

Geology of the Dhaher (Bargish) Cave System, NW Jordan

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Abstract

There has been much interest in the development of the Dhaher cave in the Koora district as a show cave. Because of this, a research program has been implemented in order to document the geology and nature of the cave, as well as the possibility for the development of the cave for tourism.

The research has led to the mapping the accessible parts of the cave, which is about 130 m long and contains three large chambers or halls. There are many interesting cave deposits inside, providing for the possibility of development as a show cave.

The cave formed due to the presence of two major fault systems within limestone in a rainy Mediterranean climate. The rate of limestone dissolution suggests the initiation of cave development in the Late Pleistocene. Isotopic data suggest that the development occurred under current climatic conditions.

Introduction

Karst geology and cave systems are some of the most fascinating and important geologic features in the public imagination. For this reason, many caves around the world have been developed as show caves, attracting tourists and generating revenue for local communities. The Carlsbad Caverns in New Mexico, USA and the Jeita Cave in Lebanon are well known, but there are numerous examples of smaller show caves around the world.

In recent years, there has been increased interest in the *Dhaher*, or *Bargish*, cave in the Koora district in northern Jordan. Press reports of the cave have whetted the appetite for the development of a new tourist destination in the area. While it is known that the cave exists, no detailed geological study or map of the cave is presently available.

The purpose of this report is to detail the geological and climatological context of this cave, to present a detailed map of the accessible portions of the cave for the first time, and to list the most important cave deposits (speleothems) present in the cave. The availability of this information is crucial in any future plans for the development of the cave as a show cave.

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Geology and climate

The Dhaher cave lies in the Bargish forests of the Koora district in northwestern Jordan (Figure 1). This area has a typical Mediterranean climate, with warm dry summers and cool rainy winters. Average rainfall in the area is about 600 mm/year (Meteorological Department Open Files). The area is covered by natural forests which themselves are unique in Jordan.

Geologically, the area consists of Upper Cretaceous limestones locally known as the Wadi Sir Formation [1], or the Massive Limestone Unit [2]. In the hydrogeological nomenclature used in Jordan, the name given to this formation is the A7 formation [3]. Despite the various terminology used, the limestone in question is a massive white microcrystalline limestone with occasional marly partings and dated to the Turonian Epoch of the Upper Cretaceous. It was deposited in a marginal marine environment during the transgression of the Tethys at that time.

The Wadi Sir Formation is characterized by being thickly bedded with thin marl partings, medium hard to very hard (most of the higher quality building stone quarried in Jordan is derived from this formation in Ajloun, to the south), with semiconcoidal to concoidal fracturing. In some areas, dolomitization has occurred. The formation is considered to be one of the most important aquifers in northern Jordan. This is because of the extensive fracturing and karst development which it underwent, allowing for the formation of the secondary porosity needed for such a formation to become an aquifer. It contrasts sharply with the marly nodular Shueib formation below it and the mainly marly Wadi Um Ghudran and the silicified Amman formation above. In northern Jordan, it is estimated that the Wadi Sir formation is around 60 m thick.

The structure of the area is dominated by the presence of the Jordan Valley rift to the west of the study area. This left lateral rift system defines the plate boundary between the Palestine crustal plate to the west and the Arabian crustal plate to the east. Movement along this rift system led to the evolution of the Ajloun dome, of which the study area is a part.

The Ajloun dome is actually a fold striking and plunging NNE [4]. Thus, within the study area beds dip towards the NW. Faulting in the area includes EW, NW, N and NE trending faults [5].

Methodology

The study involved surveying the cave interior as well as geochemical and isotopic study of some of the water and speleothems found in the cave as well as in a nearby spring (Ain Zubia). Due to the darkness in the cave, a portable electrical generator and cables were used to provide enough light to work inside.

Due to the rugged nature of the interior of the cave, the surveying process was difficult. It included the choice of a baseline, and measurement of the various extensions and rooms using a compass, tape measures and, where possible, total station surveying equipment.

