

# Investigations of a stalactite from Al Hota cave in Oman and its implications for palaeoclimatic reconstructions

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**Cover Picture:** Ring structure of Stalagmite with no central tube. Picture by Sobhijaber Nasir.

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**Abstract:** Speleothems and other cave sediments have proven to be valuable tools for climate reconstructions. They allow to reconstruct the changes of temperatures and precipitation over time even in arid areas where other types of sedimentary archives are scarce or even non-existent. In this study, a speleothem from Al Hota cave in northern Oman is investigated by means of petrographic interpretation and analyses of the isotopic composition of fluid inclusions in the stalactite. These data are then compared with the chemical and isotopic compositions of water samples in this area and are also put into a regional context to find out more about precipitation regimes and possible changes in the position of the Intertropical Convergence Zone (ITCZ) during the time the stalactite was deposited. It could be shown, that the investigated stalactite has been deposited from a mainly southern precipitation source which indicates a position of the ITCZ more to the north compared with its present position and a strong influence of the Indian summer monsoon in northern Oman.

**Keywords:** Speleothem, Cave, Climate, Isotope, Monsoon, Al Hota, Oman.

**Supervisors:** Svante Björck, Dan Hammarlund & Sobhijaber Nasir

**Subject:** Quaternary Sciences

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# Undersökningar av en stalaktit från Al Hota grottan i Oman och implikationer för paleoklimatiska rekonstruktioner

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**Sammanfattning:** Stalaktiter och andra grottsediment har visat sig vara värdefulla verktyg för klimatrekonstruktioner. Med deras hjälp är det möjligt att rekonstruera förändringar av temperatur och nederbörd tillbaka i tiden. De är även användbara i arida områden där andra sedimenttyper sällan existerar. I den här studien undersöks en stalaktit från ”Al Hota”-grottan i norra Oman med hjälp av en petrografisk undersökning och isotopanalyser av vätskeinneslutningar i stalaktiten. Denna information jämfördes med kemi- och isotopsammansättningar av vattenprover från undersökningsområdet. Resultaten jämfördes även med andra studier från mellanöstern för att få en mer sammanhängande bild av perioder med olika nederbördsmängder och av möjliga förändringar av intertropiska konvergenzsonens (ITCZ) läge under tiden stalaktiten avlagrades. Studien visar att den undersökta stalaktiten avlagrades från nederbördsvatten som kom söderifrån vilket indikerar att positionen för ITCZ var längre norrut då än under moderna förhållanden och att det fanns en stark påverkan av den indiska monsunen i norra Oman.

**Nyckelord:** Al Hota, Oman, Arabien, droppstenar, vätskeinneslutningar, monsun, ITCZ.

**Handledare:** Svante Björck, Dan Hammarlund & Sobhijaber Nasir

**Ämnesinriktning:** Kvärtärgeologi

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# 1 Introduction

## 1.1 Background

Climate change has in one way or another effects on everyone. The earths climate fluctuates in numerous ways that let many study and also speculate how the climate functions, why certain trends occur and what future alterations/expectations will occur. To make valid predictions of future climate change one needs to interpret and understand records from the past.

Today Oman and the Arabian Peninsula are arid regions, situated just outside the area affected by the Indian Monsoon. Its impact area is affected by the position of the Intertropical Convergence Zone (ITCZ), which changes over time. These changes are recorded in a number of different archives such as lake sediments (Tierney & Russel 2007), marine sediment cores (Rashid et al. 2011) and speleothems (cave deposits, Fig 1., Burns et al. 1998, Fleitmann et al. 2003). As lakes are rare in arid areas, such studies have to rely on other archives. Speleothems are used in this study as a paleoclimatic archive that preserves information about the past climate and especially about precipitation changes over time (Cronin 2010). This type of archive occurs both in humid and arid areas and is thus well suited to reconstruct how a region changes between humid and arid conditions. They are suitable archives to find out about the climate

developments on the Arabian peninsula during the Quaternary as caves and sinkholes are common in calcareous bedrock terrain in this region (Amin & Bankher 1997, Sadiq & Nasir 2002, Pint 2003) and because most of these systems have been developed during the Quaternary.

## 1.2 Project area

The main aim of this thesis is to interpret a stalactite from Al Hota cave (Oman) and water samples from the surrounding area and to use this information for a very restricted paleoclimatic reconstruction.

The methods used are petrographic analysis of the speleothem, hydrogen and oxygen-isotope analyses of both the speleothem and the water as well as chemical analyses of the water.

This information will also be used to test the model proposed by Fleitmann et al. (2003) who suggested that the ITCZ had a more northern position during deglaciation and the early Holocene and that most speleothems in the region were formed during this time. They assign the increase in precipitation and speleothem formation to increased activity in the Indian summer monsoon and based their model on different speleothems from the same cave.

The results of the present study will then be put in a larger, more regional context.



*Fig. 1.* Speleothems in Al Hota cave. Left: Draperies and Stalactites. Right: Stalagmite with stalactites on the bottom. Photos by Donna M. Bou-Rabee, 2012.

