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COMPLEX STRATIGRAPHIC SEQUENCES IN BELGIAN CAVES CORRELATION WITH CLIMATIC CHANGES DURING THE MIDDLE, THE UPPER PLEISTOCENE AND THE HOLOCENE

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(19 figures)

ABSTRACT. Studies of cave sediments in Belgian caves suggest that continuous sedimentary records through several climatic cycles do not exist. Climate variations induce lithologic variations. In Western Europe, cold periods mainly generate detrital sediments while warm periods are more favourable to speleothems formation. Other factors, as tectonics, can modify type and rate of sedimentation. Uranium-series disequilibrium dating and pollen analysis in karstic sediments allow to reconstruct the chronological evolution of the palaeoenvironments. In this paper, we reconstruct a synthetic climate evolution from cave sedimentary records of the Upper, Middle Pleistocene and Holocene, based on the biorhexistasy theory. Cold periods are the frame of mainly physical erosion (freeze, debris flows, etc.). Warm periods represent the biostasy conditions characterized by the development of forested soils and the predominance of chemical alteration. Thanks to examples coming from Belgian caves, the described phenomena are universal and can be applied to diverse karstic systems, taking into account the local environment.

Keywords: Karst, sediments, palaeoclimate reconstructions, palynology, U/Th dating.

1. Introduction

Belgian caves often contain sedimentary series composed of both detrital sediments and speleothems. The succession of different lithologic units reflects a variation in the causes of this sedimentation. Pollen analysis proves that the lithologic variations are the consequence of climatic changes. We present here some characteristic examples of sedimentary sequences, supported by pollen analysis and uranium-series disequilibrium dates in relation to the European climatic curves.

2. The Belgian Caves

2.1. Structure of the Belgian karst

Belgian karst mainly develops in the Palaeozoïc limestones of Middle and Upper Devonian (Eifelian, Givetian and Frasnian) or Lower Carboniferous (sensu Dinantian) - (Fig. 1). The general morpho-structural framework is an Appalachian relief : Hercynian folding followed by Mesozoic erosion led to an alternation of bands of limestone and detrital formations. An epigenetic hydrographic network cut over one hundred meters into these folded structures during the Neogene and Pleistocene periods. Karstic networks are essentially of two types, i.e. meander shortcuts and sinkholes-resurgence networks with a connection between sinkholes on the plateau and the resurgences in the valley (Fig. 2 ; Quinif, 1977).

2.2. General characteristics of the endokarstic sedimentation

The context of low plateaux with limited differences in altitude generates mainly horizontal caves formed near the base level. The principal underground sedimentary deposits are particularly localised in these horizontal galleries in the context of the meander shortcuts, as in the caves of Han-sur-Lesse or the cave of Bohon, as well as in a sinkhole-resurgence cave context, as the cave of "Vilaine Source". In this last context, the detrital sedimentation is provoked by energy decrease, principally near the resurgence. The coarse grained sediments, i.e. pebbles and coarse sands, are located near the swallow holes or result from detrital "mud" flows. The sediment source are the sandstones and the shales of the upstream basin. Moreover, this morphologic context is propitious for abundant speleothem formation when climatic conditions are favourable. The limestone thickness above the caves is in the order of a few tens of meters.

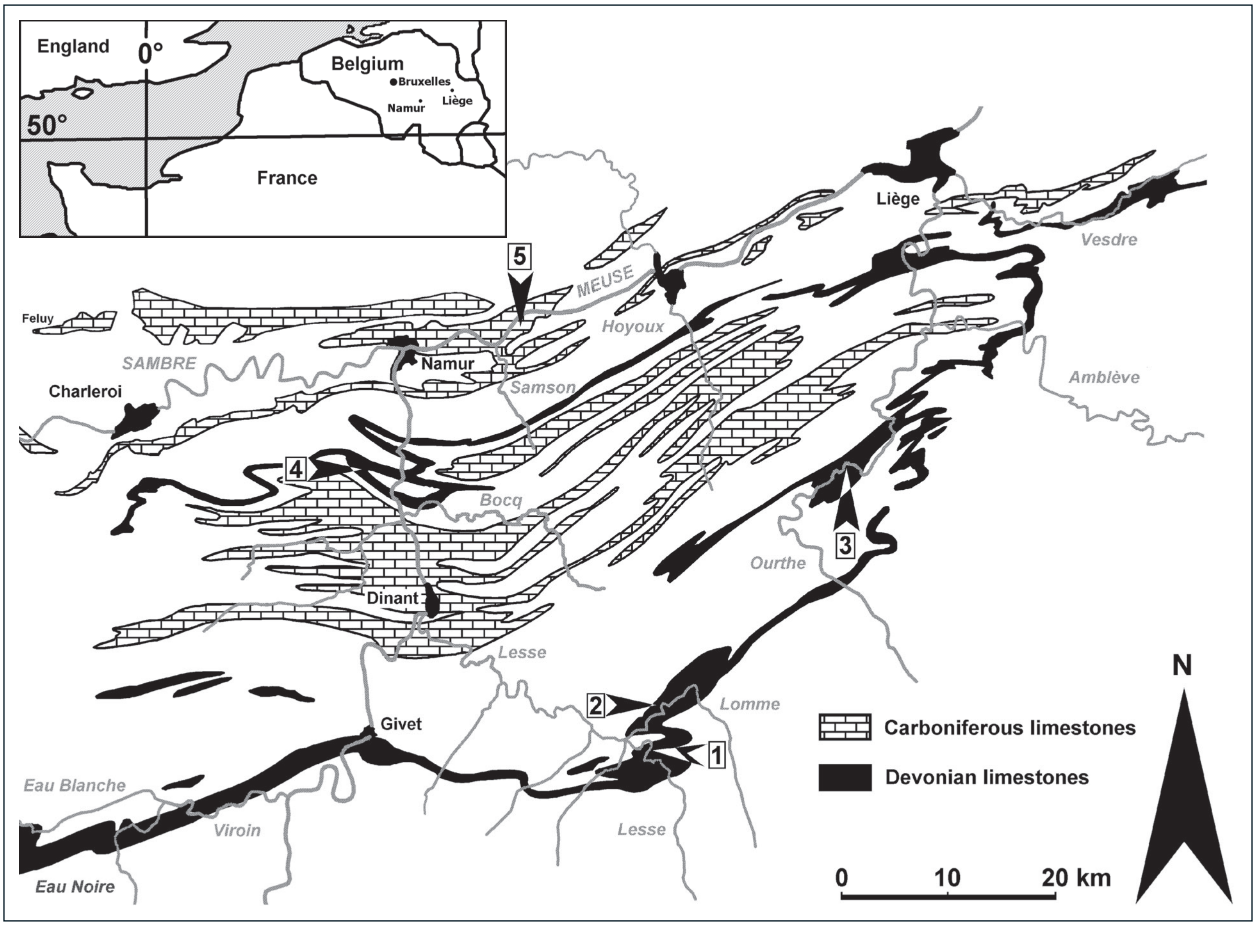


Figure 1 a. Geographical localisation of the country; b. Palaeozoïc limestone outcrop and localisation of the studied caves. 1. Han-sur-Lesse. 2. Rochefort. 3. Bohon. 4. Vilaine Source. 5. Sclayn.

