The Karstic System of Han-sur-Lesse

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Abstract

The karstic system of Han-sur-Lesse is the archetype of underground meander cutoff. Located in the “Calestienne”, a narrow bench extending along the northern margin of the Lower Devonian Ardenne, it comprises all caves and underground flow paths related to the epigenetic Lesse River across the Givetian limestone anticline of Boine. The Han-sur-Lesse caves result from a two-stage karstogenesis. First, ghost-rock karstification, the residual alterite of which is still observed locally in the system, affected the substratum of a fairly uniform topography under hot and wet climates, probably during the Cretaceous and the Paleocene. Second, as a result of the Ardenne uplift during the Neogene, river incision created a hydraulic potential that led to removal of the alterite by underground water circulation. Currently, the underground circulation short-circuits a meander of the Lesse, from the swallow hole of “Gouffre de Belvaux” to the resurgence at “Trou de Han”. Another small underground stream is separated from the main circulation by less permeable nodular shale and argillaceous limestone strata. The overall system is essentially made of horizontal galleries, with large rooms located at structural nodes or produced by the coalescence of superposed galleries. The river accumulated pebbles, sand, and clay in the caves, often capped by flowstones, the whole recording Quaternary climate oscillations.

Keywords

Karstic system • Ghost-rock karstification • Karstic hydrogeology • Han-sur-Lesse • Underground meander cutoff

9.1 Introduction

Developed in Givetian limestones along the northern margin of the Lower Devonian Ardenne, the internationally renowned caves of Han-sur-Lesse form the greatest karstic system of Belgium and represent the archetype of an underground meander cutoff. This group of caves (caves of Han-sur-Lesse, “Père Noël”, “Lesse Souterraine”, “Trou des Crevés”) belongs to the karstic system of the underground Lesse River. Since the beginning of the 1980s, multiple scientific studies, in particular in the fields of hydrogeology, paleoclimatology, underground sedimentology and, of course, karstology, highlighted its geological and geomorphological characteristics, which together allow inferences about the system as part of the regional landscape evolving in the frame of long-term morphostructural and paleoenvironmental changes since the Mesozoic. In many areas, e.g. in western Belgium, it has been shown that the classical speleogenesis may be preceded by an initial process of ghost-rock formation (Quinif 2010; Dubois et al. 2014), a form of partial limestone weathering leaving a residual alterite similar in structure to the isalterite of kaolinic

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weathering profiles in siliceous rocks (see Chap. 5). This process requires specific conditions combining a warm humid climate and low regional altitudes that point to an activity during the end of the Mesozoic. In western Belgium for instance, the presence of a Cretaceous cover dates the ghost-rock formation in Lower Carboniferous limestones to the period between the Late Jurassic and the Campanian (Quinif 2010). The Han-sur-Lesse karstic system offers a unique opportunity to check this hypothesis and suggests that, if ghost-rock residual alterite ever existed there, its erosion should have occurred as a result of the regional uplift of High Belgium and subsequent river incision, which occurred essentially during the Late Neogene and the Quaternary. River sediments and flowstone capping are present in the two levels of the generally two-storeyed caves. Pollen and isotopic analyses and dating (^{14}C, U/Th, laminae counting) of the speleothems have shed light on the temporal relations between uplift, incision, climate oscillations, and cave development. Moreover, the presence of several great rooms with fallen blocks allows for the study of formation of such voids in possible relation with earthquakes.

In this chapter, we provide an overview of various characteristics of the Han-sur-Lesse karstic system. After having given a panorama of the morphological features and deposits encountered in the caves, we focus on the structure and dynamics of the subterranean water circulation. Then, based on all available data, we show that the long-term evolution of the system fits in the two-stage conceptual frame of karstogenesis first established in western Belgium.

9.2 Geological and Geomorphological Settings

The Han-sur-Lesse area belongs to the Paleozoic massif of the Ardenne *s.l.*, folded and faulted during the Variscan orogenesis (Overlau and Quinif 1979; Delvaux de Fenffe 1985; Dumoulin and Blockmans 2013; see also Chap. 2). Located in between the Lower Devonian core of the high Ardenne to the south and the Upper Devonian/Lower Carboniferous Famenne and Condroz regions to the north, it includes Givetian hills surrounded by depressions carved in Eifelian and Frasnian shales (Fig. 9.1). The geological structure is mainly formed by faulted E–W folds affecting heavily jointed rocks (Fig. 9.2). Over the Mesozoic, the Variscan topography was eroded to a monotonous, low-elevation planated landscape, while the dense vegetation cover developed under Cretaceous warm and humid climates allowed for effective weathering of limestone rocks. Although this is not definitively demonstrated, the Paleogene marine transgressions that deposited sands and clays on parts of the Ardenne plausibly briefly drowned the study area (see Chap. 5). This is to some extent supported by the epigenetic character of rivers such as the Lesse, whose first installation took place, probably in the Oligocene, on either loose cover sediments or a thick weathering mantle, independently of the basement structural grain and the variable resistance to erosion of the rocks. Only recently, during the Late Neogene and, especially, the cold periods of the Quaternary, has differential erosion shaped an Appalachian topography of alternating ridges on hard rocks and depressions in weaker rocks. Depending on the respective contrasting rocks, while the Condroz region displays the classical scheme of Upper Famennian sandstone ridges separated by depressions in Lower Carboniferous limestones, the Han-sur-Lesse area opposes ridges corresponding to Givetian limestones and depressions in Eifelian or Frasnian shales (Poty 1976).