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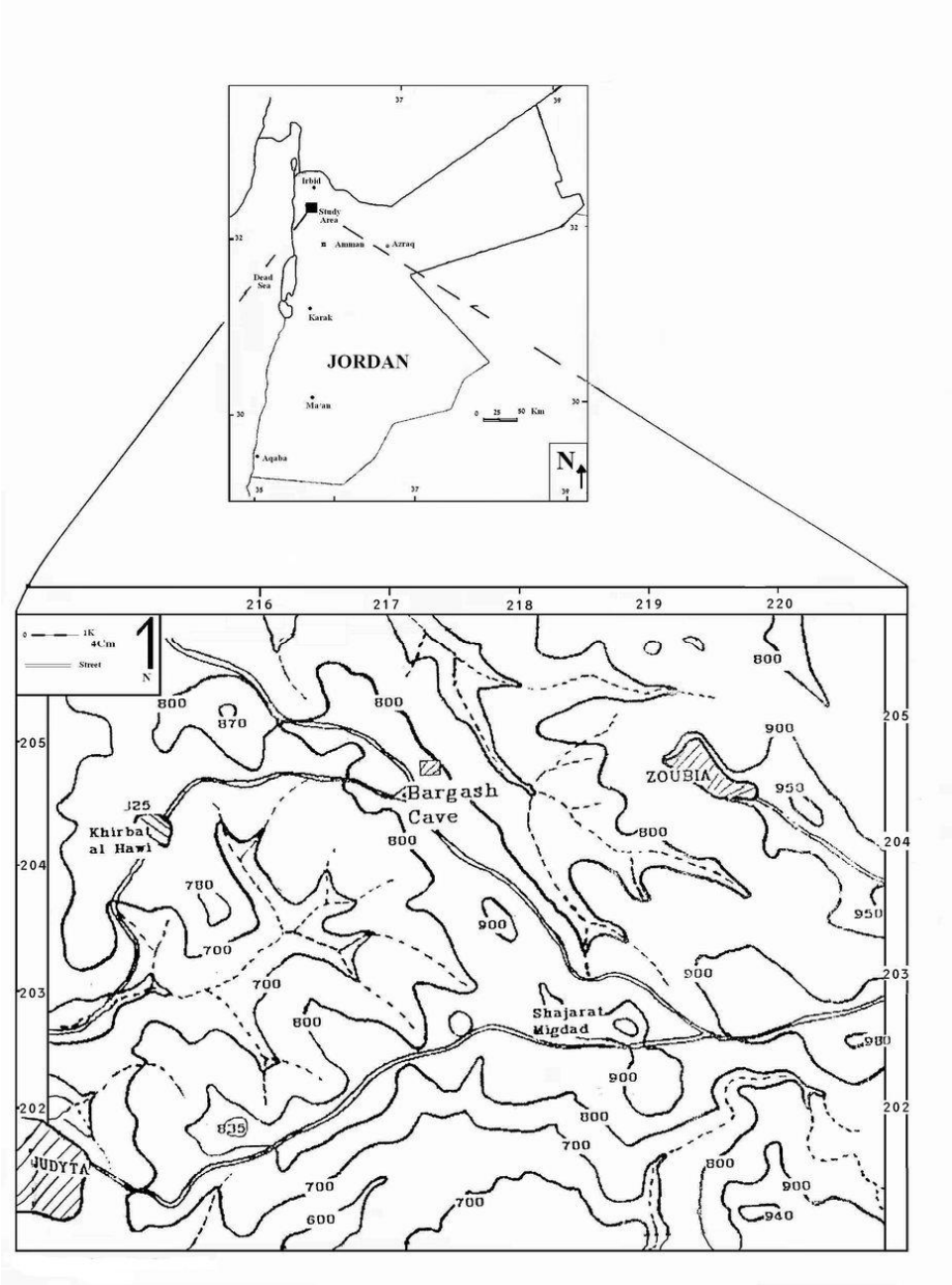


Figure 1: Location map of the study area.