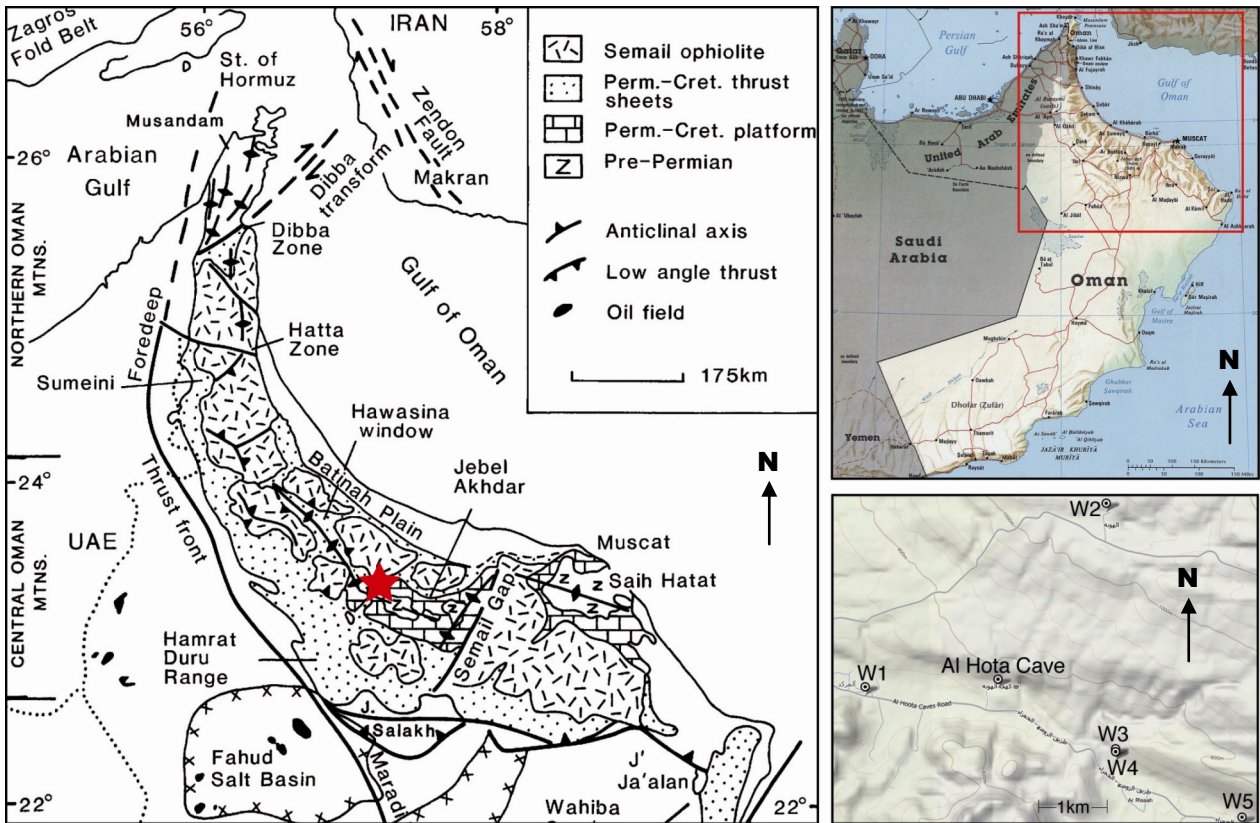


Fig. 2. Left: Structural map of the Oman mountains, after Robertson & Searle (1990). Red Star marks study area, shown in more detail on bottom right. Top right: Topographic map of the eastern Arabian Peninsula, red square marks coverage of left map (CIA 2013). Bottom right: Study area and sample locations. Background image taken from Google maps.

### 1.3 Study area

Oman is situated in the South-Eastern part of the Arabian Peninsula (Fig. 2). It consists of different morphological and climatic regions which are separated by mountain ranges. Many large caves occur in these mountainous areas.

Al Hota cave (23.082° N, 57.354° E) is situated within the Hajar mountains in the northernmost part of Oman, close to the city of Nizwa, on the Southern side of the Jabal Akhdar mountain range, which is part of a large anticline which has been formed in a thick sequence of Mesozoic limestones and dolomites (Waltham et al. 1985). Al Hota cave is situated entirely in the Natih Formation of the Wasia group (Fig. 3) which has been described in detail by Van Buchem et al. (2002).

Al Hota cave has two large entrances, Al Hota entrance (1040 m a.s.l.) as its inlet and Al-Fallah (810 m a.s.l.) as its outlet (Fig. 4 and Fig. 5). The length of the cave system is slightly less than 5 km and the altitude difference between the entrances and the vertical extension of the cave is thus 230 m (Waltham et al. 1985).

According to Van Buchem et al. (2002), the deposition of the rocks in the Natih Fm. began in the late Albian and continued through the Cenomanian to the Turonian. i.e. the Natih Fm was deposited in the latest parts of the lower and the early parts of the upper Cretaceous. This is in contrast to older studies that

PERIOD	EPOCH	STAGE	AGE (MA)	GROUP	FORMATION	
CRETACEOUS	Upper	Maastrichtian	70-	Aruma	Simsima	
		Campanian			Fiqa	
		Santonian	80		Muti	
		Coniacian				
		Turonian	90		Natih A	
	Cenomanian	Natih B				
	Lower	Albian	100-	Wasia	Natih C/D	
					Natih E	
						Natih F/G
						Nahr Umr

Fig. 3. Generalized stratigraphy of the study area. Al Hota cave is situated in the Natih formation which is highlighted in gray. Modified after Van Buchem et al. (2002).

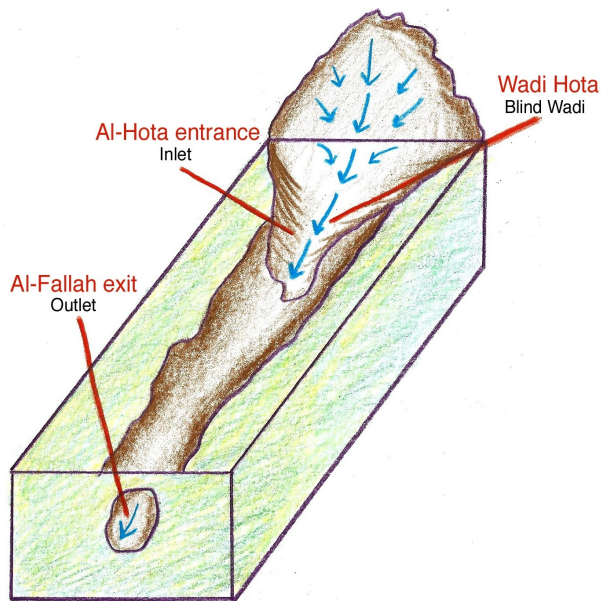


Fig. 4. Principal sketch of the Al Hota cave system. Al Hota entrance acts as a sinkhole in Wadi Hota and as an inlet of the cave, water is flowing down into the cave system towards the outlet at Al-Fallah exit.

assigned a Cenomanian age to the entire Natih Fm (e.g. Tschopp 1967). The Natih Fm and the entire Wasia group consist of limestone of different types, both of the bedded and the massive variety.

Upfolding of the Jebal Akhdar anticline (Fig. 6) took place during the late Cretaceous (Mann & Hanna 1990, Hanna 1990). Hanna (1990) assigns this tectonic event to the Early Alpine period, while earlier researchers such as Glennie et al. (1974) assigned it to the Late Alpine period. During this time, an ophiolite sheet was thrust upon the previously deposited



Fig. 5. Al Fallah entrance to the right, access tunnel for tourist train to the left. Note the vertical jointing in the bedrock. Picture by Sobhijaber Nasir.

sediments (Hanna 1990). Due to the tectonic stress, the limestone was fractured (Fig. 7) and these fractures were subsequently filled with calcite crystals. These fractures then served as the starting point for karst development (Mais et al. 1995). Waltham et al. (1985) describe the surface karst of the Jebal Akhdar area. They state that the main features are karren, especially microkarren which they assign to rainfall events and dew formation. They also state that there are hardly any larger surface karst landforms such as dolines and sinkholes.

