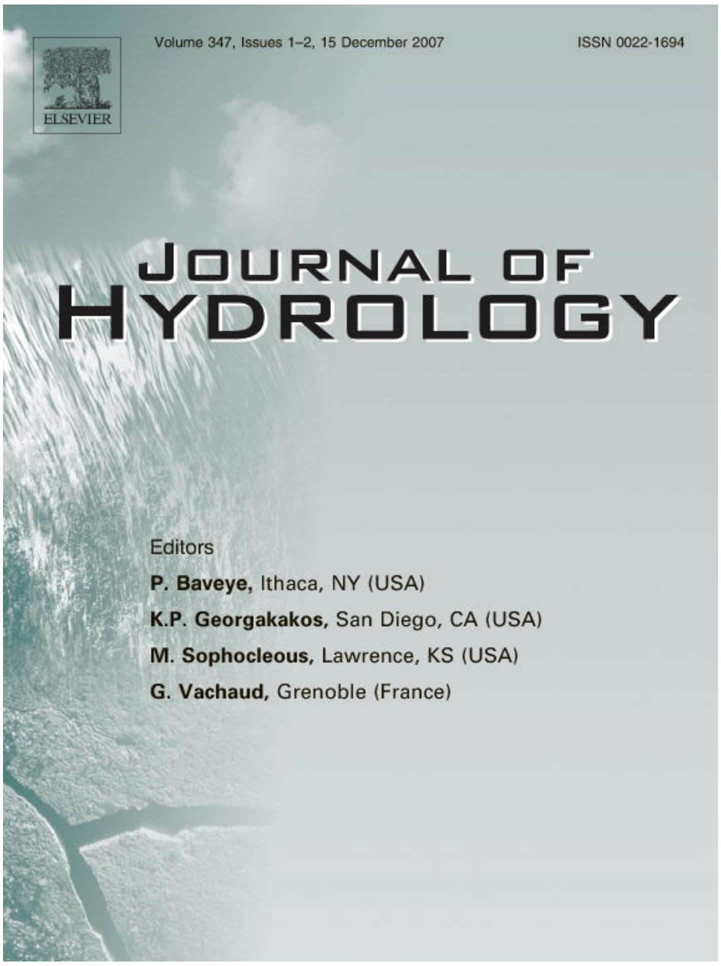
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Understanding conditions behind speleothem formation in Korallgrottan, northwestern Sweden

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Summary In this study we investigate and characterise the environmental factors that control active speleothem growth in Korallgrottan, northwestern Sweden, in order to get a better understanding of seepage processes in karst areas and to determine whether the fossil speleothems from this site are suitable as palaeoclimatic archives. The drip rates from fast-dripping stalactites (>100 ml/day) vary substantially with the season and the snow regime. Comparisons with measurements of river discharge and simulated ground water recharge show that the drip rate from fast-dripping stalactites can be used as an estimation of the weekly to monthly ground water recharge. Slow-dripping stalactites however, have a steadier drip rate, with almost no seasonal variations. The $\delta^{18}O$ composition of the drip water from both fast- and slow-dripping stalactites show some seasonal variation (±1.2‰), but is fairly stable compared to outside precipitation (±11.1‰). The $\delta^{18}O$ signal from fast-dripping stalactites is biased towards summer conditions, while the signal is dampened at slow-dripping sites and an annual or even longer signal is evident. This holds true even though calcite precipitation may not occur continuously throughout the year. Similarly, the trace elemental composition of drip water is more stable in the slow-dripping stalactites, reflecting mean annual values or longer. Generally the drip water reaches the highest saturation level during the summer and autumn when biological activity in the soil zone is most intense, and the partial pressure of carbon dioxide, which controls limestone dissolution, is high.

Introduction

Stable isotope growth laminae and trace element analysis of well-dated speleoethems can, under suitable conditions, provide records of past temperature, precipitation and vegetation (McDermott et al., 2001; Mangini et al., 2005; Baldini et al., 2005; Smith et al., 2006). In a climatically stable cave environment speleothem carbonate can be deposited under isotopic equilibrium, then the oxygen isotopic composition of the carbonate ($\delta^{18}O_c$) may be expressed as a function of cave temperature and the

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isotopic composition of the drip water ($\delta^{18}O_w$) (Hendy, 1971).

Cave temperatures recorded deep inside the cave are normally close to the annual mean surface temperature. Cave temperatures recorded in caves in cold environments can however display a cooling effect inside the caves, resulting from the drainage into the caves of cold water coming from melting snow or glaciers. Under these conditions a stable climate usually is not established (Onac, 2000).

The amount of water vapour in caves generally allows atmospheric conditions to be close to saturation and the relative humidity typically ranges between 95% and 100%. Exceptions have been observed in caves having unidirectional ventilation, in which thermocirculation can be very intense (Onac, 2000). The climatic signals of speleothems generated in caves with variable temperature and humidity will generally be more difficult to interpret.

Studies of stalactite drip water from a cave with a thick bedrock cover (>70 m) in Belgium (Genty and Deflandre, 1998) have shown that there is a good correlation between drip rate and water excess (precipitation–evapotranspiration). Studies from a more shallow cave (~15 m deep) in England, however, reveal a more complex relationship between drip rate and precipitation, with both an increase and a decrease in drip rate with increased precipitation (Baker et al., 1997). The drip water that flows through a stalactite during one year does not have to be the same water that has fallen as precipitation during that same year but can also consist of older water stored in pores and fissures of the limestone rock, or be a mixture of water from recent precipitation and older water (Genty and Deflandre, 1998). Drips from faster throughflow show greater variability in chemical composition and are more sensitive to rapid climatic changes (Lauritzen and Lundberg, 1999). In order to draw the correct interpretations of the geochemical signal of the speleothems studied, it is important to understand what hydrological situation that dominates in the cave.