Water samples were collected in pre-cleaned polyethylene bottles and sealed tightly. Electrical conductivity and pH were measured using standard electrodes in the laboratory. The major cations (Ca^{++} , Mg^{++} , Na^+ and K^+) were analyzed using Atomic Absorption Spectroscopy. Chloride and bicarbonate were analyzed using standard titration techniques, and sulfate was measured using spectrophotometric techniques [6].

Isotopic analyses were conducted in the Water Authority of Jordan laboratories in Amman using a Finnigan Mat Delta E mass spectrometer. This was used for the determination of the stable isotopic composition of water (oxygen and deuterium isotopes) and speleothems (oxygen and carbon).

The isotopic ratio is expressed in standard δ (delta) notation as follows [7]:

$$\delta^{18}\text{O}_{\text{sample}} = [({}^{18}\text{O}/{}^{16}\text{O}_{\text{sample}} - {}^{18}\text{O}/{}^{16}\text{O}_{\text{standard}}) / {}^{18}\text{O}/{}^{16}\text{O}_{\text{standard}}] 1000 \text{ and}$$

$$\delta^2\text{H}_{\text{sample}} = [({}^2\text{H}/{}^1\text{H}_{\text{sample}} - {}^2\text{H}/{}^1\text{H}_{\text{standard}}) / {}^2\text{H}/{}^1\text{H}_{\text{standard}}] 1000 \text{ and}$$

$$\delta^{13}\text{C}_{\text{sample}} = [({}^{13}\text{C}/{}^{12}\text{C}_{\text{sample}} - {}^{13}\text{C}/{}^{12}\text{C}_{\text{standard}}) / {}^{13}\text{C}/{}^{12}\text{C}_{\text{standard}}] 1000$$

The standards against which the isotopic ratios of oxygen and carbon are measured are Pee Dee Belemnite (PDB), and the isotopic ratios of hydrogen are referenced to Standard Mean Ocean Water (SMOW).

Description of the cave

Physical nature

The Dhaher cave has a total length of 130 meters. The entrance is a vertical 2 meter deep shaft with a diameter of 1 meter. The cave consists of the main cave passage which is typically 1-2 meters wide and 2-4 meters high. There are a number of large chambers and a few branches and passages. The largest chamber is about 50 square meters with a cave height of up to 11 meters. Figure 2 is a map of the cave, showing the upper and lower elevations at various locations as related to the base level at the entrance.

The entrance to the cave is rather long and narrow, with a semi circular cross section, with parts requiring crawling on the stomach to get in.

The Dhaher cave is a structural cave; it is mainly formed along two fault systems, one with a $\text{N}70^\circ\text{W}$ trend and a second with a $\text{N}45^\circ\text{E}$ trend. Each system consists of many parallel faults extending in the whole cave. In general the cave has linear extension along the faults.

Rain water infiltrates in the vadose zone which consists of jointed and faulted limestone rocks. The waters infiltrated through joints and faults and at flat ceilings parallel to bedding planes. Through passing the water through the faults and joints dissolution pores get larger and become more and more interconnected, so that the aggressive water advances more easily and deeper into the rocks interior; and the fissures become split.