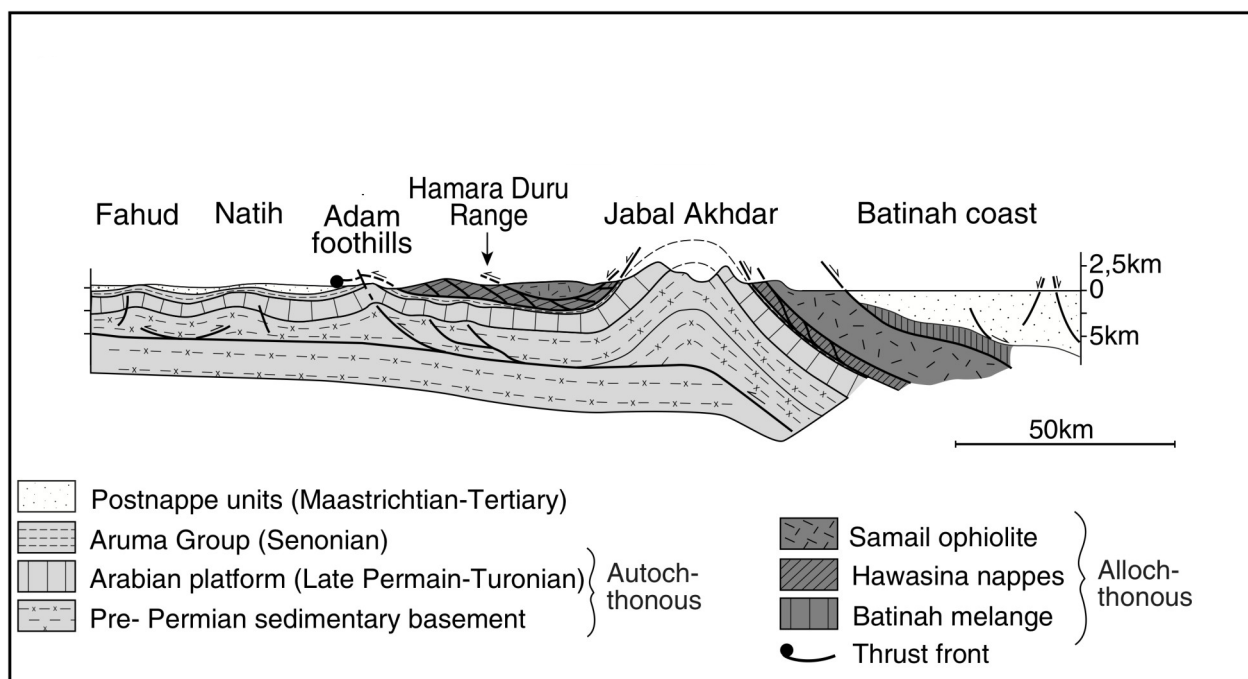


Fig. 6. Generalized profile of the structural geology in the study area. Al Hota cave is situated on the southern flank of the Jebal Akhdar mountain range. Source: Van Buchem et al. (2002).



Fig. 7. Fractured limestone of the Wasia Group. Picture taken outside Al-Fallah exit by Donna Bou-Rabee 2012.

The system to which Al Hota cave belongs is a major subterranean wadi with Al Hota cave as an inlet and Al-Fallah as its outlet (Fig. 8) in Wadi Munbuk. It has also been chosen as study site due to its easy accessibility and the infrastructure which has been installed to facilitate tourism.

## 1.4 Climate

The climate in the study area can be defined as arid to semiarid with mean monthly temperatures ranging between 33°C and 35°C during summers and between 20°C and 25°C during winters. The annual precipitation at nearby Al Hamra weather station ranged from 50 to 250 mm per year during the period 1974-1997. According to Fleitmann et al. (2003), the modern mean air temperature in the cave is 26°C.

Heavy monsoon rains have mostly affected caves in the southern parts during summer, while heavy rainstorms have mostly affected the northern part during winter, which led to large fluctuations in groundwater level during the Quaternary (Fleitmann et al. 2003). Fleitmann & Matter (2009) name three sources for precipitation in the study area: Mediterranean frontal system, convectional or orographic precipitation and tropical cyclones. The most common of these moisture sources is the

Mediterranean frontal system while tropical cyclones only reach the area around Al Hota cave once every 5-10 years.

Ground water fluctuations have played a major role in the formation of the cave. Several periods of predominately humid and dry conditions have occurred in Southern Arabia as a result of monsoonal dynamics related to insolation-driven migration of the ITCZ (Burns et al. 1998, 2002, Fleitmann et al. 2007, Fleitmann & Matter 2009).

Today, the northern part of Oman is situated north of the ITCZ, a boundary which at present is roughly equal to the southern coast of the Arabic Peninsula (Fleitmann et al. 2003). This is also the northern limit of monsoon rainfall, which only reaches Oman's south coast. The position of this boundary is not fixed (Fig. 9), but has changed over time (Burns et al. 1998, 2001, Fleitmann et al. 2007). When the ITCZ moves northwards, precipitation in Oman increases, leading to so called "pluvial periods" that are recorded in speleothems shown as very low  $\delta^{18}\text{O}$  values (Fleitmann et al. 2003). Such a period of monsoon rainfalls in northern Oman occurred for example between 9.5 and 6.3 kyr BP (Fleitmann & Matter 2009).

## 2 Methods

### 2.1 Field work

Fieldwork was carried out in June 2012. During this time general reconnaissance work and sampling were carried out, both inside Al Hota cave and in its surroundings. Five water samples and one stalactite were taken for further analyses.

### 2.2 Water analysis

Electrical conductivity, pH and water temperatures were measured in the field for samples W1-W5 (Fig. 2, Table 1). The samples were further analyzed at Food and Water Laboratories Centre, MRM & WR, Oman. The parameters measured include among others the cations  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ , the anions  $\text{HCO}_3^{2-}$ , and  $\text{SO}_4^{2-}$ , pH, total hardness and total alkalinity.

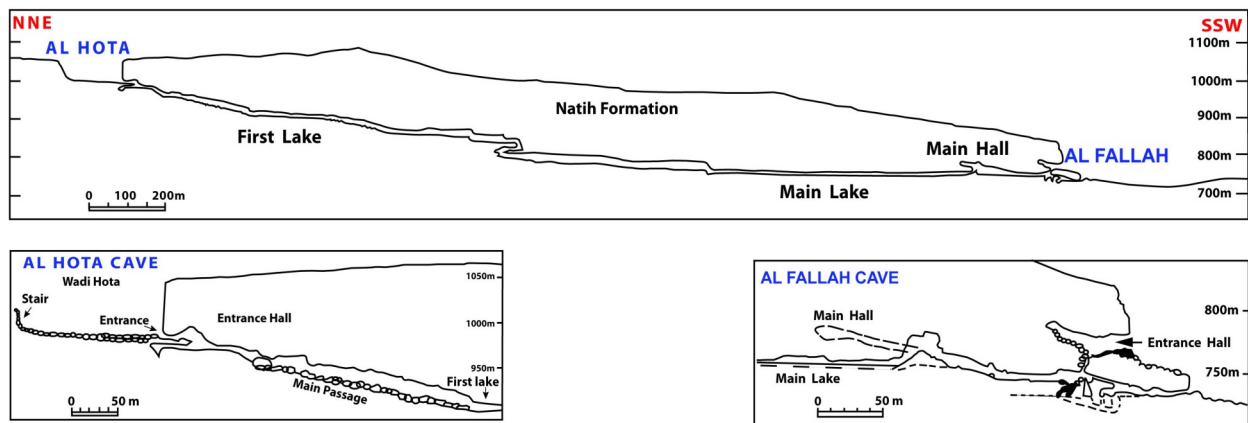


Fig. 8. Top: Cross-section through Al Hota cave system. Bottom: Detailed drawings of both entrances (after Troll 1990).

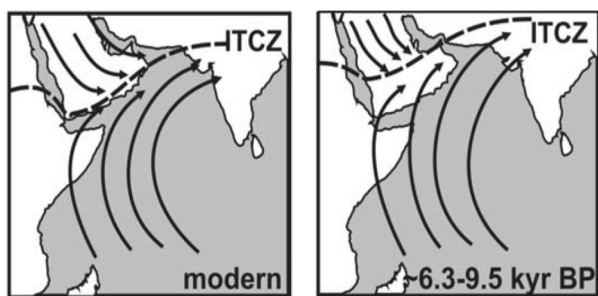


Fig. 9. Two maps showing different configurations of ITCZ and summer monsoon winds. The map to the left shows the modern-day configuration with the ITCZ following the southern coast of Oman and Yemen, the map to the right shows a more northern position of the boundary of the ITCZ with summer monsoon winds reaching northern Oman and the study area (Fleitmann et al. 2003).

