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Late-glacial and Holocene climate reconstruction as inferred from a stalagmite - Grotte du Père Noël, Han-sur-Lesse, Belgium.

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ABSTRACT. The 64.5 cm long Père Noël stalagmite PN-95-5 was deposited between 12.9 ka and 1.8 ka (U-series dated) with an uncertainty on the ages of the order of ca. 100 years. Besides changes in the macroscopic aspect of the stalagmite along its longitudinal section, changes in its isotopic ($\delta^{18}O$ and $\delta^{13}C$) and chemical (Sr/Ca, Mg/Ca) composition are observed. These changes, combined with changes in stalagmite diameter are interpreted in terms of changes in climate in the Han-sur-Lesse region. This multi-proxy approach based on previous studies of the chemical and isotopic functioning of the cave suggests a generally wet early Holocene, important and rapid dry-wet changes around 8.5 ka, a wetter and warmer period between 7.9 ka and 6.6 ka and a dry and/or colder climate after 6.6 ka. This preliminary interpretation from the Père Noël speleothem should be further tested against other speleothems and other archives to construct a regional climate model for the Holocene.

KEYWORDS: Speleothem, stable isotopes, Mg, Sr, growth rate, U-series dating

1. Introduction

Secondary chemical cave deposits (e.g. calcite speleothems) can provide high-resolution proxy tools for paleoclimate reconstruction (Genty et al., 2003; Verheyden, 2001; Verheyden et al., 2006; 2008b; Wang et al., 2001; 2008; Zhornyak et al., 2011; Drysdale et al., 2009).

Several studies on the paleoclimatic interpretation of speleothem proxy data have been performed during the last decades (Genty & Quinif, 1996; Fairchild &Treble, 2009; McDermott et al., 2011; Tremaine & Froelich, 2013).

Speleothems are chemically and isotopically rather stable. Diagenetic processes such as partial dissolution exist but are often clearly visible in the speleothem (Frisia, 1996). Important deposition hiatuses are characterized by a dust or clay layer and if some uncertainty remains, U-series dating can be performed at each side of the presumed hiatus.

Theoretically, the oxygen isotopic composition of a speleothem depends on the $\delta^{18}O$ of the precipitating seepage water and the oxygen fractionation factor during calcite precipitation. This oxygen fractionation factor depends on ambient temperature. It is ca. 1.0285 at 25ºC and increases by ca. 0.22‰ per 1ºC temperature decrease between 10 and 25ºC (Kim & O'Neil, 1997). In shallow caves without important cave climate anomalies, the cave air temperature is close to the mean annual air-temperature above the cave. The cave temperature and therefore the changes in fractionation due to cave-temperature changes have a direct link with regional climatic parameters (here the air temperature). Several caves display a rather constant $\delta^{18}O$ of the cave seepage water which approximately equals the annual weighted mean of the $\delta^{18}O$ of the rain water above the cave (Mattey et al., 2008; Verheyden et al., 2008a). The $\delta^{18}O$ of the rainwater in temperate regions is partly temperature dependent. Researchers have observed a correlation between the average isotopic composition of precipitation and mean annual surface-air temperature at given locations (Dansgaard, 1964). The study of Rozanski et al. (1993) based on the data from the International Atomic Energy Agency (IAEA/GNIP) network reveals an actual average $d\delta^{18}O_p/dT$ ratio of +0.58‰/ºC for non-polar sites. The combination of both temperature-dependent effects, i.e. of the fractionation factor and of the precipitation $\delta^{18}O$ indicates a theoretical temperature dependence of the $\delta^{18}O$ of speleothem calcite ($d\delta^{18}O_{stcalc}/dT$) of +0.36‰/°C (=0.58‰-0.22‰) (Verheyden, 2001). However, in practice it is very difficult to discriminate between the temperature and other factors influencing the $\delta^{18}O$ of precipitation (amount effect, changes in moisture source and storm tracks) and the change in precipitation effect is, in most cases, predominant. In practice, $\delta^{18}O$ of speleothems is therefore interpreted mainly as changes in $\delta^{18}O$ of precipitation. In the monsoon regions a good correlation is observed between $\delta^{18}O$ of the speleothem and monsoon intensity. For Europe, a study by McDermott et al. (2011) shows a decrease in $\delta^{18}O_{speleothem}$ values as a function of the distance from the Atlantic ocean and as a result of progressive rain-out. This general circulation pattern doesn't seem to have changed much during the Holocene on a long-term (>50 years) scale. Lower $\delta^{18}O$ speleothem values during the early Holocene are related to a steeper gradient of $\delta^{18}O$ decreasing from west to east, which may be linked to colder climatic conditions (McDermott et al., 2011).