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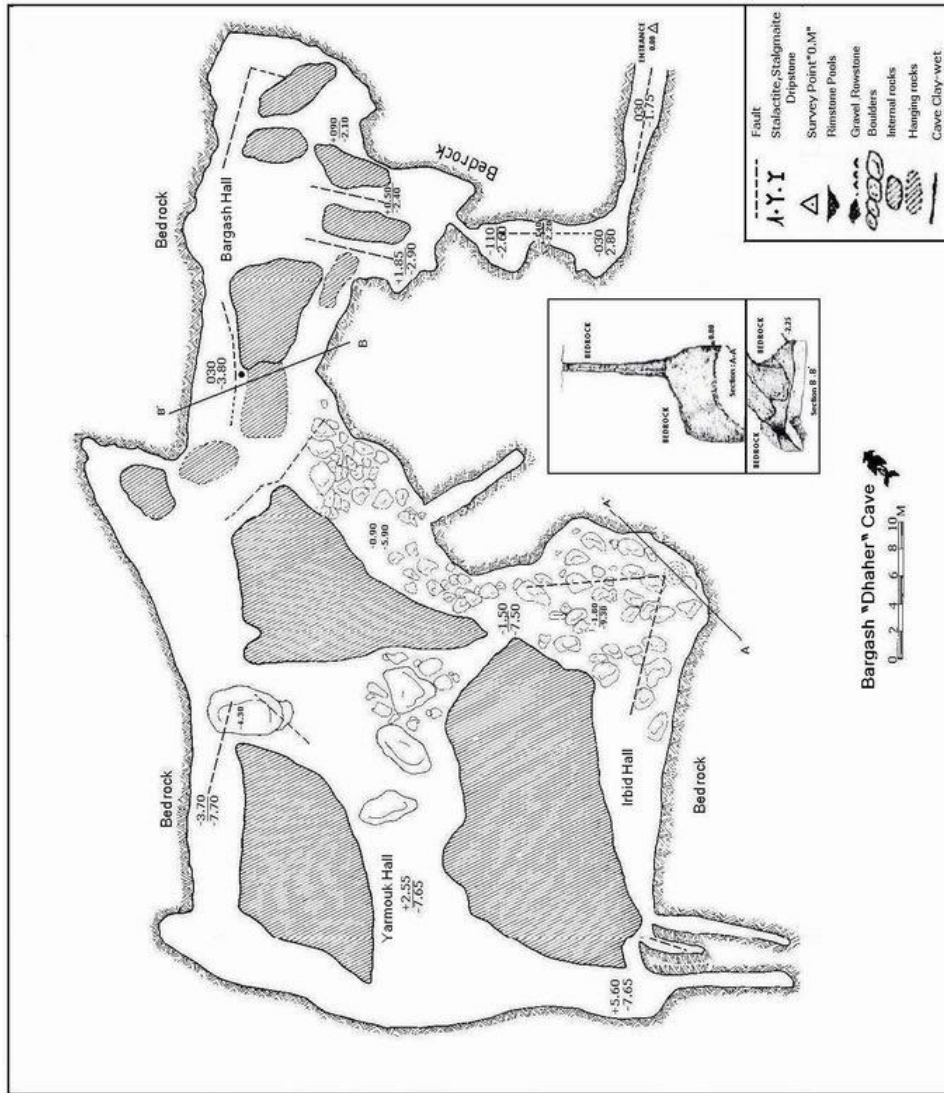


Figure 2: Map of the main features of the cave.

Biological factors accelerate the carbonate rock dissolution. Plant roots allow transmission of water, which helps erosion and improves the water holding capacity of the rock. Respiration increases CO₂ content in the vadose zone, which also helps in the limestone dissolution. It has been observed that the stalactites in the cave form at the extensions of the joints, which typically include plant roots.

Water seeping along fractures, especially faults and major joints, dissolves the limestone and widens them and weakens the rocks along these fractures. This causes

the formation of stalactites as well as eventual failure of the ceiling. The weakest areas in the ceiling are the points of intersection of the two fault systems. Shafts along these points are formed. Later on some of these shafts are scoured by flowing sandy, pebbly water forming bell holes.

Within the cave, three significant halls are identified (Figure 2). At the end of the entrance to the cave, Bargash hall, 12 m long and 5m wide is found. The maximum height of the ceiling is about 11 m, and the chamber seems to have formed as the result of a N50°E lineament. The hall contains some beautiful speleothems, including some striking stalactites and cascade deposits.

Irbid hall is 15m long and up to 7 m wide, with a maximum height of about 10m. A chimney which penetrates to the surface and the bottom of the room is covered with coarse gravel. The hall seems to have formed along an N20°W lineament.

The largest hall is the Yarmouk hall, which is about 20 m long, up to 8 m wide and a maximum ceiling height of 11. The ceiling is cut by two lineament sets, at N70°W and N45°E. The floor of the hall is covered with rock material ranging in size from pebbles to boulders produced by the collapse of part of the ceiling at the lineament intersections.