Electrical conductivity is used as a measure for the total concentration of ions (in karst waters mainly  $\text{Ca}^+$ ,  $\text{Mg}^{2+}$  and  $\text{HCO}_3^{2-}$ ) and also for rough estimation of the total dissolved solids in the water. Sasowsky & Dalton (2005) describe the importance of pH measurement both in the field and in the laboratory. They state, that pH values can be used to compare the acidity of waters, the  $\text{CO}_2$  partial pressure and the saturation of the water with dissolved calcite. If this saturation index is negative, the water has the ability to dissolve calcite and if it is positive, the water can deposit calcite and let speleothems grow. Sasowsky & Dalton (2005) show that the exact determination of pH is of utmost importance for such calculations. As both the specific conductivity and the pH are affected by water temperature, this parameter has been recorded for each sample.

The concentration of the ions can be used to determine which minerals have been dissolved by the water (White 2007). While the bicarbonate ion is a key component in the deposition of carbonate minerals such as calcite and aragonite, the sulphate ion plays an equally important role in the system of sulphate minerals such as gypsum. A high concentration of  $\text{Ca}^+$  ions is a sign of a large amount of dissolved limestone;

this can only be the case if the water is also rich in  $\text{CO}_2$ . According to White (2007)  $\text{Mg}^{2+}$  is also an inhibitor of calcite growth.

## 2.3 Isotope analyses of a speleothem and ground water

Five samples from the calcitic stalactite (Fig. 10) were analyzed for the  $^2\text{H}/^1\text{H}$  ratio of fluid inclusions within the stalactite. The analyzes were carried out at Queen's University Faculty for Isotope Research (QFIR), Kingston, Ontario, Canada. The same laboratory carried out measurements of  $^2\text{H}/^1\text{H}$  and  $^{18}\text{O}/^{16}\text{O}$  on water samples W1 (from the cave outlet) and W2 (from near the cave inlet, cf. Table 1).

Isotope measurement of the fluid inclusions has been performed by pulverizing the samples from the stalactite which were then put into a Finnigan TC / EA (High Temperature Conversion Elemental Analyzer) where the fluid inclusions are extracted and the  $\text{H}_2\text{O}$  contained in them is split by pyrolysis (McDermott et al. 2006). The hydrogen is converted to  $\text{H}_2$  and the oxygen to  $\text{CO}$ . The gases are separated and then led into an isotope ratio detecting mass spectrometer (IRMS, Thermo Instruments Delta XL+, Kurt Kyser, pers. comm.). The process for the water sample was the same except that they could be put into an autosampler for liquid samples. The results are reported on the VSMOW scale to make them comparable to previous studies (Fleitmann et al. 2003).

## 2.4 Petrographic analysis

Five thin sections were prepared from the limestone of the Natih Formation as well as five thin sections from different parts of a large stalactite sample from the cave (Fig. 10) These thin sections have been used for a petrographic study using polarized microscope and digital photos (Fig. 16). The thin sections were investigated to describe growth style of the individual calcite crystals in the stalactite in order to reconstruct the conditions at the time of crystallization.

Table 1. Details on the sampling localities for the water samples. For a map see Fig. 2.

Sample	Location	Latitude	Longitude
W1	Bore well Water (near to lower entrance of Al Hota cave, on the main road)	23° 4'48.51"N	57°19'52.23"E
W2	Bore well Water (near to upper entrance of Al Hota cave)	23° 6'17.58"N	57°21'59.52"E
W3	Cave Water (Stagnant water on the wadi)	23° 4'16.90"N	57°22'4.73"E
W4	Cave Water (fresh from cave)	23° 4'18.42"N	57°22'4.46"E
W5	Agriculture Garden (dug well sample)	23° 3'45.11"N	57°23'11.39"E
W6	Mosque (sub-surface sample)	23° 3'33.72"N	57°23'49.44"E

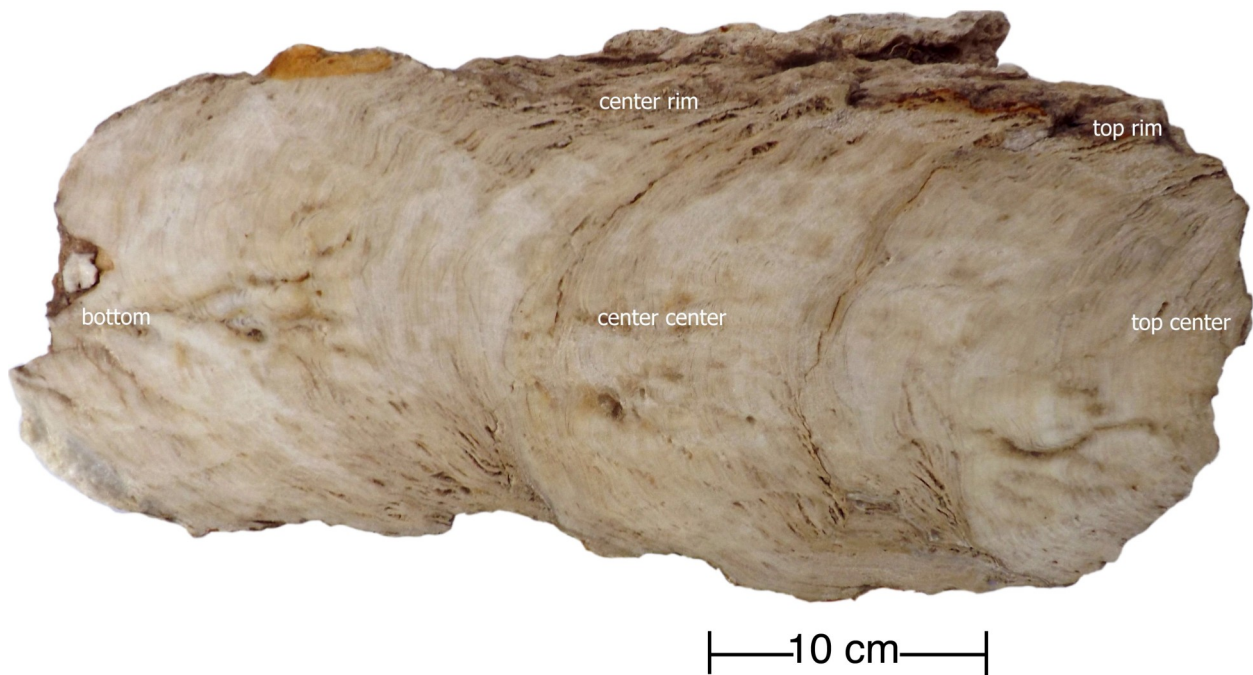


Fig. 10. Photograph showing the sampled stalactite and the positions of the subsamples for thin sections and isotope analyses. As the growth direction of the stalactite is from right to left, "top center" was deposited first and "bottom" last. The scale bar is 10 cm long. Picture by Sobhijaber Nasir 2012.

### 3 Previous studies

This literature review is comprised by specific articles presented in logical groupings according to their genre and area of study and placed in chronological order within each grouping. Method papers contain studies and analysis methods that are not specific to the North Oman area, but contain important general information that is used in establishing how research is performed on speleothems. The section concerning regional geology contains research papers that have focused on areas in the studied region of Northern Oman and its surrounding areas. The final section, Oman cave papers, focuses on research performed on speleothems from caves in the Oman region.