Even though the general processes behind speleothem formation are well understood, monitoring studies from drip stone caves (e.g. Baker et al., 1997; Genty and Deflandre, 1998; Baker and Brunsdon, 2003; Tooth and Fairchild, 2003; Spötl et al., 2005; Baldini et al., 2006) have demonstrated the fact that the relationship between regional climate and speleothem formation is very site-specific. A better understanding of the processes behind speleothem formation and their site-specific characteristics is needed for more accurate paleoclimatic interpretations of fossil speleothems.

Here we present the results from a monitoring study of cave microclimate, drip rate and the geochemistry of stalactite drip water in Korallgrottan, northwest Sweden. The main objective of this study is to get a better understanding of seepage processes in karstic areas and thereby be able to make more reliable interpretations of environmental proxy indicators in speleothems from this site.

Description of the site

Korallgrottan (Fig. 1) is situated in northwestern Sweden in the Caledonian mountain range (64°53′16″ N, 14°9′30″ E, 540–600 m a.s.l). The cave is the largest known in Sweden, with approximately 5.5 km of passages. The cave is closed to the public, but guided tours with groups of 10–15 people, in a restricted area between the two entrances, are arranged regularly between June and October.

Korallgrottan has developed in a 200–300 m wide belt of Bjurälv limestone, which is of late Proterozoic–early Paleozoic in age (Zackrisson and Sjöstrand, 1990). The bedrock surface above this part of the cave is overlain by a 30–50 cm thick soil cover. The vegetation above the cave is rich in herbs and mosses with sparse forest with old spruce and birch.

Nearby meteorological stations have an average annual precipitation of 856 mm and an annual average temperature of 1.1 °C (1961–1990). January and July mean air temperatures are −10.2 °C and 12.3 °C, respectively (Fig. 2a) (Alexandersson and Eggertsson Karlström, 2001). From November to April most of the precipitation falls as snow and the snow cover generally remains until May. The isotopic composition of the precipitation in the area (Fig. 2b) shows large seasonal variations, with higher values during the summer months (Burgman et al., 1980; Calles and Westman, 1989). Today no streams flow through the major parts of Korallgrottan, hence all water reaching the studied parts of the cave originates from local precipitation, which most likely is stored some time in the limestone above the cave.

Methods

The monitoring study was carried out from 2000-06-27 to 2006-04-23; during this time 16 visits were made to Korallgrottan to collect water samples and data from a monitoring station. Korallgrottan was visited once or twice a year between 2000 and 2004 and from April 2005 to April 2006 the cave was visited every second month The monitoring study was concentrated to the Korkskruven area, about 200 m away from the nearest entrance (Fig. 1). In this part of the cave the bedrock cover is 12–13 m thick.

Logging

An automatic sampling station (Aanderaa Instruments, 2006) registering drip rate, relative humidity and temperature, was installed in Korallgrottan in June 2000. The data discussed in this paper extend from 10 December 2000 until 23 April October 2006. Because of technical problems there are some gaps in the series. The monitoring station included a data logger and sensors. Silicon tubes were attached to the tips of stalactites. These lead the drip water to pipettes situated above the sensors measuring the drip rate. As each drip fell into the sensor it was counted by a pulse counter. The number of drips was converted into volume, using a calibration performed in the laboratory (1 drip = 0.05613 ml). Laboratory experiments showed that drip size remained stable even when the drip rate was varied. Relative humidity was monitored for about two months but owing to technical problems, no continuous record is available. Data were stored every 2 h. Air temperatures were also measured at four other locations inside the cave, from December 2000 to September 2001, and from June 2002 to October 2002, using small temperature sensors, called Thermochron iButtons (Dallas Semiconductor, 2006). The sensors are small, button-like devices with built-in computer memories that