Since the carbon fractionation is only slightly temperature-dependent, speleothem calcite will mainly reflect the $\delta^{13}C$ of the soil CO_2 controlled by vegetation (Geyh & Franke, 1970; Genty &Massault, 1999; see Verheyden, 2001). Speleothem $\delta^{13}C$ will, for example, reflect the difference in $\delta^{13}C$ signature between C3 or C4 type vegetation, i.e. vegetation with different photosynthesis paths (Cerling., 1984). In our temperate regions where only a C3 type vegetation is, and most probably was, present throughout the Holocene (Ehleringer et al., 1997), the speleothem $\delta^{13}C$ depends mainly on the combined input of soil-derived carbon (from soil CO_2), host limestone carbon and degassing processes during deposition of the calcite. Geyh & Franke (1970) and Genty & Massault (1997) estimated a ca 85% contribution of soil CO_2 in speleothem carbon and a ca 15% contamination with limestone carbon. These contributions can change, mainly due to changes in soil activity and soil CO_2 production. An active soil, i.e; during warm and humid conditions, will therefore be reflected in the speleothem as a lower $\delta^{13}C$ signature (Genty et al., 2003). Mattey & co-authors (2008; 2010) linked seasonal variations in the $\delta^{13}C$ of speleothem calcite to large variatons in pCO_2 driven by cave ventilation and drip rate with lower speleothem $\delta^{13}C$ during wetter periods.

This paper presents the petrographic, isotopic and chemical changes in a stalagmite from the Père Noël cave at Han-sur-Lesse and interprets them in terms of climatic and environmental evolution in the region.

2. Location and sample

The Père Noël cave (50.0°N, 5.2°E, 230 masl) is situated about 200 km inland in a temperate maritime climate. The Père Noël cave (Fig. 1) opens in the Fromelenne Formation (Coen & Coen-Aubert, 1971; Delvaux de Fenffe, 1985), a compact Givetian limestone of the so-called Calestienne, the Devonian limestone-belt crossing Belgium from West to East folded during the Variscan Orogeny

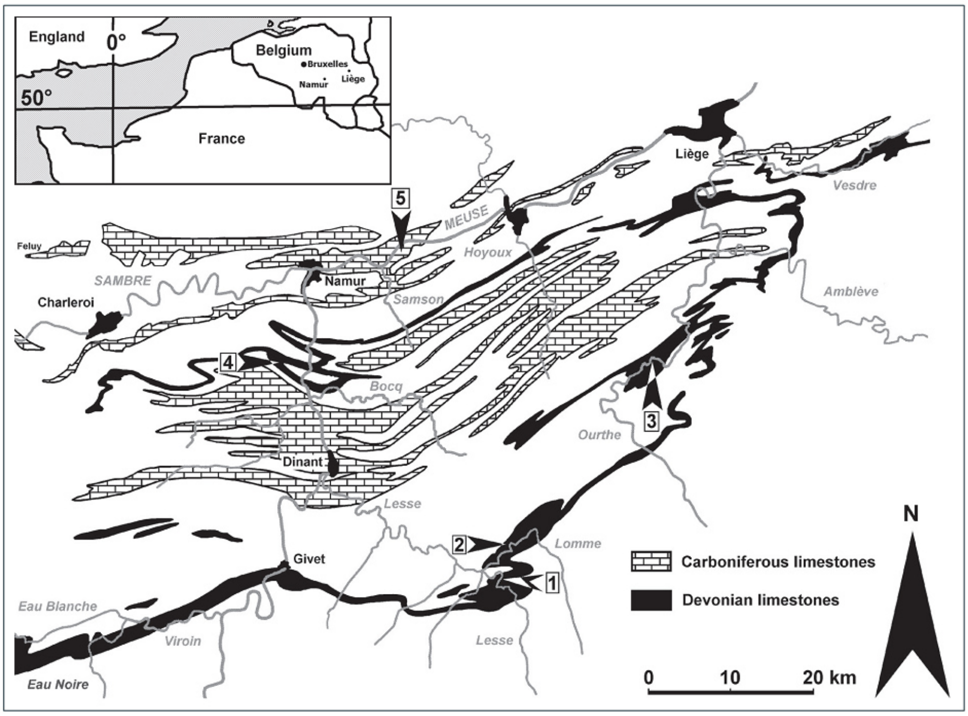

Figure 1. Localization of the Père Noël Cave at Han-sur-Lesse (1) The cave opens in Givetian limestone in the so-called Calestienne, the Givetian (Devonian) limestone-belt crossing Belgium from West to East and passing through Givet. The Calestienne forms the southern margin of the superficial carbonate deposits in Belgium.