#### 3.1 Method papers

Bar-Matthews et al. (1997) performed high-resolution petrographic, stable isotope and age measurements on samples of seven fossil speleothems from different areas within the Soreq Cave in Israel in order to gain insight into the climatic evolution of the area during the late Pleistocene and Holocene epochs. The speleothems were cut perpendicular to their length and the growth pattern of laminae was studied. This analysis served to allow the researchers to gain a better understanding of how climate conditions have changed and shifted into the climate of today. Through the course of their research, they determined that before 7000 yr BP the climate was wetter and cooler in the Israeli region, as evidenced by the unique petrography of the speleothems formed between 10,000 and 7000 cal. yr. BP; these showed irregularly thin laminae of

varying colors, which occur as a result of a decrease in precipitation.

Fairchild et al. (2006) recognized the importance of the study of speleothems as a means to establish patterns that affect the climate system. They determined five variations that have an effect on speleothem composition: atmosphere, vegetation/soil, karst aquifer, growth patterns, and secondary alterations. They found, as they progressed through these variations, that the impact of the climate was progressively reduced. This led the researchers to the conclusion that the development of speleothems is more complex than previously thought and does not relate entirely to climate variability.

Fairchild and McMillian (2007) discuss the use of speleothems as a means to determine wet and dry climatic periods through growth rate analysis and measuring the levels of Mg/Ca and Sr/Ca in drip waters, which become elevated during dry periods due to CO<sub>2</sub> degassing. The variations found in these levels serves as a means to help researchers understand the trends in climate change by studying the speleothems through high resolution methods which show the annual variations of trace elements and growth. Ongoing research is being conducted to determine how this will relate to future climate changes.

Szwarcz (2007) explains the composition of speleothems and their stable isotope systematics; explanations of the different isotopes found in speleothems are given and photo examples of different speleothem formations are also shown. The importance of speleothems in the study of the

paleoclimate is explained as a method of determining the variations in climate during different periods, such as the Holocene.

White (2007) discusses methods including radiocarbon and U/Th dating of speleothems, paleomagnetic reversals, and cosmogenic isotope dating of clastic sediments to analyze cave sediments from various areas throughout the world. High-resolution is utilized to construct profiles due to the thin nature of the layers of the speleothems. Through analyzing the isotope ratio of oxygen, carbon, deuterium/hydrogen, and other trace elements, geologists are able to obtain a detailed paleoclimate record that dates back over several hundred thousand years. These analytical methods will provide a relevant testing method to use on speleothems found in Northern Oman.

### 3.2 Regional geology papers

Records of monsoon rainfall in the Indian Ocean were only available for the past century until Burns et al. (2002) conducted their study in southern Arabia in which they analyzed the annual layer thickness and stable isotopes of laminated stalagmites of speleothems collected from that area. It was determined through analyses of stable isotope ratios (oxygen and carbon) that the intensity of the monsoon in the past century do not deviate much from those that have occurred over the past 780 years, though what has changed recently is the amount of precipitation, and it is postulated that this is a result of increased sea surface temperatures in the Indian Ocean, which can be attributed to global warming.

A sedimentological analysis showed that the Natih Formation in Oman was comprised of two types of depositional systems: a flat mixed carbonate-clay ramp with abundant benthic foraminifera, and a ramp consisting mainly of carbonate bordering an intra-shelf basin containing abundant rudists, mid-ramp and basinal facies. It was concluded that any variations to the modeling found in the orange line comparisons are likely due to varying local climate conditions (Van Buchem et al. 2002).

Parker et al. (2006) found that paleo-environmental variations in lacustrine sediments from lakes in southeastern Arabia correlate to the strength and duration of rainfall during the winter and from the strength of the summer Indian Ocean Monsoon (IOM) during the Holocene. Changes in the terrestrial environment, as lakes and dunes formed, were concluded as main factors for human occupation and subsequent land use in the region. Currently, there are two opposing views as to how the IOM rains shifted northward during the Holocene and the formation of the dunes from the westerly winds. One view is that the IOM moved to the north because of a shift in the ITCZ that brought rainfall across the continent. The opposing view is that the rains did not occur this way. Instead, it is suggested that precipitation was a result of local convection. To resolve these opposing views,

Parker et al. (2006) state that additional research is required.

### 3.3 Oman cave papers

Glennie and Singhvi (2000) studied weather patterns that had an effect on the Shaman winds in order to determine how lakes and sand dunes were formed. Shaman winds occur mainly during the winter, originate from the Arabian Gulf, and blow in a southerly direction towards the Emirates. When the winds reach Rub al Khali (empty quarters desert north of Oman) they begin to turn in a clockwise direction. It has been determined that during the Holocene epoch the Wahiba Sands were brought up from the south by monsoon winds. This was done by studying aeolian and lacustrine deposits, which show that the sands originated from the floor of the Arabian Gulf and were transported via glaciers when the sea level was low, prior to the increased humid period during the Holocene.

By growth and isotopic analysis of speleothems from Al Hota Cave, Burns et al. (2001) attempted to develop a climate record over the course of the previous four glacial-interglacial cycles; through this analysis, they found that rapid growth occurred during the early to mid Holocene, which points to increased moisture conditions. The results of their studies show a shift to the north of monsoonal rainfall, and it has been surmised that this northern shift was due to conditions present at the glacial boundary, and not due to solar radiation originally inferred, based on the association of the continental pluvial periods with peak interglacial conditions (Burns et al. 2002).

Fleitmann et al. (2003) performed analyses on speleothems from Al Hota Cave to produce a record where periods of increased growth occurred during the following time periods: 330,000-300,000, 200,000-180,000, 135,000-120,000, 82,000-79,000, and 10,500-6000 years BP. Very little growth, if any, was found in the speleothems for the periods in-between, leading to the conclusion that during the growth periods the monsoonal rains migrated northward to Northern Oman.

By analyzing deep ocean sediment cores through stacking and principal components analysis (PCA), Clemens and Prell (2003) were able to determine five individual records from 350,000 years ago that show changes in the strength of the monsoons over time and correlate them to seasons. They were able to deduce from the results that the intensity of a monsoon is influenced by global ice volume and by latent heat export which is in turn maximized in conditions when a warm summer follows a colder winter in the Earth's southern hemisphere. This latent heat was then transported by the summer monsoon winds, and increased the amount of precipitation by strengthening the monsoon low as evidenced by the patterns found in the orbital bands.

The profiles of high resolution stable isotopes from three stalagmites found in a shallow cave in Southern Oman were analyzed by Fleitmann et al. (2003) and provided a record of the variations in monsoonal rainfall for the past 780 years. The larger annual growth bands are attributed to high  $\delta^{18}\text{O}$  values that are present during periods of greater monsoonal rainfall. Fleitmann et al. (2003) found evidence in stalagmite S3 of a longer oxygen isotope profile that pointed toward a drier monsoon season during the time period of AD 1320-1660 that is comparable to the decrease of monsoonal rainfall in the area since the 1960s. They related the change to higher sea surface temperatures in the Southern Indian Ocean.