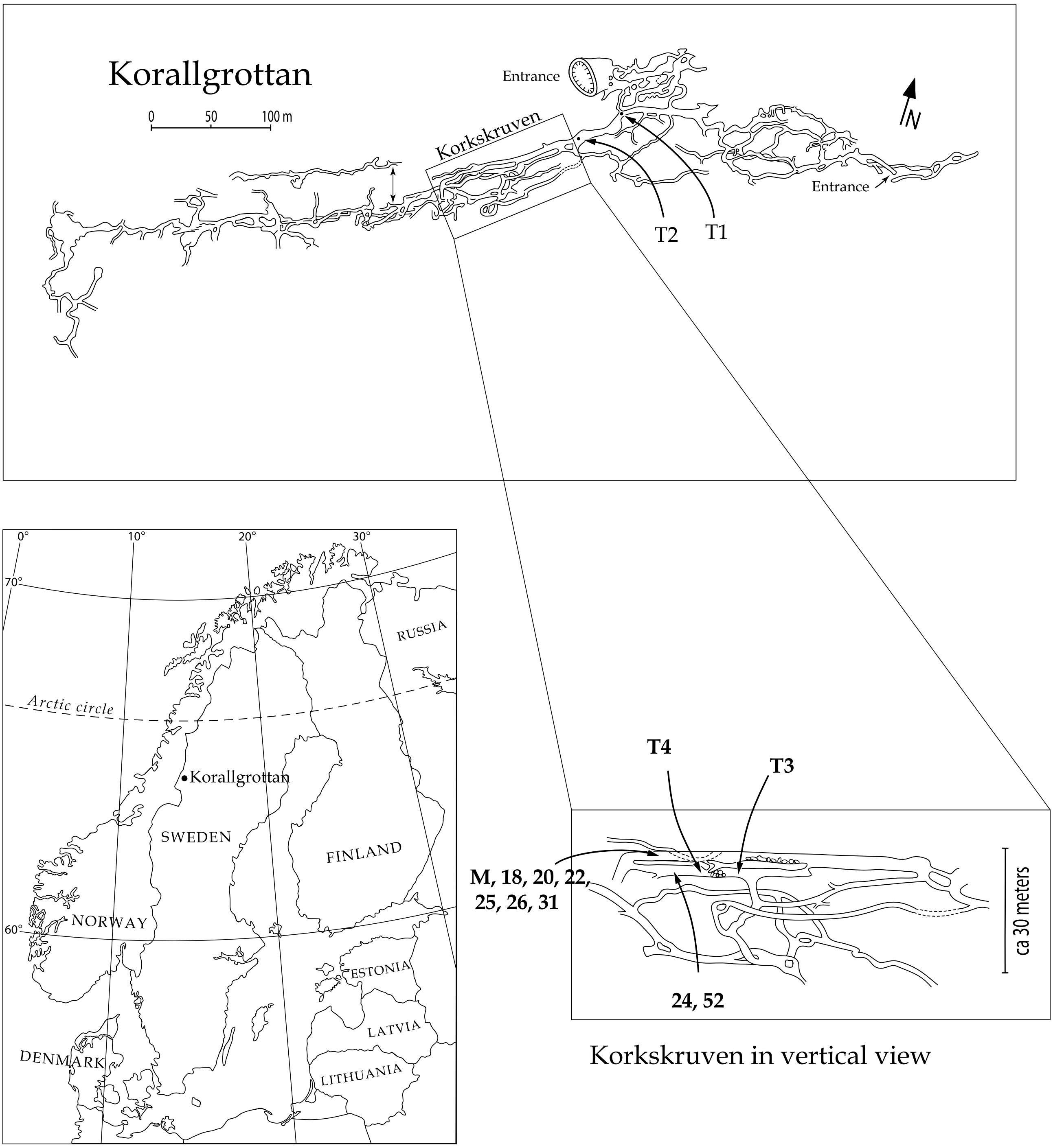

Figure 1 Map of Korallgrottan after Krafft and Örtwall (2002) showing the location of the monitoring station (M), the sites for drip water collection (18, 22, 24—26, 31, 52) and the temperature sensors (T1—T4), together with a map of Scandinavia indicating the location of Korallgrottan.

monitor time and temperature, with a resolution of 0.5 °C and an accuracy of ±1 °C. Temperature data were sampled once every 3 h.

Estimation of groundwater recharge

As a comparison to the measured stalactite drip rate we tested three different approaches for estimating the dynamics of groundwater recharge: observations of precipitation, of specific discharge, and as a simple model simulation. For the latter, the HBV model (Bergström, 1976, 1992) in the version described by Seibert (1997) was used to simulate daily groundwater recharge rates. In this conceptual runoff model recharge rates are computed using a snow routine, in which the snowmelt is computed by a degree-day method, and a soil routine, in which the groundwater

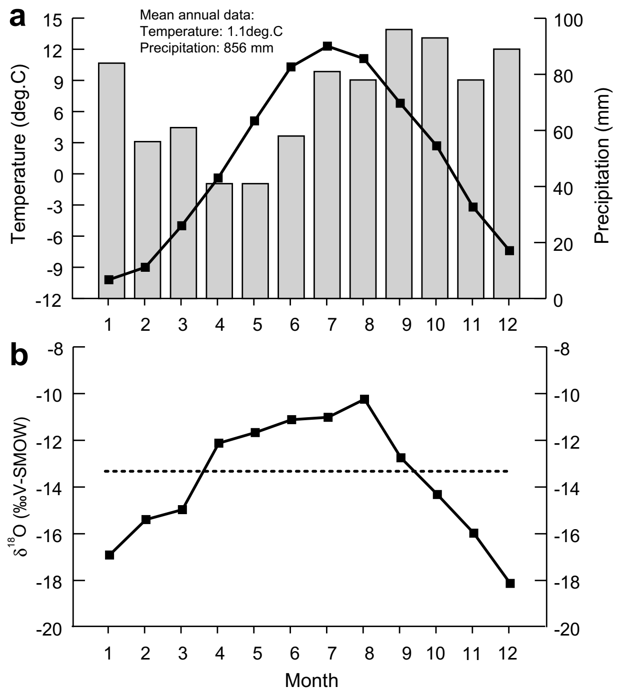

Figure 2 (a) Mean monthly temperature and precipitation data (line and bars, respectively) from Jormlien and Ankarvattnet (1961–1990; Alexandersson and Eggertsson Karlström, 2001). (b) Monthly mean values of $\delta^{18}O$ in precipitation from Bredkälen. The isotopic data were collected between January 1975 and December 1988 (Burgman et al., 1980; Calles and Westman, 1989). The weighted annual mean for the years 1975–1988 (dashed line) is −13.67‰.

recharge and actual evaporation are computed based on the simulated water storage in a soil box. Finally, runoff is simulated using three linear equations representing the outflow from the groundwater reservoir and a triangular weighting function representing channel routing. Daily precipitation and temperature as well as monthly estimates of potential evaporation are required as input. Both precipitation and temperature are assumed to vary with elevation (+10% and −0.6 °C per 100 m, respectively) and for both the snow and the soil routine, calculations are performed for each elevation zone (100 m) separately.

As a first step the model was calibrated to the observed discharge data. Recognizing the equifinality of different parameters sets, we used a Monte Carlo approach, in which the model was run 1 million times with randomly generated parameter sets with parameter values from uniform distributions within given ranges for each parameter (Seibert, 1997). Of these parameter sets the 100 sets providing the best fit to the observed data (evaluated using the sum of squared errors) were used as an ensemble of acceptable parameter sets. Groundwater recharge for a certain elevation zone was then estimated as the ensemble average of the internal flow rates from the soil routine computed for each time step.

Meteorological data were available from Swedish Meteorological and Hydrological Institute (SMHI) from stations at Jormlien (20 km south of Korallgrottan) for temperature and from Ankarvattnet for precipitation (4 km south of Korallgrottan). Discharge observations were available from SMHI for the Ankarvattnet catchment (430 km^2). Elevations in this catchment area ranged from 460 to 1415 m a.s.l.