(Delvaux de Fenffe, 1985; Willems et al., 2011; Marion et al., 2011; Bonniver, 2011: 21-51) (Fig. 1). A minor dolomitisation of some limestone beds is observed. Overlying host rock reaches a thickness of ca. 70 m (Vandersleyen, 1967) with a southwards dip of approximately 45º. The cave was opened for human access by digging out the entrance in 1964 (Deflandre, 1986). The cave is part of the cave system of Han-sur-Lesse which results of the meander cutting of the Lesse river through the Massif de Boine (Quinif & Bastin, 1986, Bonniver, 2011: 52-80). Nowadays, a C3 type vegetation consisting of mixed-leaf forest with oaks, beech and hazel trees covers the bedrock above the cave. The mean annual precipitation at Han-sur-Lesse is ~750mm/a and the mean annual air temperature is ~10°C (unpublished measurements at Han-sur-Lesse). The area above the cave is the property of the touristic caves and is protected from direct human influence.

The 'Salle du Bivouac' from which was retrieved the stalagmite is the main room in the cave (Fig. 2). The fluvial pebbles in the room are a witness of the former presence of a paleo-Lesse which has not flowed through the cave since more than ~150,000 years ago (Quinif & Bastin, 1986). The water entering the cave today consists of local precipitation, seeping directly through the overlying limestone, of an access to the aquifer, and of a small water flow, probably partly coming from the nowadays Lesse river. (Bonniver, 2011: p 72). The small entrance, which is situated near the top of the hill, was closed with a door after its discovery to prevent vandalism. After a steep descent of ~25 meters, a small passage leads to a first small chamber. A second steep descent of ~20 meters leads to the 'Salle du Bivouac'. It is the biggest chamber of the cave and is ~50 meters wide, ~200 meters long and up to ~30 meters high. Most speleothems in the Père Noël Cave are candle-shaped calcite stalagmites. Huge columns, sometimes broken, rounded stalagmites and draperies are also present. The PN-stm-95-5 stalagmite was sampled during May 1995 in the upper right part at the end of the room (Fig. 2 and 3). It grew on a limestone block and was cut of the block with a hammer and chisel and kept at Mons University in Belgium. The base of the stalagmite represents therefore first stalagmite deposition on the block. Based on the macroscopic aspect of the stalagmite, 9 sections (Fig. 4) are chosen to clarify the reference to the stalagmite parts during the discussion.

3. Analytical Methods

The PN-stm-95-5 stalagmite was dated by TIMS U-series dating at the Department of Earth sciences at Open University, UK. The results were published in Verheyden et al. (2000). An additional

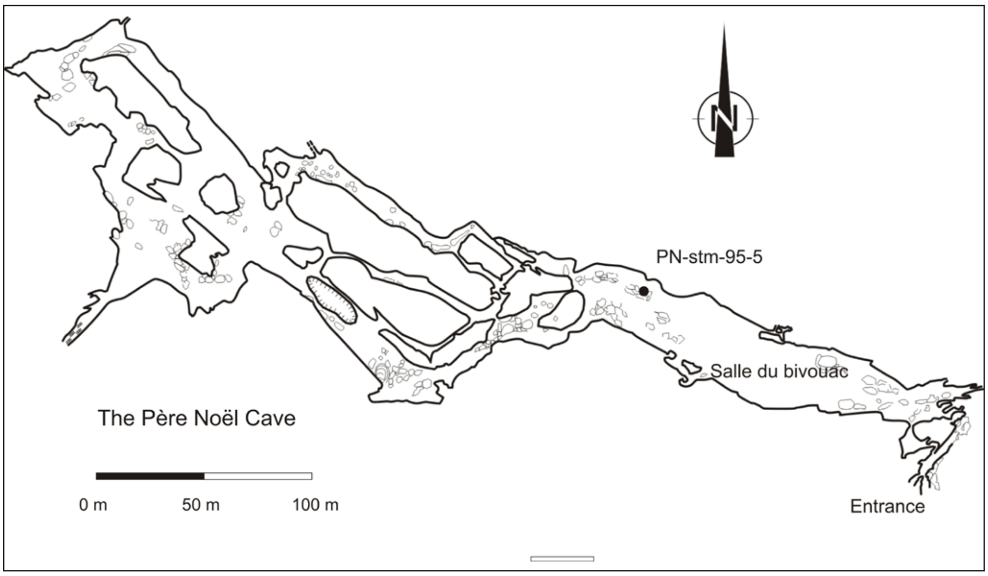

Figure 2. Plan of the Père Noël cave and location of the PN-stm-95-5 stalagmite.