Stalagmites from four caves in Northern and Southern Oman and Yemen underwent high-resolution oxygen isotope profiling to determine variations in rainfall along a latitudinal transect from  $12^\circ$  to  $23^\circ$  N that is normally controlled by the ITCZ and the Indian Summer Monsoon. Results of the profile show evidence of increased short-lived monsoon events occurring during the trend of decreased monsoonal precipitation during the mid-Holocene epoch (Fleitmann et al. 2007).

Fleitmann and Matter (2009) studied stalagmites from the Al Hota Cave in Northern Oman and in the Qunf Cave in Southern Oman. The stalagmites were dated by U/Th to gain insight on the climate history of the area. Increased speleothem growth is related to climate conditions that are wetter. Therefore, by studying them, scientists can determine past precipitation that has been produced by monsoon winds and the latitudinal shifts of the ITCZ. This also allows for the study of the caves' response to the external environment as these records of growth and isotopes showed a relationship between each pluvial period and an interglacial stage of the marine oxygen isotope record. (Fleitmann & Matter 2008).

## 4 Results

### 4.1 Water analysis

Four (W1,2,3,5) of the six analysed samples (Table 1) show relatively low Mg content (Fig. 11) while Ca content is high in five of the samples (W1-5). This is due to the fact that the local lithology and especially the Wasia formation contain large proportions of calcite but very little dolomite (Seemann & Koller 2002).

The water directly from the outlet of the cave (W4) has a very low total ion concentration but relatively much of this small amount is Mg. When comparing absolute Ca and Na concentrations (Fig. 12) it becomes clear that the cave water (W3, W4) is low in both ions, concentrations being lowest for water directly exiting the cave. This can be explained by limestone sinter formation at this point, a process which lowers the concentrations (Seemann & Koller 2002). Samples from springs and wells in Wadi Tanuf (W5,6,2) show higher Mg concentrations and larger Na/K ratio than waters directly from the cave (Fig. 13).

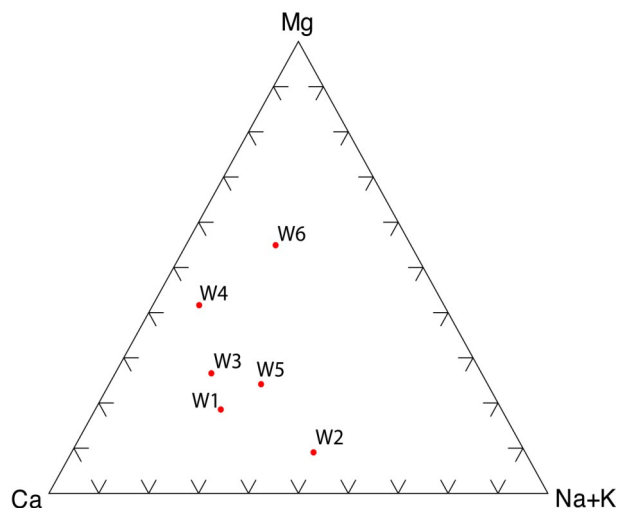


Fig. 11. Triangular plot showing the composition of sampled waters in the Ca-MG-Na+K field. These ions are the main cations in karst waters. The diagram shows relative concentrations and can be used as an indicator of the influence of the local lithology. After Seemann and Koller (2002).

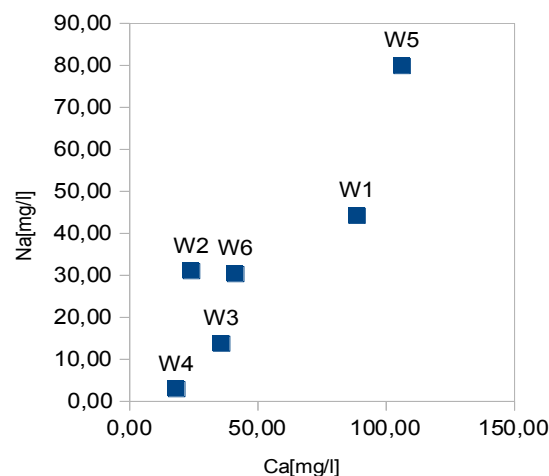


Fig. 12. Plot showing absolute concentrations of  $\text{Ca}^+$  vs.  $\text{Na}^+$ . These values can be used to distinguish between waters directly from a cave (W3 and W4) and other water samples. After Seemann and Koller (2002).

This implies that these waters originate from different aquifers.

According to Alsharhan et al. (2001), water of the  $\text{HCO}_3^-$  type is typical for a water of local source, while the anion composition develops first towards  $\text{SO}_4^{2-}$  and later to a  $\text{Cl}^-$  water type with increasing transport distance (Fig. 14). Samples W1, W3 and W6 are clearly local waters according to this definition. W2 and W5 seem to come from a more regional aquifer and have been transported for a longer distance. Alsharhan et al. (2001) also relate salinity (and thus conductivity) changes with the differences in transport distance but this effect could not be seen in the data used for the present study as these changes

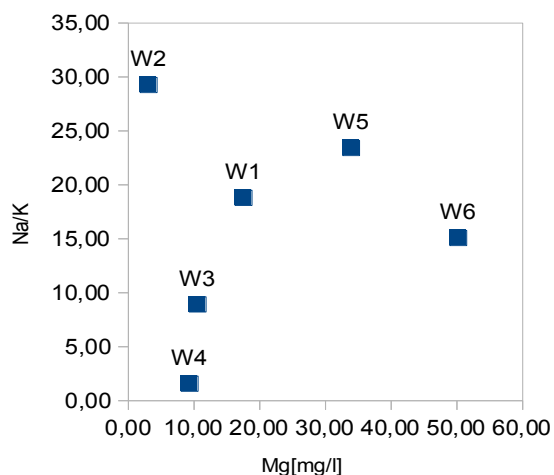


Fig. 13. Diagram showing absolute Mg concentration vs Na/K ratio. This plot is used to distinguish between waters from different aquifers (Seemann & Koller 2002).

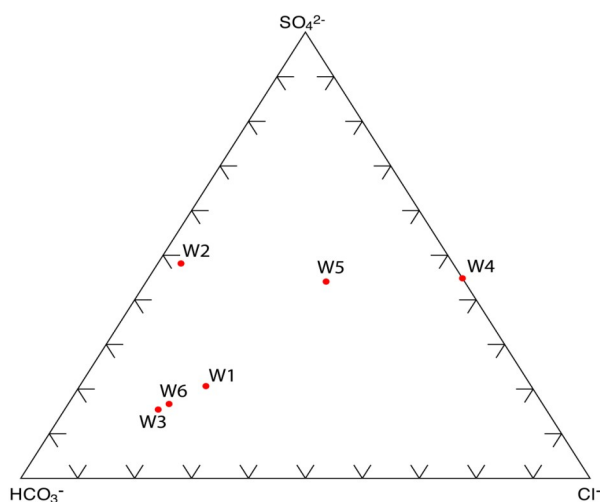


Fig. 14. Triangular plot of main anions ( $\text{HCO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ ) of karst waters. The values shown are relative to the other main anions. After Alsharhan et al. (2001).

were possibly obscured by human impact such as fertilizers.

Sulphate contents are quite low in all of the samples. This shows that no gypsum is dissolved from the aquifer and that the aquifer is not overexploited in the study area (Alsharhan et al. 2001).