To evaluate the different recharge estimates the following computations were performed:

1. Smoothing with a Gaussian filter (6, 9, 20 days) to be able to concentrate on the general pattern rather than on daily variations.
2. Allowance for shifts in time (0–30 days) of the drip rate record and comparison of the regression coefficients between the records.
3. Computation of autocorrelation coefficients of the records.

Geochemical analysis of drip water and precipitation

Stalactite drip water was collected during each visit for stable oxygen isotope and trace element analyses. Two stalactites, sites A and B, about 1 m apart, were monitored for daily drip-rate variations. Stalactite A was monitored from 2000-12-09 to 2002-11-12 and stalactite B from 2003-10-05 to 2004-04-23. From 2003-10-04 to 2006-04-23 water was also collected in between visits at sites 18, 20, 22, 24–26, 31, 52 (Fig. 1). The water samples were collected in sterilized polypropylene tubes (direct measurements) and in thin rubber bags attached to stalactites (in between visits). The pH and EC of the water samples collected were measured in situ in all solutions where sufficient fluid was available. Samples of local precipitation collected about once a month have also been analysed. The stable isotopic composition of the water was analysed on a Finnigan Mat Delta Plus mass spectrometer at the Department of Geology and Geochemistry, Stockholm University, a Finnigan Mat 250 mass spectrometer at the Geophysical Institute, University of Copenhagen, and a VG SIRA mass spectrometer at the NERC Isotope Geosciences Laboratory in Nottingham. Results are given in ‰ in relation to Standard Mean Ocean Water (SMOW) with a precision of ±0.05–0.1‰. The cation composition of solutions were analysed on Varian Vista Ax with a precision of 2–4% at the Department of Geology and Geochemistry, Stockholm University. The anion composition was analysed on a Dionex IC DX-300 with a precision of 2–4% at the Department of Geology and Geochemistry, Stockholm University. Saturation indices where calculated using the Phreeqc Interactive programme.

The stable oxygen and hydrogen isotopic values of the local precipitation were used to calculate the local meteoric waterline.

Results

Cave microclimate

The temperature at the monitoring station varied from 2.2 to 3.2 °C, with an average of 2.7 °C during the monitored period, which is very stable compared to the outside temperature that varied between 20 and −30 °C. The annual

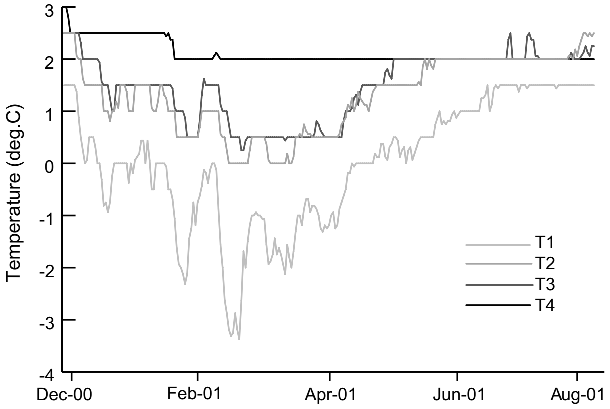

Figure 3 Temperature variations at different locations in Korallgrottan (T1—T4) between December 2000 and September 2001. T1 is closest to the entrance and T4 is closest to the monitoring station.

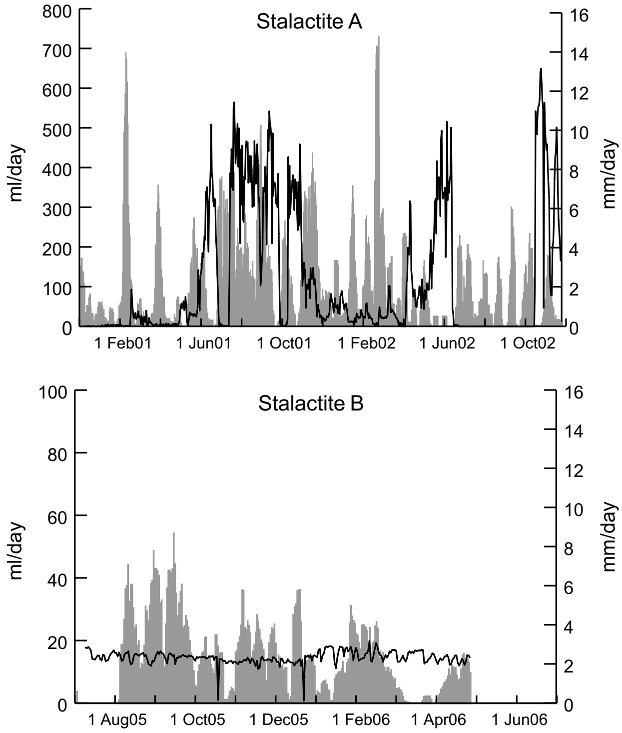

Figure 4 Drip rate from stalactites A and B (black lines) compared with precipitation (blue bars). Note the different scales and time periods for stalactites A and B

average temperature in Jormlien for the years 2001—2005 varied from 1.8 to 2.9 °C with an average of 2.4 °C. In the cave, the lowest temperatures occurred in summer (June—August) and the highest in winter (December—February).

Temperature measurements at other locations in Korallgrottan showed that the parts of the cave that are close to the entrance have stronger temperature variations than the more interior parts (Fig. 3). During winter the temperatures closer to the entrance are colder and much more variable than those further inside.

Because of technical problems with the humidity sensor, no long record of this parameter exists. However, when the sensor was working, during short periods in December 2000 and October 2003, it showed values above 99%.