Cave deposits observed

Stalactites and stalagmites: These are the most famous forms of speleothems (cave deposits). Stalactites hang downward from the ceiling and are formed as drop after drop of water slowly trickles through cracks in the cave roof. Stalagmites point upward and form as water drops to the floor, loses CO₂ and deposits calcite. Both stalactites and stalagmites grow in concentric layers and may reach lengths of several meters.

Soda straws: These are hollow on the inside and have water dripping through them. Over time the inside clogs with calcite, causing the stalactite to grow larger. These begin to form as drops of water hanging from the ceiling. As they lose carbon dioxide, they deposit a film of calcite. Successive drops add ring below ring, and the water dripping through the hollow center of the rings, until a pendant cylinder forms. Tubular or "soda straw" stalactites grow in this way; most are fragile and have the diameter of a drop of water, but some reach a length of perhaps a meter or more.

Flowstone. These are deposits of calcium carbonate, gypsum, and other mineral matter that has accumulated on the walls or floors of caves at places where water trickles or flows over the rock. In the case of the Dhaher cave, these consist exclusively of calcite. Layered deposits of calcium carbonate precipitated on rocks from water trickling over them. They are three meters long and two and a half meters wide.

Dripstone. This consists of calcium carbonate deposited from water dripping from the ceiling or wall of a cave or from the overhanging edge of a rock shelter; commonly refers to the rock in stalactites, stalagmites, and other similar speleothems. Sometimes the drip water flows down the walls and over the cave floor creating flowstone or rimstone deposits. Where drip water seeps from a joint and then drips over the edges of ledges, or seeps along cracks on sloping ceiling, draperies are formed. The color of

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dripstones and flowstones caused by organic matter and/or iron and manganese oxide and hydroxides brought in as solutions from the surface, giving the speleothems an orange brown to deep brown or black color.

Cave popcorn: Small, knobby growths of calcite on the cave walls are called cave popcorn. Popcorn commonly forms in one of two ways in the cave: where water seeps uniformly out of the limestone wall and precipitates calcite; or, when water drips from the walls or ceilings of the cave and the water splashes on the floor or on ledges along the walls. This splashing action causes loss of carbon dioxide and the subsequent precipitation of calcite.

Cascade: Seeping of slowly water along the bedding plane causes the formation of what looks like a frozen waterfall. There is a beautiful example of this feature at the end of the entrance to the cave.

Curtain: A speleothem in the form of a wavy or folded sheet hanging from the roof or wall of a cave, often translucent and resonant. This occurs at fault planes where water seeps along a linear structure. Draperies or curtains develop where the feed water trickles down an inclined wall.

Bell hole: Downward wide and the top narrow, these result from strong water movement, resulting in angular gravel below the surface of the extensions of faults. These materials are a "soluble" residue of limestone and dolomite solution. On the cave walls thick zones of weathered limestone or dolomite remain when the solution process ends. This usually happens when there is no more inflow of aggressive water or when flowing water no longer transports the carbonate weathering products. Carbonate rocks do not dissolve immediately; and this signifies that they are not carried away completely from their primary place in ionic form, but that the disintegrated particles may remain on the cave passage walls. An incomplete dissolution may just prepare the carbonate rock for the mechanical transport of its particles by the flow of water. The weathered zone of limestone and dolomite is soft when it is wet and solid when dry.

Rimstone dams: these features build up in channels or on flow stones, the height range from millimeters to many meters; they may be single or interlocking to create a stair case of pools. Rims are straight, curved or crenulated [8]. We can see small rimstones in the cave.

Evolution of the cave

The rate at which caves form is related to the amount of rainfall in the area, the rate of recharge and the amount of CO₂ available [8]. Chemical and isotopic techniques were employed in order to gain an idea about the age of the Dhaher cave, if only in a preliminary value.