Electrical conductivity is highest in the sample from the agriculture garden (W5) and from beneath the mosque (W6), which could indicate anthropogenic pollution. This interpretation is supported by the relatively high contents of nitrate in these two samples.

## 4.2 Isotope analyses of a speleothem and ground water

All samples from structural water from the stalactite (Table 2) have a strongly negative  $\delta\text{D}$  value (range -96 to -103, mean value -100). The magnitude of the  $\delta\text{D}$  value can be explained by the low precipitation

amounts in the study area (Dansgaard 1964). This isotopically light composition points towards a deposition of the calcite during peak interglacial times (Fig. 15, Fleitmann et al. 2003). Water samples W1 and W2 have  $\delta\text{D}$  values of -12 and -16 and  $\delta^{18}\text{O}$  values of -1.8 and -3.1 respectively. Fleitmann et al. (2003) stated that water from a southern moisture source is more depleted in heavy isotopes than water from a northern source. When the samples analysed in this study are plotted on a  $\delta^{18}\text{O}$  vs.  $\delta\text{D}$  graph as presented by Fleitmann et al. (2003), W2 plots between northern and southern moisture source while W2 has a composition similar to waters from a southern source.

## 4.3 Petrographic analysis

### 4.3.1 Top rim (A, B)

Large, elongate crystals with preferred orientation and parallel extinction can be seen in this thin section (Fig. 16). The color is darker than in other parts of the stalactite. This difference in color is visible both macroscopically and microscopically and can, according to Ayalon et al. (1999) be due to a higher concentration of clay and other detritus that interfered with crystal growth. Large crystals have probably been deposited from slowly dripping water and are indicative for colder and drier periods (Ayalon et al. 1999).

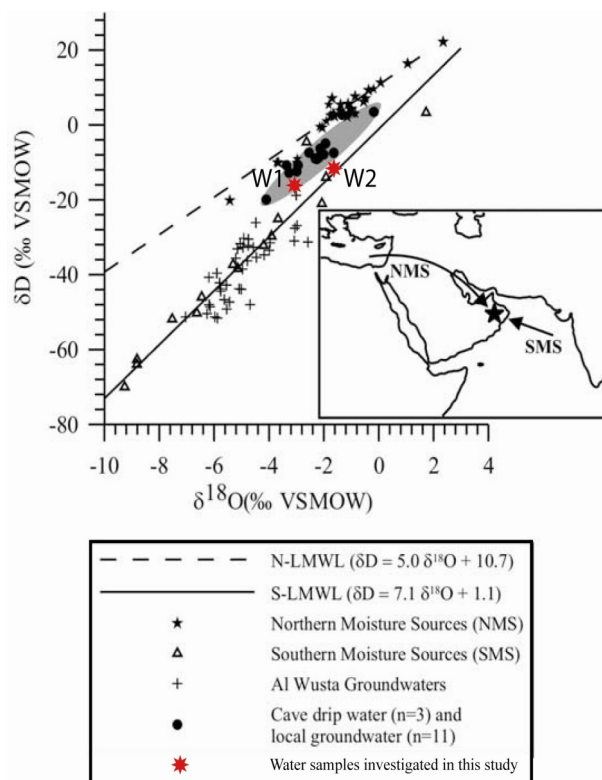
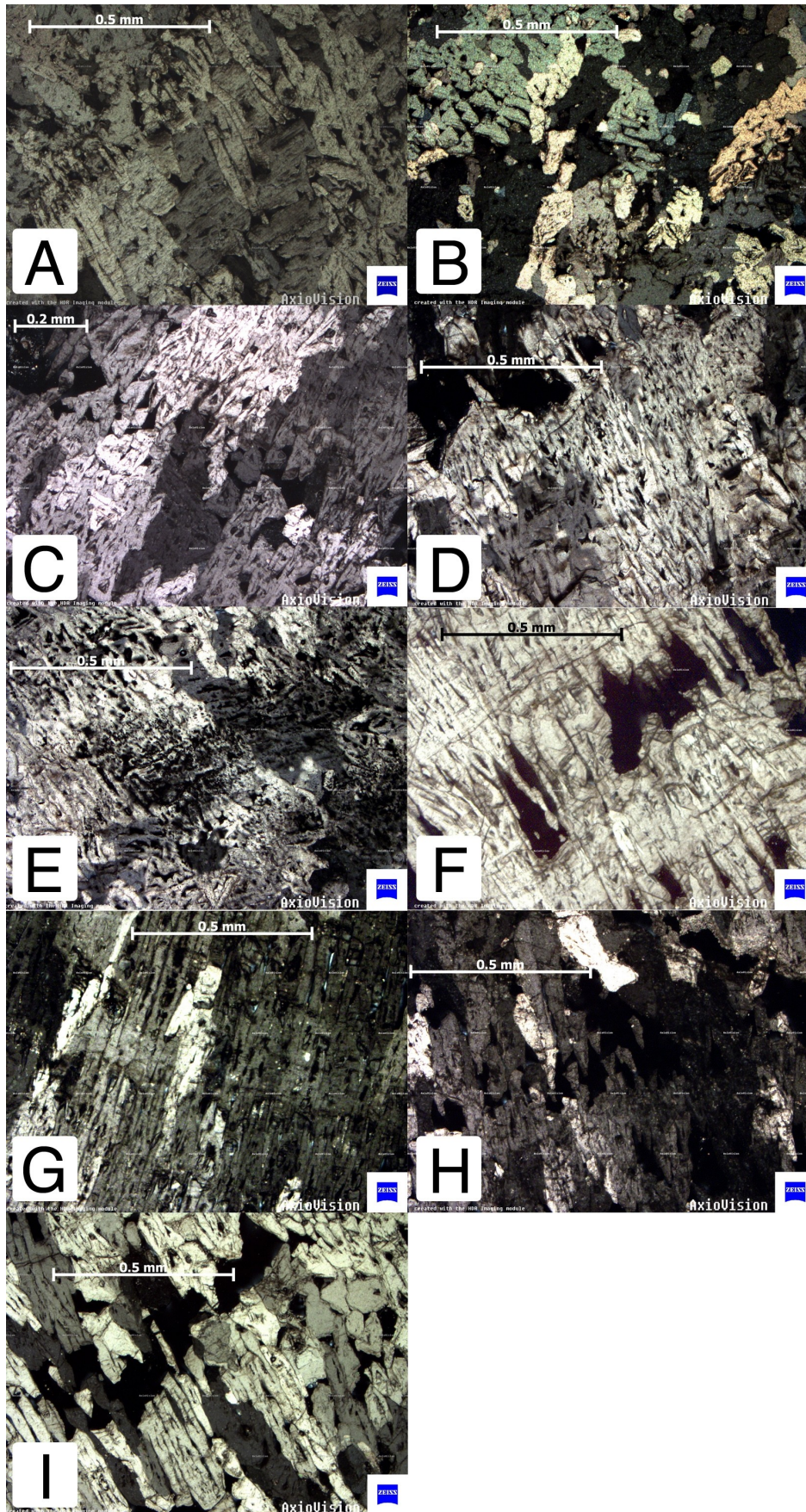


Fig. 15. Plot of the isotopic composition ( $\delta^{18}\text{O}$  vs.  $\delta\text{D}$ ) of waters from different precipitation sources and calculated regression lines. The upper line marks waters from a northern moisture source (NMS), the lower line samples from a southern moisture source (SMS). Modified after Fleitmann et al. (2003). The red stars mark samples analyzed in the present study.