Stalactite drip rates

The stalactite measured at site A is a relatively fast-dripping stalactite, with an average drip rate of 113 ml/day. The drip rate is highly variable (0—700 ml) and follows the seasonal hydrological variations (Fig. 4). During the winter months (December—March) when temperatures fall below 0 °C the dripping basically stops and when temperatures rise above 0 °C and the snow cover melts in May—June the stalactite drip rate shows an immediate increase. There is a great variation in the summer drip rates between different years. In the summer of 2001, the drip rate reached the highest values for that year, while in the summer of 2002, the dripping ceased entirely between July and September. During the autumn, high drip rates occurred in both years. The highest drip rate of the entire period monitored occurred in October 2002. The response time between the precipitation events and the increased drip discharge also varied substantially during the monitored period (Table 1). The response time was estimated by calculating the number of days it took for the drip rate to increase after an increase in the daily amount of precipitation (rainfall). An event of high precipitation on 2 July 2001 (36 mm) is reflected as a small increase in discharge on 10 July, eight days later. During a period in the summer of 2002 the drip rate of stalactite A stopped, and despite a strong precipitation event of 22.4 mm in early September, it did not return. Once the stalactite started dripping, a more moderate precipitation event of 13.4 mm on 29 September was reflected as an increase in drip rate on 14 October, i.e. 15 days later. During

Table 1 Lag time between a precipitation event and response in stalactite drip rate

Precipitation event	Amount (mm)	Response in cave	Response time (days)
14 January 2001	25	15 January 2001	1
2 July 2001	36	10 July 2001	8
10 August 2001	15.4	11 August 2001	1
2 October 2001	5.8	5 October 2001	3
17 February 2002	42.9	17 February 2002	0
3 September 2002	22.4	No	
29 September 2002	13.4	13 October 2002	14

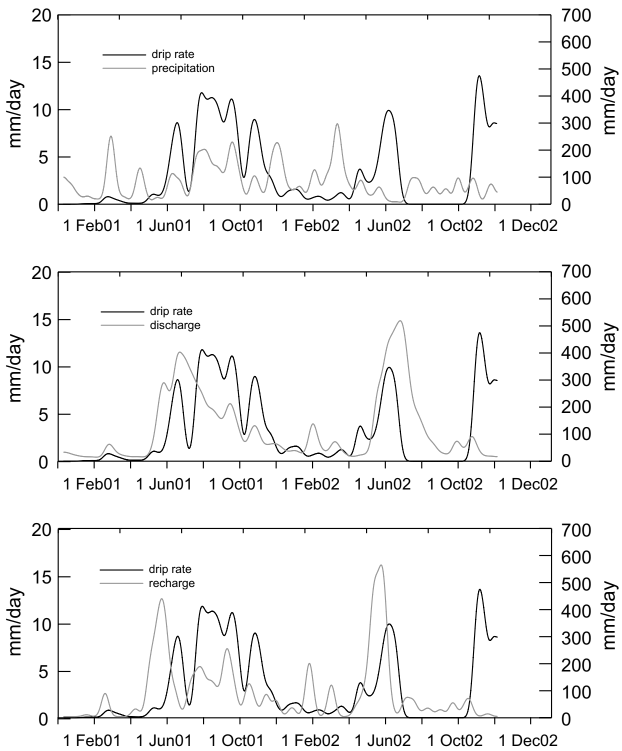

Figure 5 Stalactite drip rate (site A) compared with precipitation, measured specific discharge and simulated ground water recharge from between 2000-12-09 to 2002-11-12. The records are smoothed with a Gaussian filter (~20 days).

the autumn months, October–November 2001, a period of high drip rates was recorded. This period started a few days after a period of eight days of rainfall (see Fig. 5).

The stalactite at the other site, B, displays a different pattern, with an average drip rate of 15 ml/day during the monitored period (June 2005–April 2006) and with basically no seasonal signal.

Comparison between drip rate and estimated ground water recharge dynamics

As shown in Fig. 4, the drip rate at site A resembles the precipitation pattern quite well during summer and autumn, while the resemblance is less during winter and fall. The winter and fall variations are better represented by both the measured specific discharge and the simulated ground water recharge (Fig. 6), which also have low values during the winter (December–April) and high values during the snow melt between May and June. According to the correlation factors, the observed smoothed (~20 days) specific discharge is the record that best reflects the drip-rate variations ($R = 0.55$). However, with a time lag of about 20 days, there is a better correlation (0.61) with the smoothed (~20 days), simulated ground water recharge. The autocorrelation coefficients (Fig. 6) show that precipitation displays the shortest response, while the specific discharge displays the longest response. The drip rate is in between the specific discharge and simulated ground water recharge which in turn is somewhat slower than the precipitation.

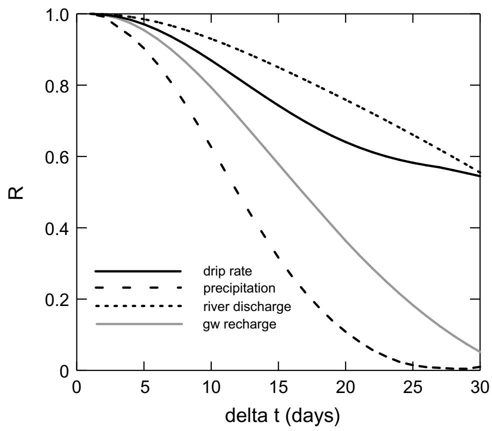

Figure 6 Autocorrelation coefficients (0–30 days) of stalactite drip rate, precipitation, measured specific discharge and simulated ground water recharge. The records are smoothed with a Gaussian filter (~20 days).