The hydrological cycle is basically a mass balance equation describing the amount of water entering or leaving a steady state system. In essence, it states that the input (rainfall and snow) is equal to output (runoff, evaporation and infiltration). In this case, we are interested in infiltration, as this is the amount of water which is actually working

to dissolve the limestone. In order to determine infiltration, it is necessary to understand the entire water cycle equation in the area.

The input function is easy to determine given the availability of precipitation data over several decades at nearby stations (Ras Muneef and Wadi El-Rayan). Based on data from these stations, it is safe to assume the annual rainfall in the area to be on the order of 500mm/a. It is worth noting that through the Quaternary period, there have been several climatic changes which seem to reflect glacial-interglacial periods in Europe [9, 10]. Thus, the calculations herein represent denudation rates during the current dry, warm interglacial period, and thus probably represent an underestimate of what has occurred during the life of the cave.

Runoff is a function of the soil cover and slope of the area. In very general terms, and based on the geomorphology of the area, it is estimated that the runoff coefficient in this area is about 25% [11]. Evaporation is an important component which can be assessed by comparing the isotopic composition of the ground water with that of the local precipitation. Bajjali [12], who collected rainwater data from all over Jordan, has studied the stable isotopic composition of rainwater in the area. The nearest area reported by him was from water collected at the station at Ras Muneef. Ground water was also collected from the cave and from Ain Zoubia, and subsequently analyzed for its stable isotopic composition. Data used are presented in table 1.

Table 1.: The isotopic results of the analysis of the water samples. Ras Muneef data is the mean weighted average (n=15) from Bajjali (1990).

Sample	$\delta^{18}\text{O}$	$\delta \text{ D}$
Ras Muneef	-7.25	-33.19
Drip water	-6.11	-27.8
Cave spring	-6.10	-25.9
Ain Zoubia	-6.10	-27.3

Comparison between the rain and ground water was done using the well known phenomenon that as water evaporates, it becomes enriched in the heavier isotopes of oxygen and hydrogen. This roughly follows what is known as the Rayleigh distillation equation, as follows:

$$R = R_0 f^{(\alpha-1)}$$

R_0 is the initial isotope ratio in the water, R is the ratio when only a fraction, “ f ”, remains, and α is the equilibrium fractionation factor during evaporation. This equation applies mostly to conditions of low humidity, and should be modified appropriately for the higher humidity seen in the area [13].

Thus, the purpose of the exercise is to determine f , or the fraction of water which infiltrates into the cave system. Based on the variations between the $\delta \text{ D}$ and the $\delta^{18}\text{O}$ of the samples, it is estimated that f is about 0.95, given the very small enrichment seen in the ground water.

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Thus, to calculate the amount of water moving through the karst system becomes a simple task. The catchments area of the cave area is about 100000m², which is five times the area of the cave. Assuming that 500mm/a fall onto the area, it is estimated that 50000 cubic meters of water fall in the immediate vicinity of the cave, of which 25% flows away as runoff, leaving 37500 cubic meters. Evaporation leads to the loss of about 5% of the remainder, leaving about 35600 cubic meters flowing through the limestone of the area.

Comparing the chemistry between input and output water allows determining the amount of carbonate dissolved by the water moving through the rock [14]. Table 2. gives the results of the chemical analyses performed on the rain water [12] and the ground water in the area.

Table 2.: The chemical results of the analysis of the water samples. Units are in mg/l

Sample	TDS	pH	Ca	Mg	K	Na	HCO ₃
Rain	58.7	7.14	6.5	3.0	1.0	4.4	17.9
Drip water	503.0	9.5	95.8	26.46	0.30	16.6	460
Cave spring	610	7.1	57.4	25.5	0.41	16.8	310
Ain Zoubia	752	6.31	51.5	26.88	0.16	18.1	284

These results show significant removal of Ca²⁺, HCO₃⁻ and Mg²⁺ from the system through dissolution. It is noteworthy that the ratio of Mg²⁺ to Ca²⁺ is higher than would be expected from dissolution of limestone. Two reasons might account for this. The first is the presence of dolomite in the area. The second might be selective concentration of Mg²⁺ due to the dissolution of high-Mg calcite and the precipitation of low Mg calcite in materials such as stalactites. In either case, the sum of the magnesium and the calcium represents the amount of net carbonate removed from the system.