mm from top	U(ppm)	$^{234}U/^{238}$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}Th$	Age Years before 2000AD	error +/-2s	laboratory
5	0.2339	2.3657	30	0.01847	2024	11	Open Univ -UK
45	0.2971	2.3914	59	0.0354	3907	16	Open Univ -UK
115	0.1985	2.4656	980	0.05846	6515	37	Open Univ -UK
190	0.1680	2.4973	1216	0.06134	6843	37	Open Univ -UK
250	2.7809	2.4961	2345	0.06414	7164	22	Open Univ -UK
365	0.2275	2.5064	1902	0.07013	7853	45	Open Univ -UK
395	0.2418	2.5142	1401	NA	8232	39	U-Minnesota, USA
435	0.3037	2.5779	724	0.08163	9185	21	Open Univ -UK
520	0.2528	2.6538	299	0.09121	10303	55	Open Univ -UK
635	0.1790	2.729	161	0.11122	12671	71	Open Univ -UK

Table 1. U-series dating of the Père Noël PN-stm-95-5 speleothem.

dating was done by MC-ICPMS (Thermo-Finnigan Neptune) at the Earth sciences department of the University of Minnesota. The chemical procedures used to separate the uranium and thorium for ^{230}Th dating are similar to those described in Edwards et al. (1987). Dating results are summarised in Table 1, with ages given in years before 2000 AD.

Subsamples were obtained from the stalagmite by micro drilling every 5 mm along the longitudinal axis. The $\delta^{18}O$ and $\delta^{13}C$, signatures were determined by IRMS at the Vrije Universiteit Brussel following classical procedures as described in Verheyden et al., 2000. Results are given in ‰ VPDB and analytical precisions were ≤0.1‰ (2s) for $\delta^{18}O$ and ≤0.06‰ (2s) for $\delta^{13}C$. Outliers were confirmed or eliminated after double measurement. Mg/Ca and Sr/Ca signatures were determined by ICP-AES at the University of Birmingham following the procedure described in Verheyden et al., (2000). The chemical results were previously published in Verheyden et al. (2000).

4. Results

The Père Noël stalagmite consists of low-Magnesium calcite and is 64.5 cm long. The internal longitudinal section of the stalagmite presents a succession of brown parts and milky white parts along its longitudinal axis (Fig. 3). Periods of dense calcite, observed as dark grey or dark-brown calcite, occur. No clear hiatus is observed in the stalagmite. The longitudinal section also reveals changes in the stalagmite diameter along the longitudinal axis of the stalagmite from clear 'candle-shaped' forms to thicker general 'tall' stalagmite forms.

The stalagmite was deposited between ca. 12.9 ka and 1.8 ka (extrapolated ages, Verheyden et al., 2000). Highest growth rates are observed between 7.8 ka and 6.6 ka (23mm/century) while the lowest growth rates are observed after 6.6 ka (2mm/century), leading to the end of calcite deposition at 1.8 ka. Figure 4 presents the four geochemical and isotopic proxy records as well as the growth curve of the stalagmite as compared to its general macroscopic aspect in each stalagmite section.

5. Discussion: Palaeoclimatic and environmental interpretation of the Père Noël stalagmite: a multi-proxy approach.

As previously investigated in the Père Noël cave and presented in Verheyden et al. (2008a), the isotopic composition of the calcite in the Père Noël cave is largely controlled by the water availability (drip rate) in the cave. Changes in isotopic equilibrium conditions, driven by the changes in cave humidity and linked to changes in recharge, ie. precipitation minus evapo-transpiration, overprint the theoretical temperature and/or precipitation control of the $\delta^{18}O$. Degassing of CO_2, increasing $\delta^{13}C$ values of the calcite, becomes increasingly important at lower drip rates and overprint the vegetation signal. Changes in Mg/Ca and Sr/Ca in the calcite are interpreted as due to changes in water residence time linked to changes in water availability, thus recharge (Verheyden et al., 2008a). This explains the covariation over much of the Holocene period of the four geochemical parameters in the speleothem, since all four increase with lower water availability.