Drip water geochemistry

All oxygen and hydrogen isotope drip water samples lie close to the global meteoric water line (Craig, 1965), which in turn lies very close to the local meteoric water line (Fig. 7), calculated from nine points. The $\delta^{18}O$ composition of the precipitation outside the cave varies between −28.0‰ and −5.8‰ during the monitored period, while the composition of the stalactite drip water is fairly stable, varying between −12.9‰ and −10.6‰, with an annual average between −12.5 and −12.2 (October 2003–October 2004) (Table 2). Even if the composition of the drip water did not show the large-scale variations as did the outside precipitation, it did show smaller seasonal variations. In the bi-monthly data higher values occurred from October to April, with the lowest values occurring in July (Fig. 8, Table 2). Sites with high and variable drip rate displayed larger variation of $\delta^{18}O$ in the drip water.

Some seasonal variations in trace elemental composition can also be seen in the drip water collected bi-monthly (Fig. 8, Table 2). At all sites, the highest Ca^{2+} concentra-

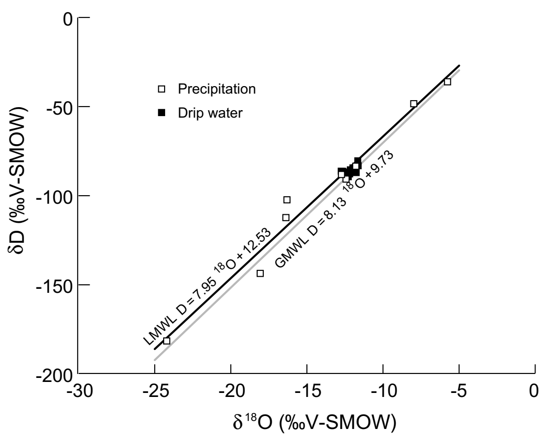

Figure 7 Stable hydrogen and oxygen isotopes of precipitation and drip water, plotted together with the local and global meteoric water lines.

Table 2 Geochemical variations in stalactite drip water in Korallgrottan, bi-monthly mean values 20,050,424–20,060,423

Drip site		*V* (ml/month)	Ca^{2+} (mg/l)	1000 × Mg/Ca	1000 × Sr/Ca	SO_4^{2-} (g/l)	$\delta^{18}O$	SI
18	Mean	37.0	42.0	64.0	0.89	3.5	−12.1	−0.82
	Min	25.0	37.0	50.0	0.86	2.9	−12.8	−1.55
	Max	60.0	48.8	81.8	0.92	4.2	−11.9	−0.42
	Std	14.0	4.9	14.4	0.03	0.5	0.38	0.50
20	Mean	16.2	38.5	86.0	1.28	6.02	−12.0	−0.61
	Max	11.0	30.3	64.5	1.10	5.06	−12.4	−0.87
	Min	23.0	47.2	105.8	1.37	6.71	−11.8	−0.48
	Std	5.37	7.95	20.6	0.10	0.76	0.20	0.18
22	Mean	26.0	43.3	66.7	0.871	4.01	−12.0	−0.62
	Max	17.5	39.2	49.9	0.823	2.55	−12.8	−1.47
	Min	50.0	49.7	97.2	0.909	5.23	−11.6	−0.13
	Std	13.5	4.47	19.3	0.037	1.24	0.54	0.53
24	Mean	29.3	38.9	77.7	1.30	4.06	−11.9	−0.82
	Max	17.0	33.3	65.5	1.26	3.33	−12.2	−1.24
	Min	40.0	44.1	109.2	1.34	4.82	−11.3	−0.26
	Std	10.2	4.54	17.5	0.032	0.56	0.31	0.37
25	Mean	18.1	45.6	72.4	1.23	6.72	−12.1	−0.35
	Max	13.5	40.0	62.7	1.15	5.59	−12.5	−0.70
	Min	21.0	50.5	94.8	1.30	9.13	−11.8	0.20
	Std	2.78	4.56	12.4	0.058	1.32	0.26	0.35
26	Mean	13.9	40.0	84.9	1.24	5.19	−12.1	−0.37
	Max	11.0	33.2	62.9	1.19	4.28	−12.8	−0.60
	Min	18.0	46.5	127.9	1.29	6.56	−11.8	−0.08
	Std	3.09	5.91	24.3	0.048	1.05	0.40	0.22
31	Mean	76.6	42.5	64.3	1.11	4.00	−11.9	−0.72
	Max	60.0	35.3	58.7	1.07	3.41	−12.5	−1.65
	Min	95.0	52.1	75.7	1.19	4.48	−10.9	−0.30
	Std	13.8	6.89	7.26	0.047	0.43	0.62	0.53
52	Mean	54.2	35.5	134.2	1.61	3.25	−11.9	−0.61
	Max	3.5	28.6	88.9	1.44	2.91	−12.6	−0.75
	Min	100	42.2	237.1	1.94	3.86	−10.8	−0.28
	Std	41.6	4.8	59.1	0.19	0.53	0.64	0.22

tions were reached in September and the lowest in January–March. Trends of increasing Ca^{2+} accompanied by decreasing SO_4^{2-} are seen at all sites. The SO_4^{2-} concentrations show the highest values in January–April and lowest in September. The drip rate correlates well ($R = 0.9$) with SO_4^{2-} at site 18, but shows negative correlation with SO_4^{2-} at site 20. Trends of decreasing Ca^{2+} accompanied by increasing Mg/Ca and Sr/Ca ratios are seen at all sites but is especially evident at site 52, which also has higher Mg/Ca and Sr/Ca ratios than the other sites. The highest Mg/Ca ratios are reached between December anf February (22, 24, 25, 26, 31) and between February and April (18, 20, 52). The stalactites (20, 25, 26) with the lowest and most stable drip rates have the highest SO_4^{2-} concentrations throughout the monitoring period.

Most of the drip water samples collected bi-monthly reached their highest saturation indices between July and November, but only one of the samples had reached saturation (stalactite 25, June–August 2005). The drip water at sites 25 and 26 were close to saturation during the entire period. Sites 24 and 52 differed from the general pattern, reaching their highest indexes between April and June and decreasing throughout the rest of the period.