Assuming that the water at Ain Zoubia represents the average output water from the cave system, this would suggest that the removal of 1.3 mmol of Ca²⁺ and 1.2 mmol of Mg²⁺ per liter of water moving through the system, suggesting the removal of about 1.2 mmol of CaMg(CO₃)₂, which is equal to 219.6 mg, amounting to about 87.8 * 10⁻³ cm³ of the carbonate. Given that the amount of water moving through the system annually is 35600 cubic meters, this means that about 3.1 cubic meters of limestone/dolostone are removed in a year.

The area of the main cave is about 20000m², and the average height is about 5-6 meters, giving a total volume of the cave to be about 100000-120000m³. In order to create this cave at the rate that appears to be prevalent, it would take about 40000 years to carve out the cave as we now see it.

The basic assumptions in this calculation involve the climatic conditions. The region has been through a number of pluvial periods since the Late Pleistocene, and it is possible that during those times, the rate of weathering was higher. Thus, it is conceivable that the age is lower than what is indicated in this calculation. There are

other uncertainties in the calculation related to the actual amount of water moving through, especially during various climatic events. The runoff coefficient may have been underestimated. Moreover, the chemistry of the water was not sampled enough to give any reasonable idea about the seasonal and inter-annual variations in the chemistry. On the other hand, the water in the spring at the center of the cave had a chemistry similar to that seen at Ain Zoubia, suggesting that most of the dissolution reactions occur in the area immediately above and around the cave system. In any case, we believe that the initiation of development of the system began in the Late Pleistocene.

Isotopic nature of the speleothems

The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of speleothem CaCO_3 are related to the primary sources of oxygen and carbon in the cave seepage water. In the case of oxygen, this is meteoric water. In the case of carbon, it is soil carbon dioxide and carbonate bedrock. The process of speleothem deposition can be traced back to the soil horizon where biological activity produces high levels of CO_2 . This soil CO_2 acidifies seepage waters, which in turn dissolve carbonate bedrock en route to underlying caves. Upon entering a cave passage of lower CO_2 concentration (relative to the soil atmosphere), the seepage water releases CO_2 and CaCO_3 deposition takes place [15]. Because bicarbonate concentrations of karst ground waters are typically in the parts per thousand ranges, the $\delta^{18}\text{O}$ compositions of the water and the dissolved carbonate species are dominated by the water molecules themselves, which originated as meteoric precipitation. Therefore, the $\delta^{18}\text{O}$ values of speleothems are generally not significantly influenced by the bedrock isotopic composition [13]. Speleothem $\delta^{13}\text{C}$ values, however, are significantly influenced by the isotopic composition of the bedrock, and the soil CO_2 . The latter is strongly related to the vegetation overlying the cave, and vegetation at the regional scale is strongly correlated to climate.

The cave temperature effect represents isotopic fractionation between water and calcite during calcite deposition. The temperature dependence of the fractionation has been experimentally determined as ~ -0.24 ‰ per $^\circ\text{C}$ [7], meaning there is greater fractionation at cold temperatures relative to warm temperatures. The fractionation between the oxygen isotope composition in water and the precipitating calcite is defined by the following equation:

$$1000\ln\alpha = \delta^{18}\text{O}_{\text{CaCO}_3} - \delta^{18}\text{O}_{\text{H}_2\text{O}} = 2.78(10^6/T^2) - 2.89 \quad [7].$$

The ~ -0.24 ‰ per $^\circ\text{C}$ fractionation that defines the cave temperature effect therefore reflects the mean annual temperature of the area.

Although a host of factors can potentially affect the $\delta^{13}\text{C}$ values of speleothems, vegetation is a major factor because soil CO_2 is generated largely by the microbial oxidation of soil organic matter, which is derived from vegetation. C_3 and C_4 photosynthetic pathways produce large differences in $\delta^{13}\text{C}$ values. C_3 plants have $\delta^{13}\text{C}$ values averaging ca. -26 ‰, whereas C_4 plants average ca. -12 ‰ [16]. C_4 plants are typically warm-season grasses and a few herbs found in tropical and temperate grasslands, whereas C_3 plants are mostly trees, shrubs, cool-season grasses, and most herbs.