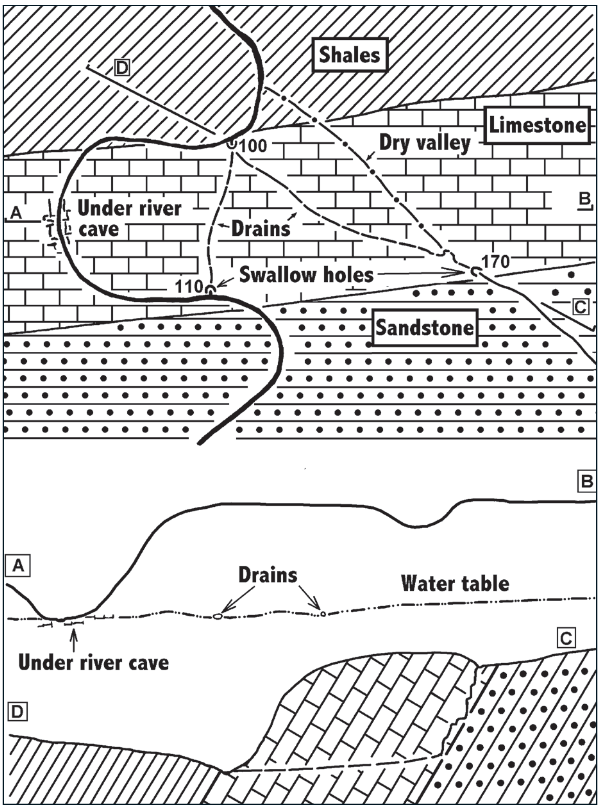


Figure 2. Karstic network types in Belgium (after Quinif, 1977). A large river (black line) is epigenetic and flows with meanders cut deep in the palaeozoïc basement. At the contact with the limestone, the river disappears and cut off its meander. The altitude difference between the swallow hole and the resurgence is small. In the thalweg, there is a under-river maze network with very slow flow. On the sandstone plateau, a small river disappears into a swallow hole ("chantoir") and has its resurgence in the main valley. There is an important altitude difference between swallow hole and resurgence. We have a vertical cave below the swallow hole after which the water passes very quickly into the phreatic zone.

3. Methods

Cave sedimentary sequences were studied in five different Belgian caves : Han-sur-Lesse, Lorette at Rochefort, Bohon, "Vilaine Source" at Arbre, Sclayn, and a small cave near Feluy (Fig. 1). Each section was mapped in detail with a litho-stratigraphic description, a granulometric analysis of detrital sediments, the pollen analysis and the U/Th dating of the speleothems. Pollen samples from detrital sediments were approximately 50 grams. Pollen were obtained from speleothems using the preparation method perfected and described by Bastin (1978, 1990). Speleothems were cut and the morphological changes along the longitudinal section (growth axis) were carefully mapped. Alpha spectrometric U/Th datings were performed at the CERAK, Faculté Polytechnique de Mons.

4. Cave of Bohon : a reference sequence

4.1. Lithostratigraphy

The cave of Bohon is a meander shortcut (Quinif, 1980) with an active level below horizontal galleries with detrital sediments of more than 3 meters thickness. We studied two sections from this cave. The litho-stratigraphic data of the sections 1 and 2 are synthesized in a reference sequence presented in Fig. 3. Detailed descriptions are provided by Bastin *et al.*, 1988.

Section 1, 2.5 m from the floor to the roof of the gallery, is constituted by two detrital units separated by a middle stalagmitic complex. The lower unit includes three successive sequences, with a transition from sands to clays. The upper sequence ends with a clay layer with mudcracks on its upper surface, sometimes filled by the calcitic roots of the first flowstone. The middle stalagmitic complex includes two flowstones separated by a clay layer. The lower flowstone supports stalagmites. The upper detrital unit begins with a clay layer passing into channelised coarser-grained sediments with oblique and cross stratification.

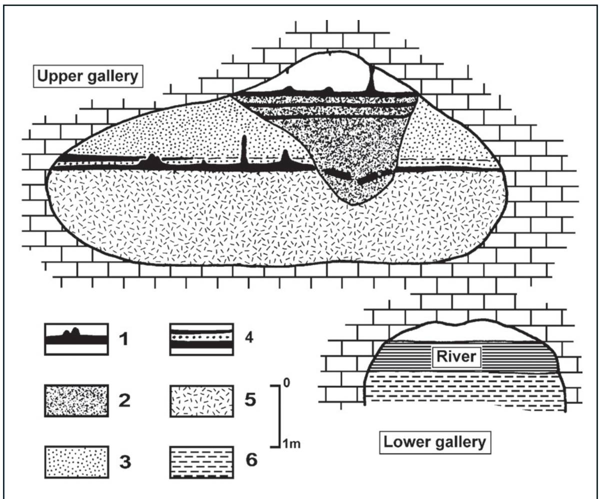


Figure 3. Synthetic sedimentary sequence in the "Grotte de Bohon". The upper gallery is almost completely filled by a complex sequence. It begins with a lower river detrital unit (5). A middle stalagmitic unit (1, 4) developed during an interruption of the river circulation and is covered by an upper detrital unit (3). This unit has been incised and the eroded gully has been filled by a final detrital unit (2) with three stalagmitic levels alternating with clay layers. 6 : Deposits of the still active lower gallery.

Section 2 complete section 1. In a lateral gallery, a final detrital unit fills a channel, incised in the upper unit, the middle stalagmitic complex and the top of the lower unit. It is covered by three flowstones with interstratified clays.

4.2. Palynology and climatic context

Pollen analysis concern both the detrital sediments and the speleothems (Fig. 4).

The upper part of the lower unit presents a pollen spectrum characterized by 94% of herbaceous plants with 90% *Cichoriae* indicating a pleniglacial climate.

In the middle stalagmitic unit, the first sub-unit (2 to 7, Fig. 4) suggests an open vegetation with some thermophile taxons. There are 50% trees, including *Quercus, Corylus, Alnus, Fagus*, plus *Betula* and *Pinus*, which are non thermophile. Among the herbaceous plants, one finds *Helianthemum*, which is a heliophile plant. This first level is attributed to the Eemian. The second sub-unit (8 to 12) is characterized by the regression of *Quercus, Fagus, Alnus*. The apparition of *Calluna* among the herbaceous plants proves the presence of leached soils, with a tendency to acidification. It is the end of an interglacial period. The pollen spectrum of the last stalagmite of this sub-unit has 70% trees. This is a period of temperate climatic conditions after a cold spell, which corresponds to the clay layer, unfortunately without pollen. Two U/Th datings prove this interpretation of B. Bastin : the middle stalagmitic unit belongs to Isotopic Stage 5.

The upper detrital unit belongs to a pleniglacial environment. It contains *Selaginella selaginoïdes*. Furthermore, the curve of *Alnus* is characteristic of an interstadial episod in the first part of this unit. This glacial character is also present in the final detrital unit of section 2.

The upper flowstones belong to the Holocene containing *Tilia, Hedera* and ferns. Moreover, *Juglans* and *Centaurea cyanus* prove sedimentation during the Roman Period. Some 10 meters away in the same gallery, a flowstone attached to the roof was also formed during the Holocene as proved by its Atlantic pollen content.

4.3. Chronology and environmental characteristics

The stratigraphic section in the cave of Bohon allows to define the relation between climate and endokarstic sedimentation in this region.

1° - Detrital sediments belong to glacial periods. The "cold" morphogenesis consists of a strong mechanical erosion at the surface, due to frost action on quartzo-pelitic formations, leading to an important detrital load in the rivers. This is the cause of the more important fillings in the caves during cold periods.

2° - Speleothems grow during interglacial periods. They result from the important ionic load of the seepage water because of a more intense biological activity and chemical weathering during these periods.

Figure 4. Pollen spectra of Bohon. Pollen analysis by Bruno Bastin (1970-1980); U/Th datings : M. Gascoyne.

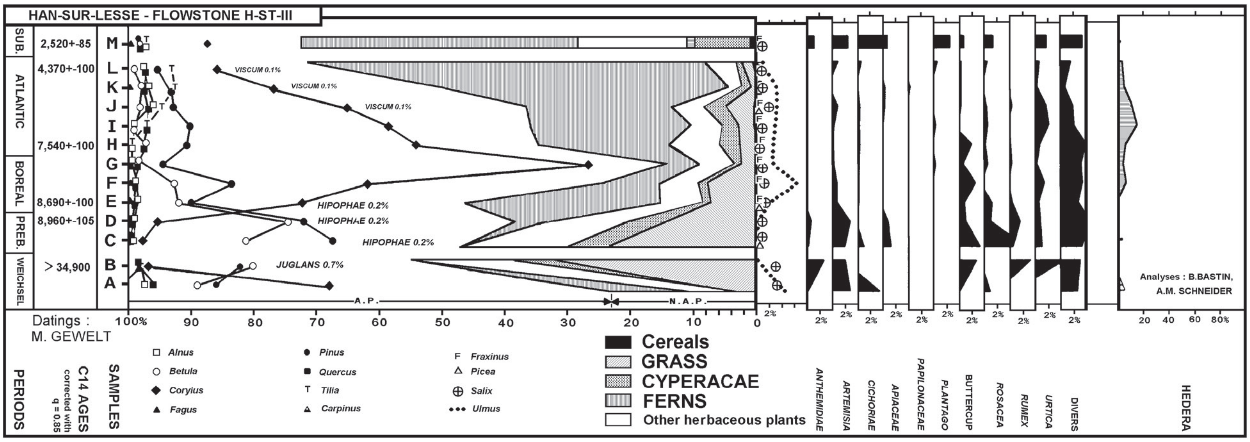


Figure 5. Pollen spectra of a Holocene Han-sur-Lesse flowstone (H-St-III). This flowstone covers the detrital deposit of the sedimentary section in the gallery of "Petites Fontaines" (Fig. 9).