Discussion

Although the period monitored in this study is short in comparison with the much longer timescales of interest for paleoclimatic reconstruction, some essential features are clearly observable in the data collected, both concerning the behaviour of drip water rate, cave temperature and the geochemistry of drip water.

Temperature

The temperature measurements indicated that the temperature at the monitoring site (2.7 ± 0.5 °C) is very close to the mean annual surface temperature in the area (2.4 °C, 2001–2005). The stability of the temperature throughout the year and the fact that the temperatures are slightly

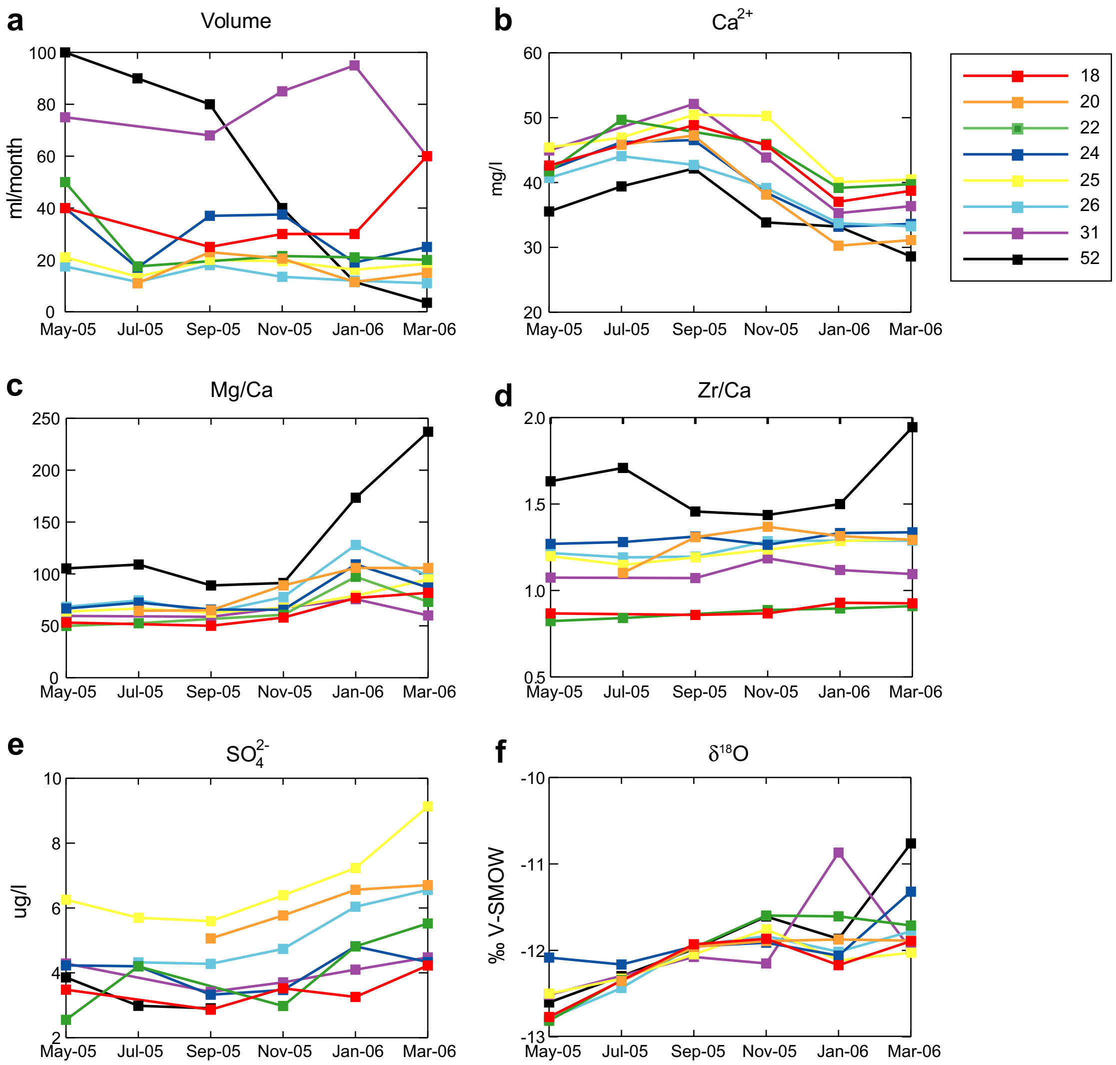

Figure 8 Temporal (bi-monthly averages) in (a) volume, (b) Ca^{2+}, (c) Mg/Ca, (d) Sr/Ca ratios (e) SO_4^{2-} and (f) $\delta^{18}O$ of stalactite drip water in Korallgrottan.

lower in summer than in winter implies that the most dominant temperature-regulating mechanism is heat transfer (conduction) through the overlying soil and bedrock, with a time lag of around six months. Temperatures measured at other sites in the cave slightly closer to the entrance are more variable and are clearly affected by the surface-temperature variations. These results demonstrate the importance of temperature monitoring in caves before choosing a site for paleoclimatic studies. The variations in temperature at different locations in Korallgrottan could certainly not have been detected if the cave had been visited and data had been collected on one single occasion.

Drip water hydrology

The drip rate of stalactite A mimics the precipitation during summer and autumn. The correlation breaks down during the winter, when the ground is frozen and covered by snow and no percolation of water takes place. The correlation also breaks down in May—June when the snowmelt gives rise to high drip rates. However, the measured specific discharge and the simulated ground water recharge have similarities to the drip rate throughout the year. The difference between the two estimates is because the measured specific discharge is a delayed and smoothed estimate of ground water recharge, while the simulated data represent the actual daily ground water recharge. The response time for the drip rate to an increase or decrease in water input is somewhat faster than the measured specific discharge, but slower than the simulated daily ground water recharge.