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The isotopic results of the analysis of two samples of carbonate from the speleothems are given in table 3. $\delta^{18}\text{O}$ results shown in table 3 indicate the same water source in the cave and spring. The average $\delta^{13}\text{C}$ in C_3 plants is -26‰ and -12‰ in C_4 plants [17], which means that the carbon isotope results ($\delta^{13}\text{C} = -10.77\text{‰}$ and -10.73‰) approach the average of C_4 plants which indicate warmer climate.

Table 3: The isotopic results of the analysis of the carbonate samples.

Sample	$\delta^{18}\text{O}$ (PDB)	$\delta^{18}\text{O}$ (SMOW)	$\delta^{13}\text{C}$ (PDB)
Black center	-5.28	-31.53	-10.77
White center	-5.09	-31.72	-10.73

By applying the equation of Friedman and O'Neil [7] above and assuming the isotopic composition of water is the same as what is observed currently in the drip water, then it is possible to calculate the precipitation temperature of the carbonate. The calculation yields a crystallization temperature of almost 10-11°C, which is reasonably close to the ambient temperature of the cave, suggesting that the stalactites were deposited in climatic conditions similar to the present, as indicated by precipitation temperature and isotopic composition of the water.

Summary and conclusions

The study which includes mapping of the cave and description of sediments and analyzing of rock and water samples showed important results. The Dhaher cave has a whole length of 130 meters, with many large chambers, few branches and passages. These have been mapped and are shown in figure 2. The main passage and the whole cave with its passages and chambers were formed along two major fault systems in the limestone. Each system consists of many parallel faults extending in the whole cave; the two systems consist of one with a N70°W trend and a second with a N45°E trend. In general the cave has linear extension along the faults.

Three big rooms have been formed in the cave; the Yarmouk hall, Irbid hall, and Bargash hall. In general the cave sediments can be classified according to the criteria mentioned above into: speleothems (Dripstone, Flowstone, Rimstone dams), cave screens and the cave earth. $\delta^{18}\text{O}$ results indicated to a similar source for the cave water and spring. The average $\delta^{13}\text{C}$ in C_3 plants is -26‰ and -12‰ in C_4 plants, which means that the carbon isotope results ($\delta^{13}\text{C} = -10.77\text{‰}$ and -10.73‰) approach the average content of C_4 plants which are common in this area and which indicate a warm climate. Denudation rates calculated suggest the cave began development in the Late Pleistocene.

The development of the cave as a show cave is possible, since the setting in which it exists is unique, and the cave contains many beautiful speleothems of various shapes and sizes. In any case, the site needs to be protected against vandalism if it is to become a tourist destination. Care should be given to study the stability of the ceiling before any significant development is undertaken.

Acknowledgments

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جيولوجية نظام كهف الظهر (برقش) شمال غرب الأردن

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ملخص

نظراً للاهتمام الحالي لتطوير كهف الظهر في لواء الكورة للأغراض السياحية فقد تم إجراء دراسة لتوثيق طبيعة وجيولوجية الكهف. كما تم دراسة إمكانية تطوير المغارة لإغراض السياحة. تم رسم خارطة للأجزاء الرئيسية من الكهف ، والذي يبلغ طوله 130م ويحتوي على ثلاثة قاعات رئيسية. هناك العديد من الترسبات الجيرية الجميلة والتي يمكن ترويجها للزوار. لقد نشأت هذه المغارة نتيجة وجود صدعين رئيسيين في صخور جيرية في بيئة متوسطة مطرة. وتشير وتيرة إذابة الصخور إلى بداية تشكل في نهاية عصر البلايستوسين ، وتشير المعلومات النظائرية إلى النشأة في ظروف مناخية مشابهة للظروف الحالية.

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