Combined changes in the different speleothem proxy-data are discussed and interpreted in terms of changes in environment and climate. This multi-proxy approach combined with an interpretation of the proxy-data in terms of climate based on the regular monitoring of the cave (Verheyden et al., 2008a) enables us to give a preliminary climatic evolution of the Han-sur-Lesse

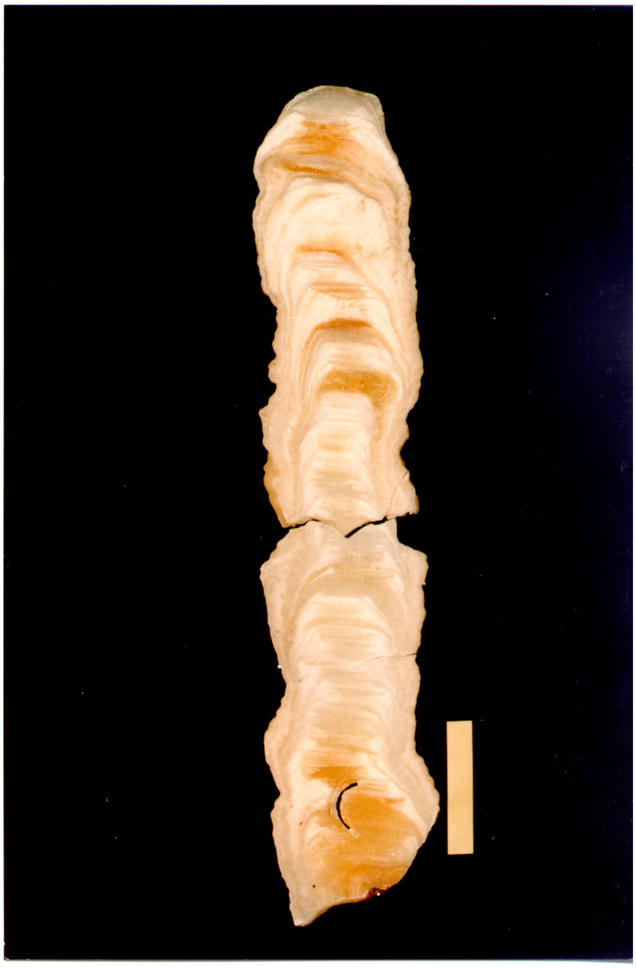

Figure 3. The Père Noël stalagmite is 64 centimetres long. Its longitudinal section presents a succession of dark brown compact and milky-white porous sections. The yellow vertical scale right-under the stalagmite is 10 centimetres long.