3° - The interstadial periods are recorded either without an important modification of the lithology or by an incision due to the decreasing river load. An increasing erosional force of the rivers can be observed during the transition from glacial to interglacial periods with an growth of the water volume.

5. The Holocene and Tardiglacial

5.1. Recording the Holocene

Numerous pollen analysis on speleothems revealed reliable climatic sequences for the Holocene (Bastin, 1982). The principal characteristics are (Bastin, 1990) : dominance of *Pinus* and *Betula* during the Preboreal, strong dominance of *Corylus* during the Boreal, extension of *Alnus*, *Quercus* and, especially *Tilia* during the Atlantic, extension (CIII) of *Corylus* at the Subboreal and of *Fagus* (FIII) at the Subatlantic (Fig. 5). The transition Boreal-Atlantic is characterised by the abrupt extension of *Tilia* to a maximum near 6300 B.P. A clear regression of tree pollen occurs at the transition Atlantic-Subboreal. In some cases, speleothem development stops during the Subboreal. At last, we see the apparance of cereals and the growth of *Fagus* in the Subatlantic.
The Holocene, as a typical interglacial period, is generally characterized by speleothem development. An active hydrologic circulation may also be responsible for an increase in clay deposits. However, in many cases, such clay deposits are probably linked to increased soil erosion caused by anthropic modifications of the surface above the cave.

5.2. The transition between Isotope Stages 1 and 2

In the endokarstic cavities, this transition corresponds to an important modification of the sedimentological processes. A chemical sedimentation follows the detrital sedimentation. The transition can be complex with different morpho-sedimentological events.

5.2.1. The Rochefort cave sequence

The "new gallery" in the cave of Rochefort contains a sequence which marks this passage. A large detrital deposit of 6.5 meters thick, which fills the gallery almost completely, is partially eroded and covered by speleothems (Fig. 6). The summit of the sandy-clayey filling is covered by a broken stalagmitic column (RO-ST-1). After this phase, a flowstone (RO-ST-2) develops on the top of a first incision besides the column in the detrital deposit. After a second incision and the partial erosion of the flowstone RO-ST-2, a big speleothem (RO-ST-D) begin develop on top of that morphology.
The chronology is as follows (Genty *et al.*, 1992).
1. Sedimentation of the detrital series.
2. Stop of this sedimentation and growing of a first speleothem generation (RO-ST-1), characterizing a first warming.

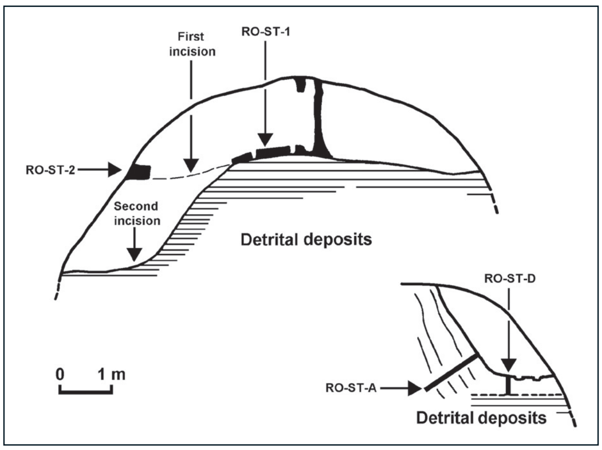


Figure 6. Section of the sediments in the new gallery of the cave of Rochefort.

3. First erosion with sedimentation of pebbles.
4. This incision is sealed by the flowstone (RO-ST-2).
5. Second erosion with breaking down of the flowstone.
6. Third generation of speleothems (RO-ST-D).
The column RO-ST-1 was the subject of 7 U/Th datings. Retaining only the results with ^{230}Th/^{232}Th › 25, the mean age is 12,250 yr ± 1,190 yr. This corresponds to the Alleröd. The flowstone RO-ST-2 has not given a reliable age ; nevertheless, the speleothem RO-ST-D brings interesting data. Sequential and crystallographic analysis by D. Genty shows that the speleothem evolves to a more and more temperate environment (Genty *et al.*, 1992). Pollen analysis indicates the passage from a dry forest environment with *Tilia* (20%) and *Corylus* (11%) to a wet forest environment with the domination of *Alnus* (27%). The base of the RO-ST-D speleothem contains already 7% *Tilia*, demonstrating the beginning of the Atlantic period. The mean age over the 14 performed U/Th datings is 5,280 yr ± 1,400, confirming the Atlantic age.

5.2.2. The deposits of the Han-sur-Lesse cave

The cave of Han-sur-Lesse is an underground cutting of a meander of the Lesse river. Near the resurgence, three galleries contain complex sedimentary sequence (Fig. 7 ; Blockmans *et al.*, 1999). Three sections were studied near the resurgence : in the "Galerie du Potiron", in the "Galerie de la Cave à vin" and in the "Galerie des petites Fontaines". In the galleries of "Potirons" and "Cave à vin", the both sequence begin with loams, characterising a cold dry period. There are followed by coarser grain-classed

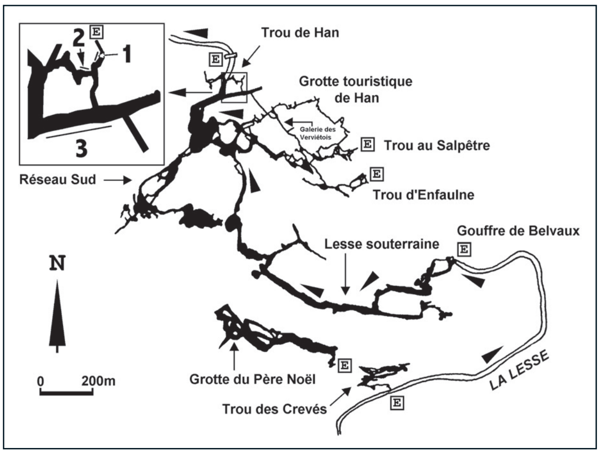


Figure 7. General map of the Han-sur-Lesse networks. The Lesse river disappears in the "Gouffre de Belvaux". It goes through the cave of "La Lesse souterraine", a part of the tourist cave and reappears in the "Trou de Han". The studied sections are in the vicinity of the resurgence of the Lesse river. E : entrances of the cave system. The black arrows indicate the current of the underground river. Insert : location of the studied sedimentary sequences ; 1 : section of the « Potiron » ; 2 : section of the "Cave à vin" ; 3 : section of the Gallery "Petites Fontaines".

