diameter.

Photograph 66: The opening of Ain al Mizraq (pic66.jpg)



Photograph 68: Pigeons flying above the lake in the Ain al Mizraq (pic68.jpg)

Photograph 67: The opening of Ain al Mizraq – from below (pic67.jpg)



Drawing 69: Section of the Ain al Mizraq (Draw69.tif)

The diameter of this practically circular cavity is 85 m at the bottom. The bottom is made up of a steep sided debris cone surrounded by a crescent lake. A number of structures made of rock masonry have been erected around the surface opening. These were constructed to assist in the drawing of water from the lake in the cave. The well structures are now crumbling, and abandoned, and some have fallen down. Corresponding to them, right under the well structures ditches, lined with pieces of rocks have been excavated in the sides of the debris cone. The ditches do not now contain any water as the level of the lake has possibly dropped. The water in the lake is of relatively good quality (TDS: 1,614 mg/l, Cl: 124 mg/l, S04: 719 mg/, Ca: 310 mg/l, Mg: 34 mg/l, Na: 115 mg/l, K: 8 mg/1).

The cavity has developed in a thinly layered sequence of Upper Triassic (?) limestone beds. There is no sign of any continuation to the cave, and no side branches were found during the exploration. The structure of the cave has been shaped purely by physical forces, as a result of cave-ins of the thin limestone layers. The walls of the cavity are composed of rings, the edges of substrata that decrease in diameter upwards except for a "belt" at the half way point.

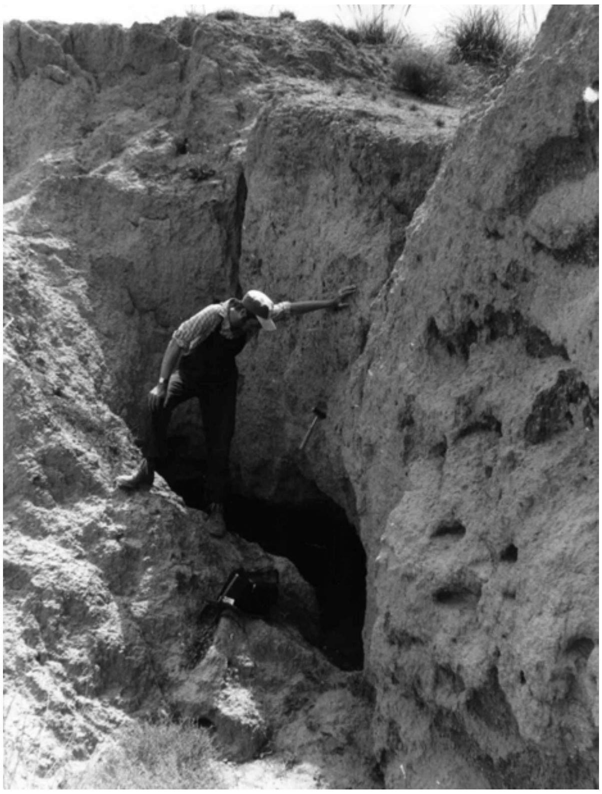
The origin of Ain Mizraq can be attributed to nothing more than the gradual cave-in of a large underground chamber. Such a chamber could only develop as a part of a karstic drainage system. Due to collapse the original large chamber no longer exists but the other parts of the drainage system may still remain. The karst water that made these cavities is still there showing itself as the regional water table in the lake at the bottom.

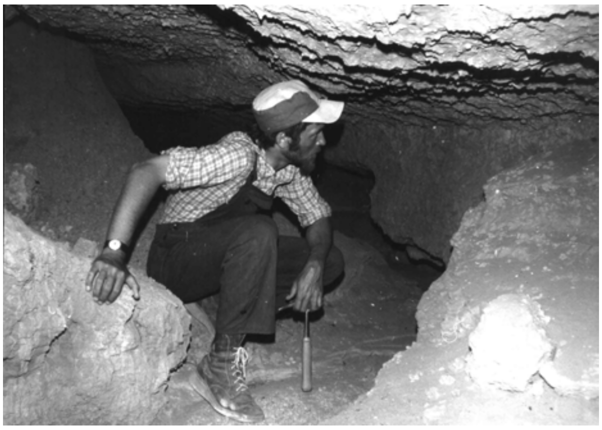
Ain al Mizraq must be considered as an important water resource. The lake in itself provides no solution for water supplies, in spite of its containing about 5,000 m^3 or more of water at present. This amount is not considerable and it is also contaminated as thousands of pigeons live in the cavity.

Scientific exploration of the Ain al Mizraq is necessary to discover its connections to the karst conduits from which practically limitless quantities of unpolluted water can be recovered. A diving reconnaissance and a test pumping is recommended to decide further measures.

9.4 Caves in Non-carbonate Rocks

Small underground drainage systems were observed in the geological formations in the neighborhood of the Bir al Ghanam karst. These small swallet-cave resurgence systems extend only between 5 and 20 meters. They were found in loess in the quaternary cover in the banks of deep-cut wadis and in numerous clay lenses of the Kiklah Formation. These cavities in non-carbonate rocks have no hydrological importance.





Photograph 70: Cavity in clay in the side of Ras Tamallilt (pic70.jpg)

Photograph 69: Cavity in loess in the Zahrat al Ghar area (pic69.jpg)

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