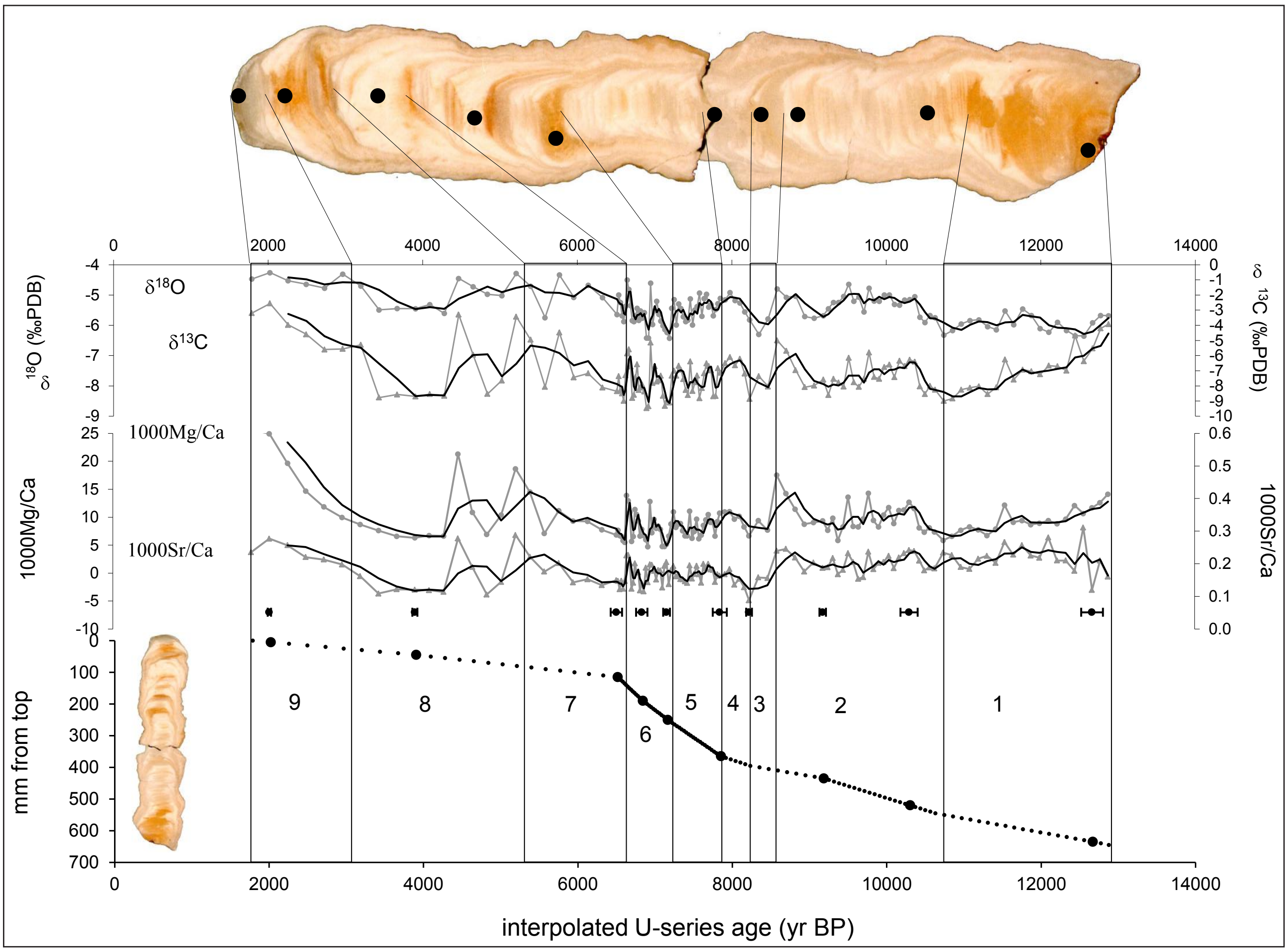

Figure 4. $\delta^{18}O$, $\delta^{13}C$, Mg/Ca, Sr/Ca and growth-rate time-series of the Père Noël stalagmite. Black dots under in the graph gives the U-series ages and the 2δ uncertainties. The numbers 1 to 9 refer to the different sections, based on the macroscopic aspect of the longitudinal section of the stalagmite and to which the text refers.

region. These findings must however be further compared to information from other speleothems and other archives in order to construct a robust regional climate record.

5.1. 12.9 ka - 10.7 ka (section 1 in Fig. 4)

The Père Noël stalagmite starts its growth at 12.9 ka on the underlying limestone block, indicating climatic and environmental conditions, favourable for stalagmite growth. The stalagmite diameter is rather large compared to its mean diameter. Dreybrodt (1988, 1999) demonstrated that for constant growth rates of a stalagmite, the stalagmite diameter shows a positive relationship with drip rate and thus water availability (see also chapter 7.2. in Fairchild and Baker (2012), for an exhaustive explanation on the topic). The rather large Père Noël stalagmite at ~12.0 ka suggests that there is enough water to flow down on the side of the stalagmite and to precipitate calcite. However, the rather low growth rate of 4.5 mm/century may be due to a low carbonate content of the water, limiting the precipitation of calcite. The decreasing $\delta^{13}C$ values indicate a progressively increasing soil activity. The still rather low $\delta^{18}O$ suggest relatively wet conditions in agreement with the important stalagmite diameter. The start of speleothem growth at the start of the cold Younger Dryas (YD) (12.9-11.7 ka) seems contradictory. The chronological and geochemical pattern of the Père Noël stalagmite suggests a humid period rather than a particularly cold period in north-western Europe. This is in agreement with warm to mild summer temperatures during a first part of the YD and the presence of a local vegetation cover during the YD as found in a north-eastern German varved paleolake (Neugebauer et al., 2012). Closer to the Père Noël cave, the Holzmaar lake (Eifel) lead to a chronology for the YD situated between 12680 ka and 11590ka (Litt et al., 2001). Speleothem growth could therefore have started before the onset of the YD followed by a stop in deposition or by a decrease in growth rate. Additional dating would increase the resolution of the growth-rate curve and give more data to base the paleoclimatic reconstruction on.

5.2. 10.7 ka - 8.5 ka.(section 2 in Fig. 4)

The four geochemical proxies covariate well in this second section, supporting, as explained in Verheyden et al. (2008a), their interpretation in terms of dry-wet changes with higher Mg/Ca and Sr/Ca and higher $\delta^{18}O$ and $\delta^{13}C$ values linked to drier conditions. The relatively high growth rate of 7.6mm/century up to 9.2ka and 4.6mm/century after 9.2ka, and relatively high stalagmite diameter suggest overall conditions, favourable for stalagmite growth, i.e. wet and relatively warm with the development of an active soil. According to the geochemical proxies, a series of shorter-term changes in precipitation occurred with dryer conditions from 10.7 ka to 10.3 ka, followed by a slow change towards wetter conditions until 8.9 ka. At 8.9 ka, a dramatic drying in the cave during the next 400 years, between 8.9 ka and 8.5 ka, is suggested by a rapid and important increase in the four geochemical proxy-data. The drying is in agreement with a decrease in the growth rate as well as in the stalagmite diameter. A slightly denser calcite is deposited at 10.4 ka, 10.0 ka, 9.7 ka and 9.2 ka (linearly interpolated between dating points). A higher resolution of the geochemical analyses is needed to test eventual correlations with changes in speleothem geochemistry.