The observed difference in the response time between the precipitation and simulated ground water recharge, as compared to the drip rate in the cave, indicates some water storage in the soil and overlying bedrock. The response time is probably determined by (i) the moisture content of the soil and bedrock, (ii) the amount and intensity of the rainfall, (iii) the evapotranspiration and (iv) the circumstance of whether the ground is frozen or not. The stalactite at site A seems to be in hydraulic contact with the meteorological signal and the drip-rate variations of this stalagmite seems to reflect weekly to monthly groundwater recharge. As far as the slower dripping stalactite at site B is concerned, there is evidence of significant water storage in the aquifer, to the extent that seasonal patterns of rainfall and snowmelt are not picked up.

The seasonal pattern of the drip rate in Korallgrottan can be quite different from seasonal patterns in e.g. England (Baker et al., 1997; Baker and Brunsdon, 2003) and Belgium (Genty and Deflandre, 1998) since it reflects the influence of a snow regime. Stalactite drip rates in Korallgrottan are very low and vary from 0 to 0.4 ml/min, which can be compared to reported drip rates from stalactites in Belgium; 0–7 ml/min (Genty and Deflandre, 1998), England; 30–120 ml/min (Baker et al., 1997) and Italy; 0.7–34.6 ml/min (Borsato, 1997). This can be explained by differences in the fissure network and the size of the discharge area for the precipitation, but in England and Belgium it can also be explained by the higher annual precipitation and by the fact that the highest precipitation amounts fall in the winter when the evapotranspiration is small.

Geochemistry of drip water

The isotopic signal of the drip water in Korallgrottan lies along the local meteoric waterline, demonstrating that the signal is of meteoric origin and that no fractionation through evaporation has occurred. The mean oxygen isotope value of drip water in Korallgrottan between October 2003 and October 2005 was $-12.4‰$. This value is higher than the mean annual $\delta^{18}O$ value of the precipitation in Bredkälen, 200 km south of Korallgrottan, which is $-13.7‰$. However, measurements of $\delta^{18}O$ from a nearby groundwater outlet and a waterfall had values between $-11.1‰$ and $-12.2‰$; these values can be used as estimates of $\delta^{18}O$ in meteoric waters at this site today. High $\delta^{18}O$ values in the drip water that occurred between October and December which could represent the last summer's precipitation. The fact that the variations are small compared to the outside precipitation indicates that the drip water from the stalactites is a mixture of both younger (recent precipitation) and older (fissure) water. The larger variability at the fast-dripping sites indicates that they have a higher proportion of younger water than at the slow-dripping sites. However, as this is a study consisting of only a single year, nothing can be said about the $\delta^{18}O$ variation or the lag time from year to year. For example, the winter isotopic signal could arrive earlier if there is a warm and wet winter and the summer signal could arrive later if there is a dry summer.

Most drip sites have relatively stable drip rates and geochemical composition. Some seasonal variations do occur reflecting the fact that the water is a mixture of older and younger water. The geochemical pattern at site 52 is more variable than at the other sites. Site 52 seems to be more closely associated with seasonal fluctuations in ground water discharge, with higher drip rates occurring late spring (snow melt) to autumn and slower drip rates during winter. The lower drip rate in the winter is accompanied with higher Mg/Ca, Sr/Ca and SO_4^{2-} values. An increase in these trace elements are generally an indication of longer residence times and could therefore be associated with dryer conditions. Calcite indices provide insight into the seasonality of calcite deposition and also have implications for which paleoenvironmental signal becomes imprinted in the speleothem. Although variability existed at the different sites, the bi-monthly mean values suggest that the saturation indices increased during summer and autumn and decreased during winter. This is probably due to the higher pCO_2 in the soil during the summer months. Elevated deposition rates during summer may bias the geochemical signature of stalagmites fed by seasonally responsive drips towards summer values. Faster-dripping sites tend to have lower saturation indices, probably owing to shorter residence times. The reason for the fact that not more drip water samples were saturated may be because the rubber bags that were attached to the stalactites can limit the degassing of CO_2.

Conclusions

This cave monitoring study reported from a snow regime area in northern high latitudes provides a basis for a better understanding of how to interpret proxy climatic information in cave speleothems from this region.

The cave temperature at the monitoring site is very stable and nearly the same as the outside annual mean air temperature. Temperatures measured about 30 m nearer the entrance, but still 170 m away from it (as compared to the major study site) show much greater seasonal variability, demonstrating the importance of choosing an appropriate site for speleothem analysis.

The drip rate from fast-dripping stalactites in Korallgrottan can vary substantially following the seasons and reflects the situation in the snow regime. During winter months, the dripping in the cave basically stops as a result of the fact that near-surface air temperatures are mostly below zero and because snow covers the ground. High discharge occurs in spring due to the melting of the snow cover. In the summer there can be a range between very high drip rates, to a total cessation of the drip rate, due to very warm and evaporative conditions. The drip rate from fast-dripping stalactites (<100 ml/day) can be used to estimate weekly to monthly ground water recharge. Slow-dripping stalactites have a steadier drip rate with hardly any seasonal variations.

The $\delta^{18}O$ composition of drip water varies throughout the year (±1.2‰), but is fairly stable compared to the outside precipitation (±11.1‰). The trace elemental composition of drip water is more stable in the slow-dripping stalactites, reflecting mean annual values or longer. Generally the drip water reaches the highest saturation level during the summer and autumn, when biological activity is most intense and the partial pressure of carbon dioxide, which controls limestone dissolution, is high. There is also a risk that supersaturation will not be reached during the snow-melting period in spring and that calcite precipitation at this time of the year may not occur.

This study shows that, even though calcite precipitation not occurs continuously throughout a year, at slow-dripping sites, an annual or somewhat longer $\delta^{18}O$ signal is imprinted in the stalagmite calcite, while the $\delta^{18}O$ signal from faster-dripping stalactites will be biased towards summer conditions.

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