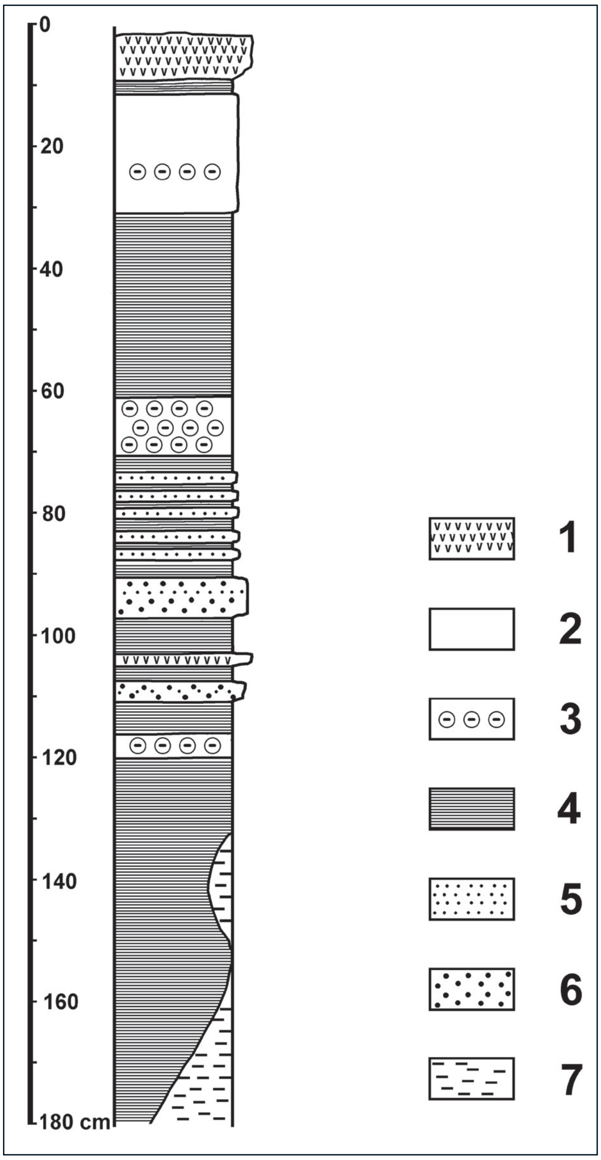


Figure 8. Lithostratigraphic column of the "Petites Fontaines" sedimentary profile in the Han-sur-Lesse cave (in insert, Fig. 7). 1. Speleothem. 2. Non laminated clay. 3. Redox front. 4. Brown non laminated clay. 5. Silt. 6. Thin sand. 7. Grey laminated clay.

sediments, deposed in channels. The detrital series end by a loam-clayey sequence, which is covered by stalagmites (U/Th dating : 22 ky ± 3 ky BP). These series are more or less continuous and can be interpreted as due to a succession of two cold dry periods separated by a more temperate and wet episode and ending with a temperate climate. The deposits of the gallery of the "Cave à vin" end with solifluxion clays, with frogs bones from the Holocene.
The morphological analysis of this part of the karstic network shows that the sedimentary sequence in the gallery of "Petites Fontaines" was deposited after the sedimentation in the galleries of "Potirons" and "Cave-à-vin". A time gap probably separates these sequences.

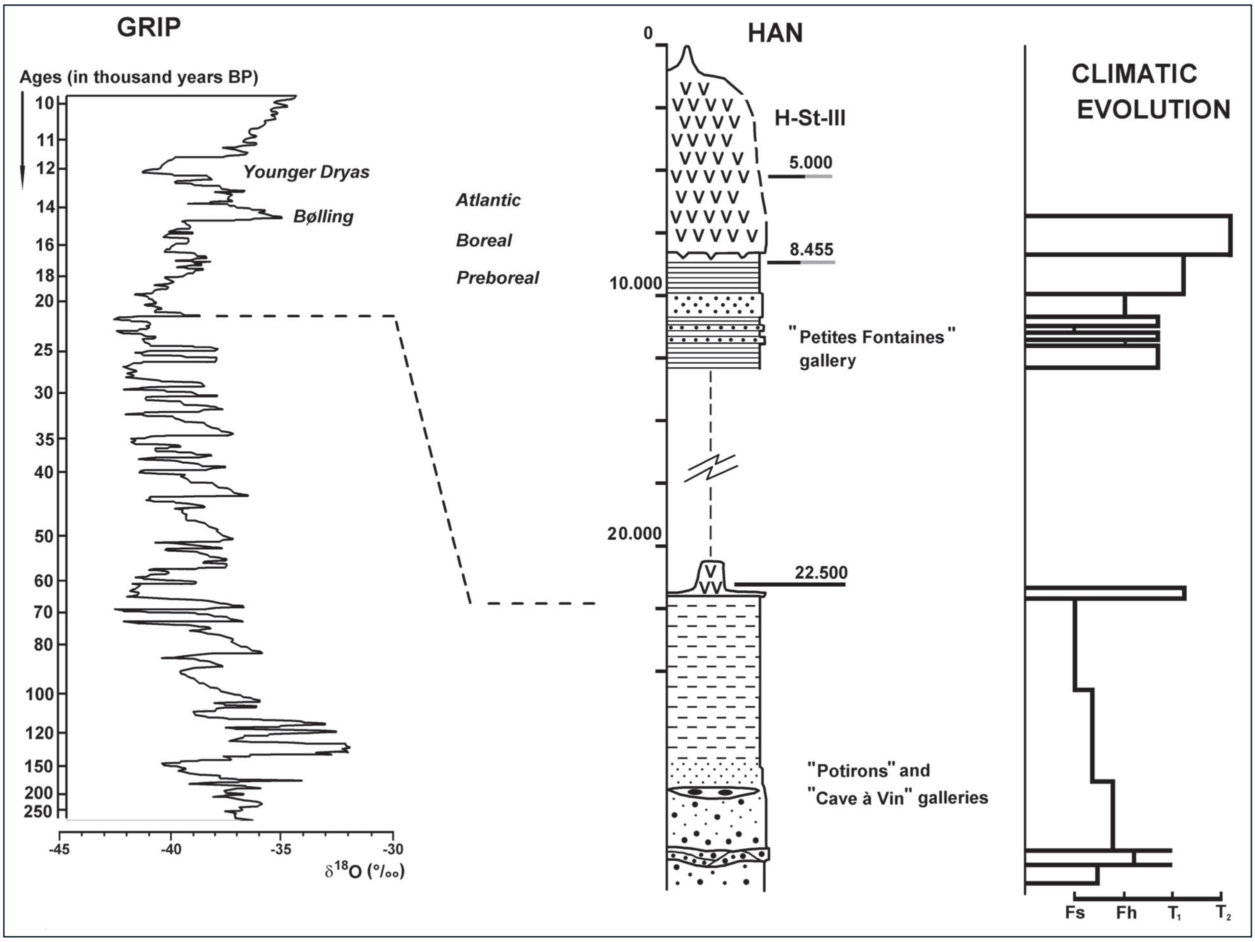


Figure 9. Climatic evolution and chronology of the studied sediments in the cave of Han-sur-Lesse output galleries. From left to right : $\delta^{18}O$ curve of the GRIP core (from Dansgaard et al., 1993), stratigraphic synthesis of the studied sediments with radiochronology (5000 and 22500 : U/Th ages on speleothems, 8455 : ^{14}C age on charcoals), climatic reconstruction (T1 & 2 : fresh and warm temperate, Fh : wet cold, Fs : dry cold). The evolution of the top of the gallery "des Petites Fontaines" deposits is indicative, with a temperate phase (Bölling-Alleröd), a dry cold phase (Younger Dryas) and wet cold phases provoking successive turbidite currents.

In the gallery of the "Petites Fontaines", the series is essentially clayey and presents an alternation of clay and loam lamina, with rare thin sand lamina (Fig. 8). It ends with a Holocene stalagmitic complex of flowstones and stalagmites. This detrital series represents a period when the cave was filled. At the resurgence, a lake occupied the galleries with a lacustrine type sedimentation. Frost crevices prove the occurrence of a cold period, between 22 ky, age of the speleothem at the top of the first part of the sequence and 8.5 ky BP, which is a ^{14}C dating on charcoal at the base of the top flowstone.

These endokarstic deposits help to reconstruct the palaeoenvironmental evolution at the end of the Pleistocene (Weichselian glacial period) - (Fig. 9). The two interstadial periods recorded at the lower part of the sequence, first by sedimentological variations in the detrital sediments and followed by the growth of stalagmites, can be correlated to two Dansgaard-Oeschger events around 22 ky BP. The Tardi-glacial period is characterized by a laminated clayey sequence, which present frost traces, possibly formed during the Younger Dryas. At the end of this sequence, the Lesse river erodes the sediments and Holocene speleothems are deposited. A big speleothem covers the erosion surface and was dated at 7.6 ky BP ± 0.5 ky BP.

6. The isotopic stage 5

6.1. The datings

The Isotopic Stage 5 is mainly characterized by speleothem deposition. Nevertheless, no continuous record of the entire Isotope Stage 5 was found in the stalagmitic series in Belgium. In Bohon cave, there is a clay layer in the stage 5. In Sclayn Cave, the interglacial period of "Saint-Germain I" (substage 5.3, Fig. 10, Bastin, 1990) is a detrital unit. Other sequence, essentially calcitic, present gaps. They do not start at the beginning of the stage 5, or do not finish at the end of the stage 5. Nevertheless, a reliable reconstruction of this stage can be made.