Overall the Père Noël speleothem suggests a wet Early Holocene with dryer conditions from 10.7 ka to 10.3 ka and at 10.4 ka, 10.0 ka, 9.7 ka and 9.2 ka.

5.3. 8.5 ka - 8.2 ka. (section 3 in Fig. 4)

The third section (Fig 4), a 1.5 centimetres thick very dense grey calcite is deposited between ca.8.5 ka and 8.2 ka and contrasts with the second section, characterized by white calcite. At the end of the second section (8.5 ka) the four chemical proxies are decreasing rapidly, suggesting a change from dry to wetter conditions in the third section. Lowest values occur at 8.2ka. It is difficult to give a precise age to the start of dense calcite deposition due to the scarcity of U-series dating in this context of rapid changes in petrography and geochemical content of the stalagmite. Taking into account a linear interpolation between the two datings surrounding the dense calcite, the deposition of dense calcite starts at 8.5 ka and lasts 300 years. The growth rate is lower (4.2 mm/century) then surrounding dating intervals (~7.5 mm/century) consistent with overall less favourable speleothem deposition conditions. However, if, based on the similarity of macroscopic aspects in the upper and lower part of section 2, we assume a constant growth rate over the entire section 2 with extrapolation of the growth rate of 7.6 mm/century up to the end of this second section, than the deposition of dense calcite (section 3) would start already at 8.9 ka, giving a duration of ~700 years for the deterioration and a growth rate of 2.4mm/century during the deterioration.

Obviously, the speleothem indicates that there is 'something going on' around 8.5 ka and the question arises if these changes can be linked with the well-known cold 8.2 ka event. This cold event registered in Greenland ice cores occurred at 8.2 ka and lasted ca. 300 years (Alley et al., 1997). This event seems to be the consequence of the sudden rupture of an ice dam of the northern American ice-cap releasing important amounts of cold fresh waters of Lake Agassiz in the North-Atlantic ocean (Barber et al., 1999, Wiersma & Renssen, 2006). Even by taking into account the uncertainties of the datings (several decades) and of the ages in between the datings (up to several hundreds of years), it is still difficult to link the deposition of the dense calcite with the 8.2 ka event since the changes in the stalagmite seems to precede the cold event and concern a longer period as also indicated by other continental proxies in the reviews of Daley et al. (2011), Röhling & Palike (2005) and Stager & Mayewski (1997). The PN stalagmite therefore seems to register a general climate deterioration underlying the 8.2 cold event on the continent and especially characterised by a humid climate as also suggested by an Italian stalagmite (Zornyak et al, 2011). Verheyden et al. (2012) discusses in detail the indications given by the Père Noël stalagmite and another one from the nearby Hotton cave for the occurrence of a wet phase (general climate deterioration) between ca 8.9 ka and 8.2 ka. Progressive drying is observed until 7.9 ka and may be linked to the cold 8.2ka event.

5.4. 8.2 ka - 7.8 ka. (Section 4 in Fig. 4)

After 8.2 ka, general climatic conditions are ameliorating from a speleothem deposition point of view. The growth rate increases to 7.9 mm/century, the stalagmite tends to a regular candle-shaped form. The decreasing stalagmite diameter and higher $\delta^{18}O$, $\delta^{13}C$, and Mg/Ca and Sr/Ca values indicates a decreasing water availability but the carbonate content of the water was still high as indicated by the relatively high growth rate. Soil may be active despite the relatively high $\delta^{13}C$ values in the Père Noël stalagmite interpreted as due to increased kinetic processes closely linked with lower drip rate on the stalagmite and in general with dryer conditions at the surface (Verheyden et al., 2008a).

5.5. 7.8 ka - 6.6 ka. (Sections 5 & 6 in Fig. 4)

During this interval, the development of a regular candle shaped stalagmite with a relatively high growth rate (16.7mm/century) occurs in section 5 and is maintained in section 6 with growth rates increasing up to 22.9 mm/century. Low values for $\delta^{18}O$ and $\delta^{13}C$ and mean values for Mg/Ca and Sr/Ca indicate relatively wet and temperate/warm conditions.

Relatively high growth rates and regular calcite deposition are in agreement with the occurrence of a Holocene 'climate optimum' formerly related to a strong extension of the Tilia pollen in our regions (Bastin, 1990). Although conditions seem rather stable regarding the speleothem diameter and growth rate, short-term changes are however occurring in the geochemical proxies. Deposition of denser reddish calcite occurs at 7.2 ka, 6.9 ka, 6.7 ka and 6.6 ka possibly related to climate deteriorations.