*Fig. 16.* Microscopic photographs (cross polarized light) of different thin sections from the stalactite. Note the different scale bars of the individual photographs. Photos A and B: top rim, C: top center, D and E: center rim, F and G: center center, H and I: bottom center. All pictures taken by Sobhijaber Nasir.

#### 4.3.2 Top center (C)

Small anhedral crystals and darker and lighter bands are visible in this thin section. The small crystals with random orientation can be assigned to deposition from rapidly flowing water containing large concentrations of  $\text{Ca}^+$  and  $\text{HCO}_3^-$  ions (Ayalon et al. 1999). This high flow rate and ion concentration leads to a larger number of crystallization nuclei and thus to less growth space for the individual crystal (Gonzales et al. 1992). This part of the stalactite is the oldest sample and could have been deposited between 17 and 7 ka BP (Ayalon et al. 1999) when temperatures and precipitation in the region were higher than today.

#### 4.3.3 Center rim (D, E)

In this part of the stalactite, the crystals are very small and randomly oriented indicating high water availability and thus humid conditions (Gonzales et al. 1992). The concentration of detritus is high, giving them a dark color. This darker color is even visible to the naked eye. It is also obvious that this part has a much coarser structure which could probably indicate crystal growth around particles such as clay.

#### 4.3.4 Center center (F, G)

Here, the crystals are large and elongated. They have a preferred orientation and their extinction is parallel. Their color is light, indicating a low concentration of detritus between the single crystals. This low concentration of detritus is another indicator of low water supply and thus of drier periods.

#### 4.3.5 Bottom center (H, I)

In the bottom and youngest part of the sampled stalactite, the crystals are elongate but there are more dark areas than in other parts of the stalactite with similar structure. This might be due to a higher percentage of detritus and indicates fast flowing water (Gonzales et al. 1992, Ayalon et al. 1999).

*Table 2.* Results from the analysis of structural water from stalactite samples as measured at QFIR. Sample IDs refer to Fig. 10. Amt-% is weight of fluid inclusions / total weight of the sample. The samples below are listed stratigraphically: the top samples are oldest and the bottom sample is the youngest. Their absolute age has, however, not been analyzed.

Sample ID	Amt %	$\delta\text{D}$ vs. VSMOW
Bottom centre (youngest)	2.1	-99
Centre rim	2.5	-103
Centre centre	1.9	-103
Top rim	2.2	-102
Top centre (oldest)	1.8	-96

## 5 Discussion

After the Natih-formation was fractured by tectonic stress and the fissures filled by calcite, this calcite was subsequently dissolved by flowing water. During the earlier parts of the quaternary, this dissolution formed large cavities in which first speleothems formed.

No absolute datings have been performed on the stalactite investigated in this study, but comparisons of its petrographic structure with the one of stalactites described in the literature (Ayalon et al. 1999, Burns et al. 2001, Fleitmann et al. 2003) support the conclusion that deposition of this stalactite began at the peak of the last glacial and continued through the early Holocene.

The results of this study show that the interpretation of fluid inclusions is a useful tool for climate reconstructions. It could be shown that a climate signal is recorded in Al Hota cave just as proposed by among others Burns et al. (2001) and Fleitmann et al. (2003). The fluid inclusions in the investigated stalactite are strongly depleted in  $^2\text{H}$  which points towards a deposition from fast dripping water during warm and humid periods (Fleitmann et al. 2003) who also suggest that the strong depletion is a signal for water coming from a southern moisture source. This hypothesis is also supported by the fact that the cave waters are isotopically light (Fig. 15).

Water from a southern moisture source implies stronger influence of the Indian summer monsoon in the study area, a condition which only occurs during periods of a more northern position of the ITCZ.

The parts of the sampled stalactite containing small, anhedral crystals and large amounts of detritus indicate deposition from fast flowing water. Such conditions occur during periods of high precipitation such as the Eemian and the early Holocene. These periods could be the “pluvial periods” described by Fleitmann et al. (2003).

Parts of the stalactite exhibiting large, well oriented crystals have probably been deposited from slowly but continuously dripping water. This is indicative for periods with less precipitation than during the pluvial periods but with more precipitation than today. Such periods occurred for example during peak glacial times and during the transition from pluvial periods to arid conditions. The high variability in crystal structure (Fig. 16) is not reflected in the isotopic composition. One reason could be that subsampling took place at too large intervals so that these high frequency changes were omitted. To avoid this problem, samples for the isotope analysis should be taken with very high temporal resolution.

All these facts point to a more northern position of the boundary of the ITCZ (Fig. 9) during the periods of speleothem deposition, as proposed by Burns et al. 2001, Fleitmann et al. (2003) and Fleitmann & Matter (2009). These pluvial periods could be at peak interglacials but more research is needed to test this hypothesis. The exact connections

between the  $\delta D$  signal in speleothem fluid inclusions and regional climate are still largely unknown as analytical problems have prohibited such studies until very recently (Fleitmann et al. 2003).

The chemical composition of the cave waters and the ground water from the surrounding areas points to a local ground water body (Seemann & Koller 2002, Alsharhan et al. 2001). This interpretation is also supported by the geomorphology of the area and the proximity to the main water divide in northern Oman, as precipitation on the southern flank of the Jabal Akhdar mountain range is only transported for a short distance before passing through the local ground water bodies that were investigated in this study.

## 6 Conclusions

- Speleothems are a useful tool for climate reconstructions as they record climate changes both in their crystal structure and in the isotopes of both minerals and fluid inclusions. Isotopic measurements on the calcite allow to reconstruct changes in the oxygen isotope ratios ( $\delta^{18}O$ ) while measurements on the fluid inclusions provide information on the hydrogen isotope ratio ( $\delta D$ ).
- Fluid inclusions are difficult to extract from the sample but have the advantage that  $\delta D$  is not affected by exchange between the fluid and the surrounding minerals.
- All samples from the stalactite are strongly depleted in deuterium (very low  $\delta D$  values) which indicates a deposition from water coming from a southern precipitation source.
- The parts of the stalactite showing small, poorly oriented crystals were probably deposited from fast flowing water, the parts showing large, well oriented crystals from slowly dripping water. The investigated stalactite was probably deposited during warm periods with high precipitation.
- Today's precipitation is low which means that speleothems are not formed during present day conditions.
- Water coming from a southern moisture source and high precipitation indicate large influence of the Indian summer monsoon, which can only occur during periods when the northern boundary of the ITCZ is situated north of the study site. such periods are called "pluvial periods" by Fleitmann et al. (2003).

## 7 Recommendations

Future studies should attempt to create an accurate chronology of the samples investigated as this will increase the possibility to correlate the results to previous studies. Such an chronology could be built on e.g.  $^{14}C$ ,  $^{231}Pa/^{235}U$  or  $^{230}Th/^{234}U$  (depending on the ages to be expected). As the speleothems in Al Hota

cave are expected to be relatively young,  $^{14}C$  and  $^{230}Th/^{234}U$  would probably be the best dating methods.

To make the results even more comparable with other studies and to facilitate correlations over a larger area, higher resolution studies are needed. Samples for these studies have to be taken along the growth axis of the speleothem with a high enough resolution to create "pseudo continuous" curves which could then be compared to records from other caves within the region.

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