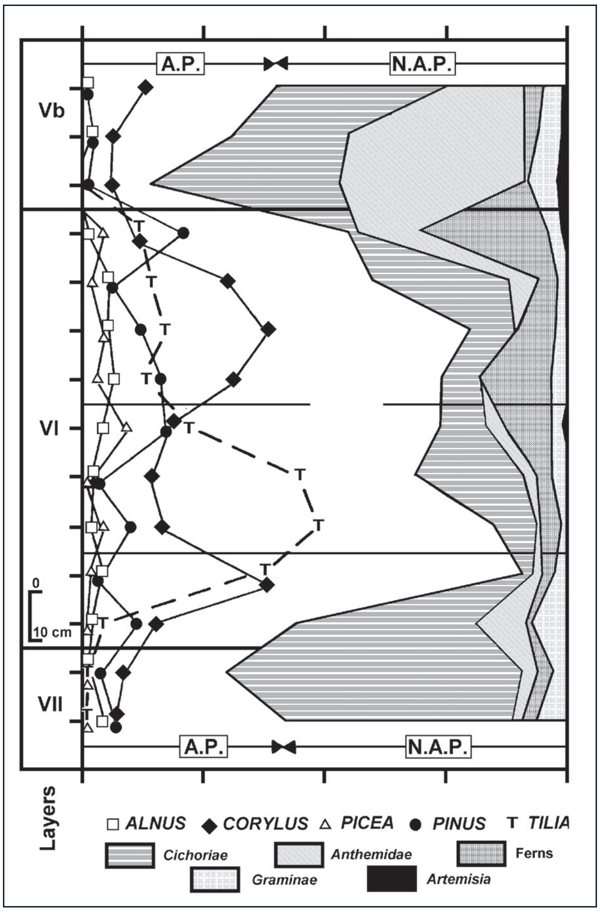


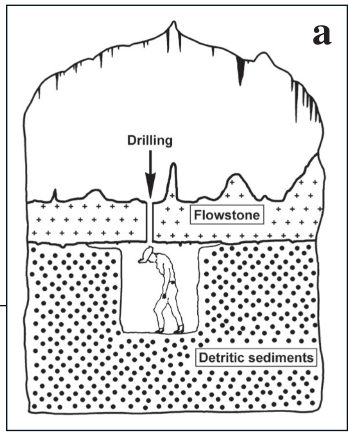
Figure 10. Pollen spectra of the loam unit definied like the interglacial period of "Saint-Germain I" (cave of Sclayn).

6.2. The stalagmitic series of the "Galerie des Verviétois" (Han-sur-Lesse)

This complex sequence was studied by 25 cores (Quinif, 1991 ; Quinif & Bastin, 1994). It is a stalagmitic unit (flowstone and stalagmites) which covers a clayey-sandy filling (Fig. 11). At some places, the gallery is completely filled by this deposit.

Three growth phases characterize the flowstone. A lower part has only been touched by the drillings and was dated from the Isotope Stage 7 (between 174,000 and 225,000 y BP). The major part of the flowstone develops during Isotope Stage 5. A growth interpolated curve calculated from the more reliable samples of the drilling H-ST-21 put the beginning of the growth at 131,000 y BP ± 5,000 y. At last, sometimes, the flowstone continues its growth during Stage 3.

The drilling H-ST-33 (Quinif & Bastin, 1994) has given good results in U/Th datings and in pollen analysis. The chronostratigraphic diagram (Fig. 12) coupled with the



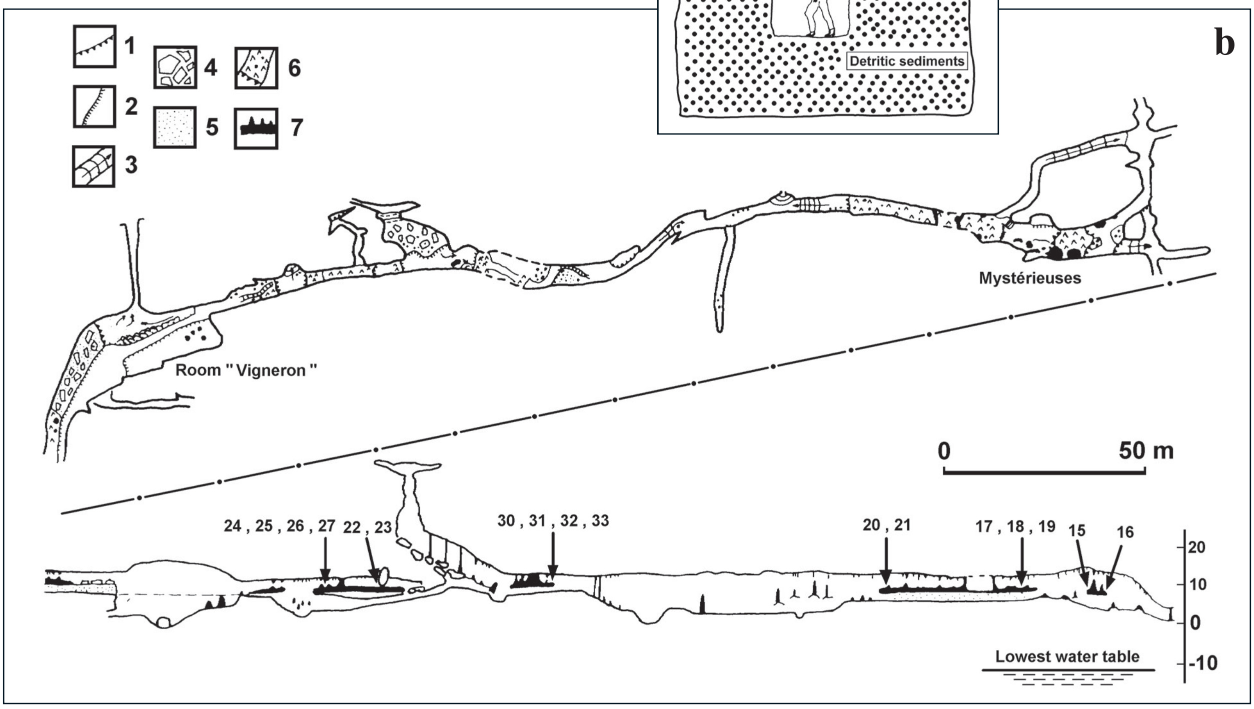


Figure 11. a. Schematic section of the "Galerie des Verviétois" (Han-sur-Lesse); **b.** Map and longitudinal section of the gallery "des Vignerons" and location of the samplings. 1. Steep slopes higher than 5 m. 2. Steep slopes lower than 5 m. 3. Slopes of the galleries. 4. Fallen blocks. 5. Without deposits. 6. Map of the flowstones. 7. Sections of the flowstones.

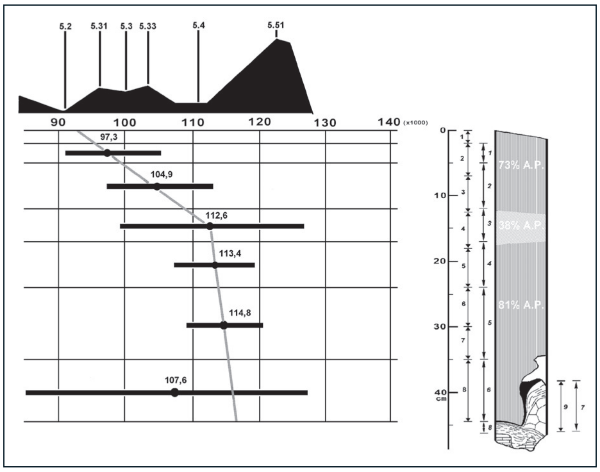


Figure 12. Chronology et palynology of H-ST-33.

SPECMAP curve assigns a first unit to the end of Substage 5.5, a second unit, characterised by a slowing down of the sedimentation to Substage 5.4 and a third unit to Substage 5.3. The pollen analysis confirms this evolution by recognizing three climate types. A forest interglacial dynamic with the presence of *Quercus, Alnus, Fagus, Hedera, Abies, Ilex* and *Viscum* is followed by a decrease of tree pollen, indicating a colder climate. After that, the dominance of *Alnus* and *Fraxinus*, as well as the presence of *Sangisorba officinalis,* determines a landscape of wet grasslands. At last, during the development of the upper unit, the forest resettles (*Quercus, Alnus, Corylus, Fagus, Carpinus,* but also *Betula*). This climate dynamic corresponds to the passage from an interglacial period to another interglacial period with typical biotopes of limestone areas.