5.6. 6.6 ka - 5.3 ka (Section 7 in Fig. 4)

The dramatic drop in growth rate from ca. 22.9mm/century to 2.7mm/century indicates the end of favourable speleothem deposition conditions. Since the increased stalagmite diameter suggests an increased water availability, cold conditions may limit the speleothem growth. The general increase in geochemical proxy-data suggests a progressive drying at the end of the section with superimposed very dry peaks at 5.2 ka and 4.5 ka (section 8).

5.7. 5.3 ka - 3.0 ka and 3.0 ka - 1.8 ka (Sections 8 & 9 in Fig. 4)

The generally dry conditions with high dry-wet variability as suggested by variable geochemical proxy data seems to continue in section 8 with a final progressive 'drying-out' of the stalagmite during sections 8 and 9, i.e. from 5.3 ka to the stop in speleothem deposition at 1.8 ka. This period may be related to a general climate deterioration since ~6ka (with an important chronological uncertainty due to the scarcity of the datings), in agreement with former findings on pollen and other speleothems in Belgian caves (Quinif, 2006). The final 'drying out' may be related to the ~2.7 ka deterioration reported by Van Geel (1996) as possibly due to an abrupt decrease of solar activity (Van Geel, 2000). When the speleothem was sampled, water was still dripping on the speleothem indicating that changes in the chemistry of the water also plays a role in the non-deposition of calcite. These changes may be locally induced and comparison with other speleothems is needed. However, it is noteworthy that another stalagmite from the same region (Hotton cave) stopped growing at 2.8 ka (Verheyden 2001; Verheyden et al., 2012).

5.8. climate cycles

A slightly denser calcite is regularly deposited throughout the speleothem deposition, i.e., at 10.4 ka, 10.0 ka, 9.7 ka and 9.2 ka, 8.5 ka, 7.2 ka, 6.9 ka, 6.7 ka and 6.6 ka (ages, linearly interpolated between dating points). A higher resolution of the geochemical analyses and datings is needed to test an eventual correlation with changes in geochemical proxies, thus related to climate variability. An eventual correlation with the regular 'cool poles-dry tropics' climate intervals as defined by Wanner et al. (2004) and/or to Bond cycles of ~1500 year intervals defined in marine sediments (Bond et al., 1997) is worth to be studied and may bring insights in the cyclic occurrence of Holocene climate changes on the continent and connections with the marine records.

6. Conclusions

The Père Noël stalagmite deposited between 12.9 and 1.8 ka displays important variations in growth rate, stalagmite diameter, petrography and geochemical and isotopic content along its longitudinal axis. These changes give indications on changes in climate in the Han-sur-Lesse region. However, the conclusions should be further compared to other speleothems from the same cave as well as to other speleothems from other caves and to other archives in order to filter out eventual local effects and to get a robust regional climatic reconstruction. Taking into account the different proxy-data in the stalagmite, following preliminary climatic evolution of the Han-sur-Lesse region is proposed.

During the Early Holocene, wet conditions prevailed with dryer conditions from 10.7 to 10.3 and at 10.0, 9.7, 9.2 and 8.5ka (or 8.9 ka depending of the age model). It is not clear if the Younger Dryas is registered in the speleothem due to the lower growth rate inducing a lower chronological resolution of measured proxies and eventually to the presence of a hiatus.

A climate deterioration with deposition of 1.5 centimetres of dark translucent calcite, lasting between 300 and 700 years and ending at 8.2 ka is clearly registered in the Père Noël speleothem. Since the deterioration occurs before and lasts longer than the well-known cold 8.2 ka event, the speleothem probably registered an underlying climate deterioration and overprinting the 8.2 event signal. From 8.2 ka on, climate conditions are increasingly favourable for speleothem deposition and growth rates up to 22.9 mm/century are reached around 6.8 ka and are related to the Holocene 'climate optimum' as registered in pollen records. Conditions, even if probably dryer than those at 8.2 ka, stay relatively humid. From 6.6 ka, a general climate deterioration occurs and finally, a progressive 'drying –out' from 3.0 ka on, ends with the stop in speleothem deposition at 1.8 ka probably due to dryer climate combined with changing water chemistry at the drip site.

Slightly denser calcite is regularly deposited, i.e. at a centennial to millennial timescale. A higher resolution of the geochemical analysis is needed to test an eventual correlation with changes in geochemical proxies and analyse possible relations with known Holocene cyclicities.

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