6.3. The stalagmitic series of the "Galerie Gillet" (cave of "Père Noël", Han-sur-Lesse)

The eastern end of the "galerie Gillet" in the cave "Père Noël" is filled by a debris flow type formation constituted by pebbles in clay, covered by many speleothems (Fig. 13). One of these (PN-ST-10) was drilled for dating (Quinif, 1989; Quinif *et al.*, 1994). Figure 14 presents the chronological and stratigraphical evolution. The stalagmitic series is composed of 2 calcitic units separated by a pebble layer. The growth interpolated curves indicate the beginning of the growth at 91,800 y BP, a hard stop between 72,300 and 56,500 y BP and the end at 38,500 yr BP. The lower unit belongs to Isotope Substage 5.1 (Martinson *et al.*, 1987) and the upper unit to Isotope Stage 3. The pebble layer represent the stop of stalagmite growth during Isotope Stage 4, which is perfectly dated. These limits are very well correlated with the SPECMAP curve.

6.4. The section of Sclayn

The cave of Sclayn is a gallery of 30 meters long with a 5 meters thick deposit. This deposit is not exactly an

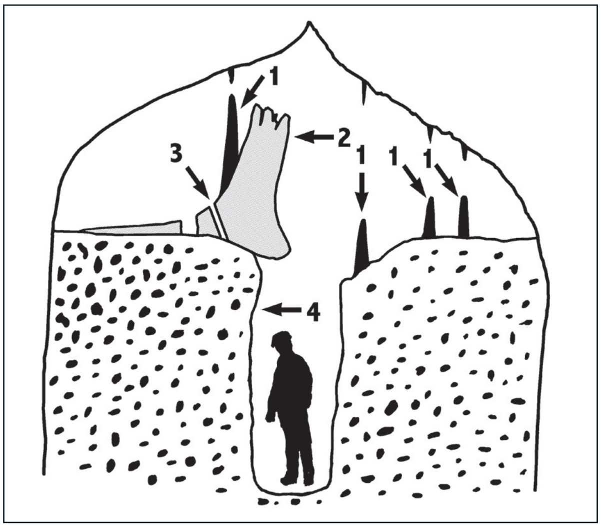


Figure 13. Schematic section of the "Galerie Gillet" (Han-sur-Lesse). 1. Holocene stalagmites. 2. Drilled speleothem. 3. Core PN-ST-10. 4. Pebble bed with clay filling.

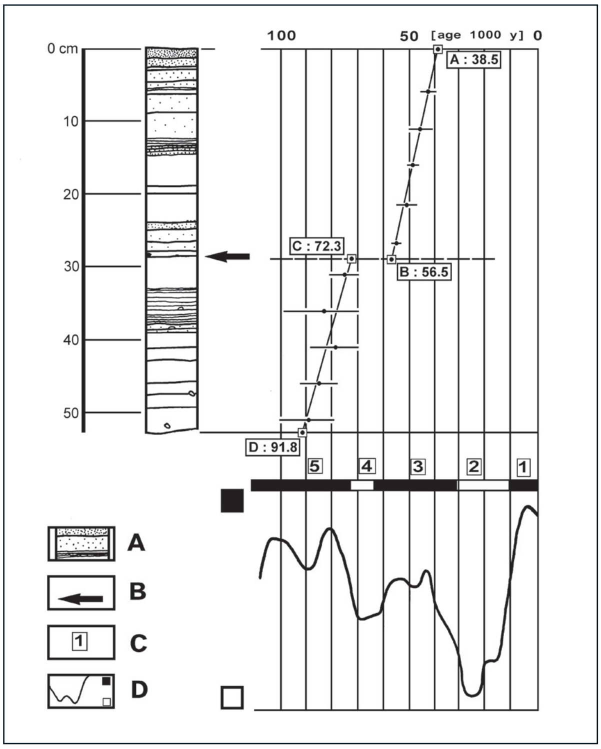


Figure 14. Chronological sequence of PN-ST-10. At left, the lithostratigraphy column is in relation with, at right, the U/Th datings which are compared with the specmap curve (at the bottom). A. Lithostratigraphic divisions. B. Pebble beds. C. Isotopic stages. D. SPECMAP curve (black square : warm, white square : cold).

endokarstic deposit because we are near the entrance of the cavern. Nevertheless, a detrital part of the series consisting of loam contains pollens of Substage 5.3 (Bastin *et al.*, 1986), corresponding to the interglacial period "Saint-Germain I" definied in the lacustrine series of "La Grande Pile" (Woillard, 1978).

6.5. The transition between Stages 5 and 4

The end of Isotopic Substage 5.1 is well represented. Three datings in a flowstone from a little cave at Feluy have given a mean age of 71,067 y BP ± 3,508 y BP (Bastin & Quinif, 1993). The pollen analysis shows an open vegetation with 24% tree pollen and the dominance of *Juniperus*. This is characteristic of the extreme end of a forest cycle and the transition to a herbaceous steppe or toundra like vegetation.
In the cave of Sclayn, three reliable datings of a stalagmite on top of a big flowstone give a mean age corresponding to substage 5.1. The pollen evolution is remarkable because it records the end of an interglacial period (Figs 15a and b).

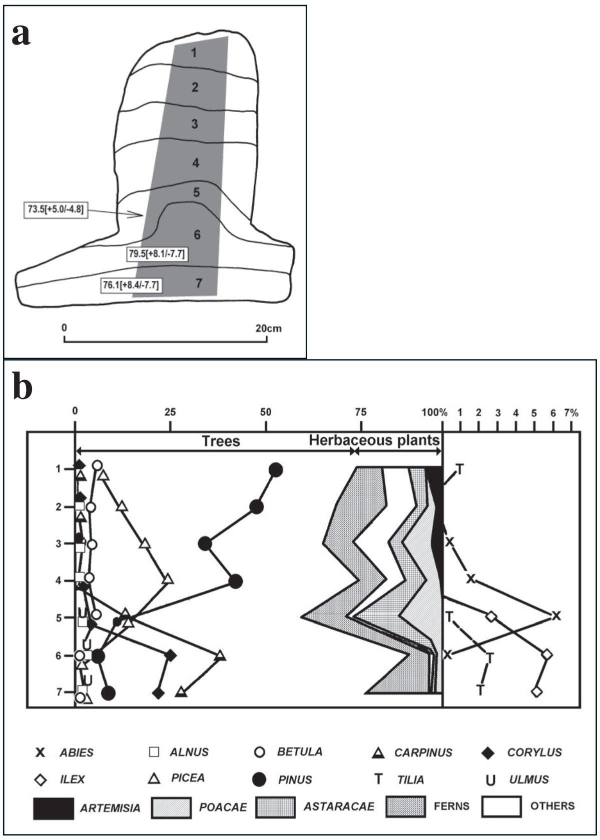


Figure 15. a. CC14 Sclayn stalagmite : sampling. The samples are taken in the middle of the stalagmite to avoid border effects; b. Pollen diagram of the CC14 Sclayn stalagmite. The end of the interglacial period of "Saint-Germain II" (isotopic substage 5a) is marked essentially by the reduction of thermophile trees like *abies, picea, carpinus* and *tilia*, the growth of *pinus* and *artemisia*.

6.6. Conclusion on Isotopic Stage 5

In the Belgian endokarst, the Isotope Stage 5 is characterised essentially by speleothems. The climate dynamic is an interglacial dynamic with cold episodes but the modifications on the sedimentological dynamic are not important as long as there is no influence of a river, e.g. in Bohon cave. Speleothems present no important variations of facies during the passage of Substages 5.2 and 5.4.

7. The last glaciation

7.1. Glacial sedimentary dynamics

Between two interglacial periods with important speleothem deposition, the Last Glaciation is characterised by a detrital sedimentation. This sedimentation is neither monotonous nor continuous. The example of Bohon demonstrated the existence of a incising channel and an interstadial recorded by the pollen content in the detrital sediments.
The cave of "Vilaine Source" is a good example of a glacial sedimentary dynamics. This cave is a long horizontal gallery close to a resurgence, which is nearly completely filled by detrital sediments and speleothems (Quinif, 1978; Quinif *et al.*, 1979). Figure 16 presents the chronostratigraphy of this series with glacial sedimentological characteristics.
1° - An incision separates two sedimentary units. The lower unit is a river deposit comparable to the Bohon sequence. The upper unit takes place in the channel. It is

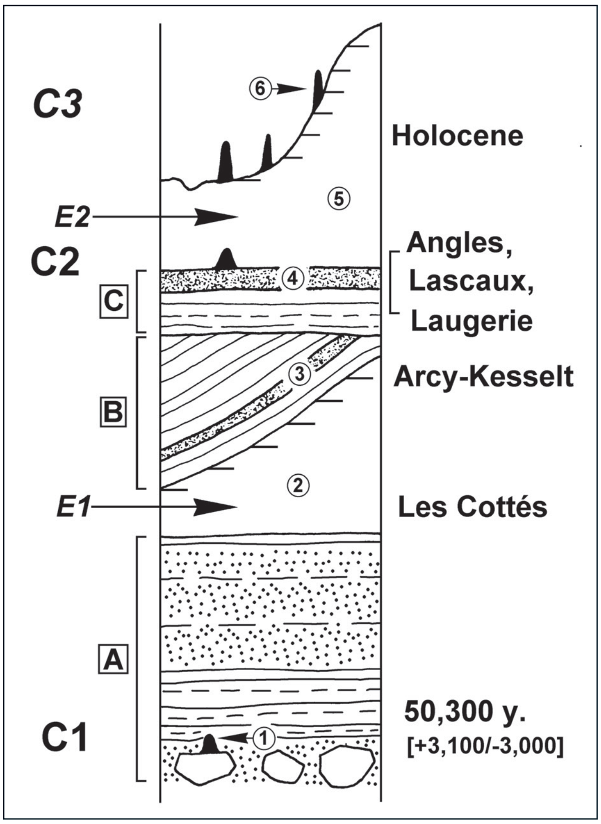


Figure 16. Sedimentary section in the cave of Arbre. C1, C2, C3 : stalagmitic phases indicating a climatic warming ; E1, E2 : erosive phases related to a temperated climate (rivers are little loaded with sediments because of the soil protection by the forest) ; A, B, C : detrital units deposed during cold climatic phases (the forest cover is very degraded, soils and rocks are not protected against the frost effects.) ; 1, 2, 3, 4, 5, 6 : climatic improvement phases.

constituted of reworked loess, as prove by its mineralogical content. The loess descended from the plateau through fissures and was deposited in calm water, without flow. Palynology confirms a pleniglacial environment, with a mean value of 74% herbaceous pollen, the domination of *Cichoriae* and the presence of *Selaginella selaginoïdes*. There are also pollen of *Alnus*, *Quercus* and *Ulmus*, indicating the existence of shelter sites like small valleys or dolinas for mesophile species. This is a fundamental aspect for the forest colonization when the climatic improvement comes back. The pollen spectra are the same in both units. This is a fundamental aspect for the methodology, the pollen spectra present no distortion compared to the type of sedimentation.

2° - Within the detrital series, without important modifications of the lithology, minor climatic improvements are recorded by the pollen content, with 40 to 50% tree pollen, the dominance of the ferns among the herbaceous plants, the presence of *Calluna*, demonstrating a decalcification process.

3° - Stalagmites, one of them was dated at 50 ky ± 3 ky (Quinif, 1990), mainly present interstadial pollen spectra, for example with 56% tree pollen, without thermophile taxons but with *Alnus*, *Corylus*, *Quercus*.

4° - Some stalagmites contain glacial pollen spectra with *Selaginella selaginoïdes*.

The sedimentary dynamics in the Belgian endokarst during glacial periods is complex. The dominating character is the detrital sedimentation. Two main facies are observed, i.e. river deposits with sands, cross stratification, channels, corresponding to a wet pleniglacial environment, and reworked loess in calm waters corresponding to a dry pleniglacial environment without endokarstic river flow. A first attribution consists to relate the dry conditions to Isotope Stage 2 and the wet conditions to Isotope Stage 4. However, reality is probably more complex. Incisions into sediments are the witness of climatic improvement. The vegetation cover limits mechanical erosion, i.e. the flows are not charged and erode the previous deposits. Moreover, pollens record also interstadial conditions into the detrital sediments. These interstadial periods do not seem to modify the nature of the sediments, they are short and weak. Finally, the presence of stalagmites indicates also interstadial environments but probably more important ones.

7.2. Isotope Stage 3

This stage is recorded by a stalagmitic series: PN-ST-10, whose lower part corresponds to the Isotope Substage 5.1 (see above). After the deposition of a pebble layer, speleothems grow between 56,500 y and 38,500 y BP. This is an approximate age because slowing down of the growth, indicated by an increasing reddish color of the upper layers, modifies the linear character of the growth interpolated curve. Isotope Stage 3 permits the development of massive speleothems, almost like Isotope Substage 5.1.

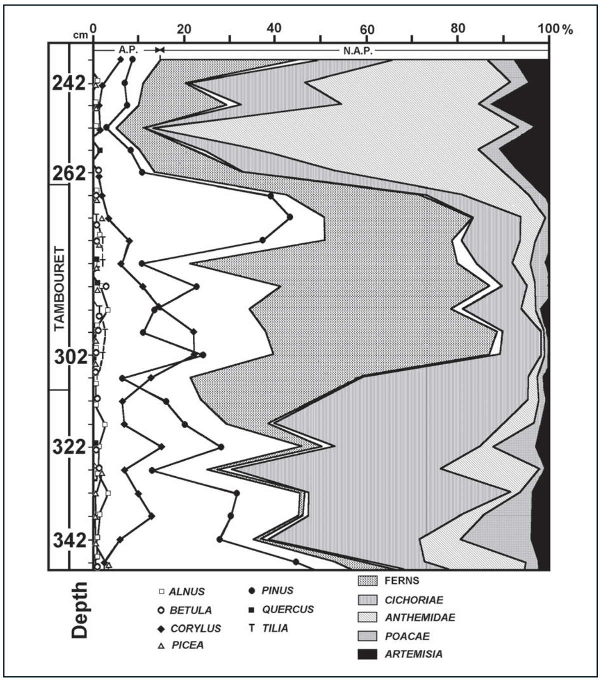


Figure 17. Pollen diagrams in the cave of Sclayn (section 16-17, square F). Because of lithostratigraphic and paleontological arguments and a radiocarbon dating, the sequence between the depths of 265 and 310 cm representing a climatic improvement is related to the interstade of "Tambourets". This improvement is marked by the appearance of *tilia* and the peak of *corylus*.

After the morphological context, the improvement of Isotope Stage 3 produces either erosion, either deposition of stalagmitic series or loam colluvion, as in the cave of Sclayn where pollen records revealed interstadial conditions. B. Bastin (Bastin *et al.*, 1986) related these to the interstadial of Tambouret (Laville *et al.*, 1985), in particular since a ^{14}C age of 38,500 B.P. was obtained in the upper layer (Fig. 17). By comparison with the Holocene, it may be thinkable that the different records of the stage 3 are not in fact non-synchronous, but successive.

8. Former stages

8.1. Isotope Stage 6

Pollen information before Stage 5 is only available in the Bohon sequence. As for the Weichselian, this glacial period provoked a detrital sedimentation. The detrital series under the speleothems of Stage 5 probably belong to Stage 6, like the sandloamy series of the "Galerie des Verviétois" in Han-sur-Lesse Cave (Fig. 10). A lower detrital unit in the cave of "Vilaine Source", situated under speleothems from Stage 5, has been studied for its litho-stratigraphy (Verheyden, 1994) and contains coarse elements, characterizing more energetic sedimentary conditions such as during the last glaciation.

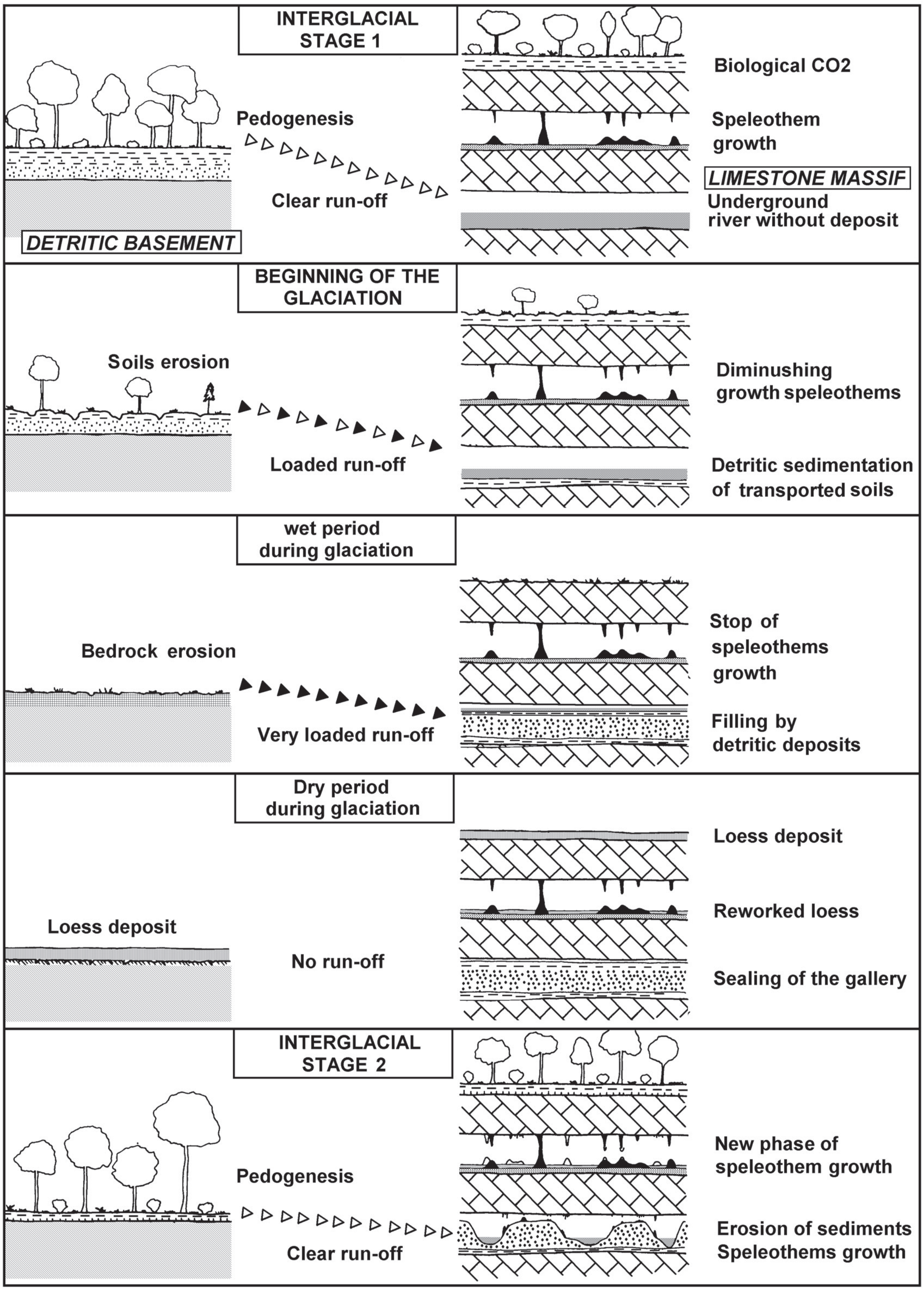


Figure 18. Evolution of a karstic network during a climatic cycle. Left : allochtonous terranes (shales, sandstones) of the upstream basin ; right : section through a limestone massif with active and inactive karst levels. A. First interglacial period. The river does not carry sediments because of the pedogenesis. There is much biological CO_2 and the speleothems grow. There is no detrital sedimentation in the cave. B. Beginning of the glacial period. The disappearance of the forest leads to soil erosion. Water flow is loaded with sediments ; there is detrital sedimentation in the karst. The development of the speleothems slows down. C. Wet glacial period. Periglacial erosion leads to a large sedimentary load in the river. The caves are completely filled. Speleothems development stops. D. Dry glacial period. Loess is deposited on the plateau. These eolian loams descend in the karst through fissures. E. Second interglacial period. Clear rivers, without sedimentary load, cut the detrital sediments in the caves. A new speleothem generation develops.

8.2 Isotope Stage 7

We have some datings from the lower parts of the flowstone in the "Galerie des Verviétois" (Han-sur-Lesse). The flowstone grows on detrital sediments containing iron roundstones. Unfortunately, precision of the datings is poor.

8.3. Previous stages

Flowstones from the higher levels of the cave of Hotton have ages at the limit of the method (Grebeude & Quinif, 1993). The precision on the data is often poor. These flowstones cover detrital sediments comparable to Weichselian series. This means that there is a certain continuity in the sedimentological processes in the karstic cavities in Belgium during the Quaternary.

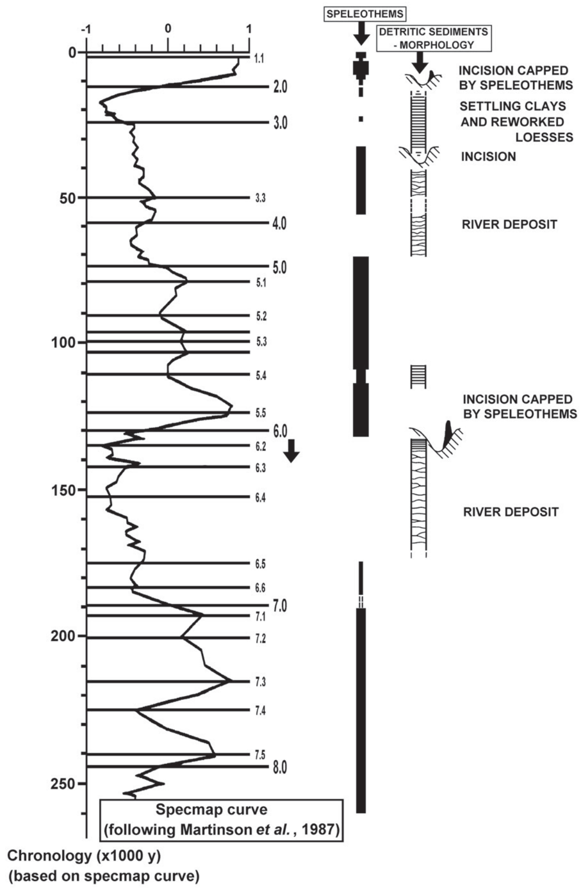


Figure 19. Summary of the climate phases from the underground deposits in relation with the specmap curve.

9. Conclusion : relation between the endokarstic sedimentation and the paleoclimatic variations

In the regional context of Belgium, the litho-stratigraphic characteristics of the endokarstic sediments are one of the most important consequence of climatic variations during the Quaternary and, thus, constitute a very good tool to study those palaeoenvironmental variations (Figs 18 and 19). Indeed, the Pleistocene modifications of the relief due to tectonic factors are limited .Therefore, sediments reflect particular climate modifications. The detrital sediments settle in cold conditions (rhexistasy periods = glacial periods), rivers deposits during cold wet periods and reworked loams during cold dry periods. Speleothems grow in temperate and wet conditions (biostasy periods = interglacial or interstadial periods). Superimposed on type of sediment supply, mechanical erosion of detrital sediments causing incisions through the lower detrital formations, and chemical corrosion of speleothems may occur. This combination of sedimentation and erosion processes is the consequence of base level fluctuations. During glacial periods, detrital sedimentation is very important in the bottom of the valley. The sediment accumulation provokes an uplift of the base level of the underground systems. For example, the Lesse valley downstream of the Han cave must have been some meters higher in altitude to justify the sedimentary accumulation observed in the galleries near the resurgence.

Because of these phenomena, the sedimentary sequences in Belgian caves are complex, with a stratification of the different types of deposits. The reconstruction of palaeoenvironments must go through the use of different parameters, i.e. litho-stratigraphy, mineralogy, pollen analyses, paleontology, geochemistry. The analysis of speleothems only cannot be used for a complete paleoclimatic reconstruction.

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