Draining the Lower Devonian siliceous basement of the Ardenne in its upper course, the Lesse River comes across the Givetian limestones of the Calestienne, which form a bench at 280–300 m elevation along the NW margin of the Ardenne massif, before flowing to the NW toward the depression carved in Lower Famennian shales. At Resteigne, the river passes through a first limestone massif where it cuts a deeply incised valley (Fig. 9.1). Then, after having crossed the shaly depression of Belvaux, it flows across the limestone hill of Han (also named the hill of Boine). There, the valley displays a wide but generally dry meander to the east and north of the hill, while the river sinks into the swallow hole of "Gouffre de Belvaux" and comes out at "Trou de Han" after the subterranean crossing of the hill. Likewise, 5 km to the southwest, the Ry d'Ave takes an underground course when traversing the limestone massif of Wellin. From Trou de Han, the Lesse finally takes again a surface course across another shaly depression at Han (Fig. 9.1). The Boine massif, which contains the karstic system of Han, is a W-plunging faulted anticline (Fig. 9.2, Wavreille anticline). Cutting the western part of the karstic system, a 1-km-long NNW-trending, east-dipping fault shows a reverse motion attesting a Late Variscan phase of E–W compression (Delvaux de Fenffe 1985) (Fig. 9.2). Finally, many joints, arranged in two N50°E–N70°E and N140°E–N150°E main systems, play an important role in the karstogenesis (Havron et al. 2004).

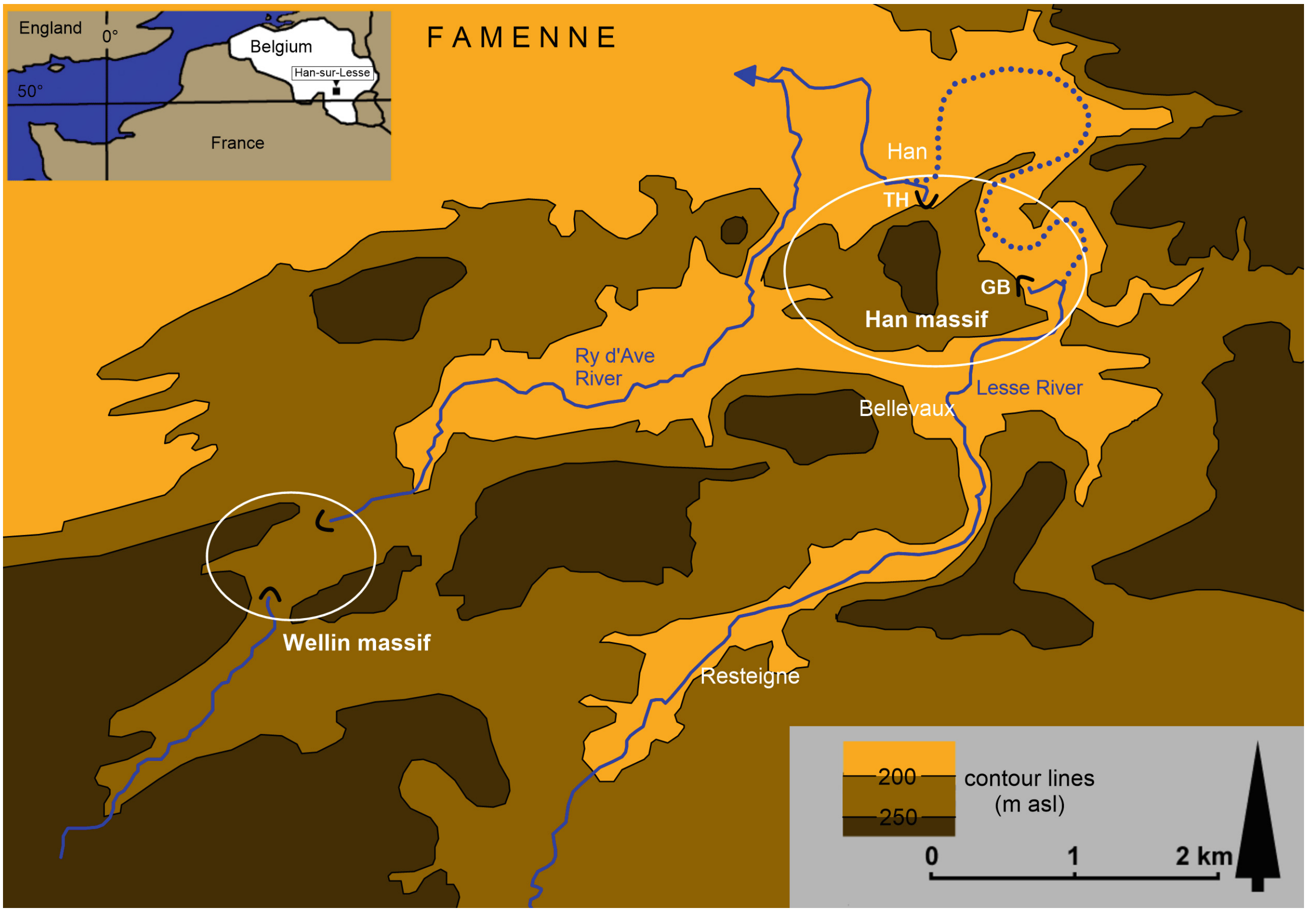

Fig. 9.1 Location of the limestone massifs of the Han-sur-Lesse—Wellin area on a simplified oro-hydrographic map (200 and 250 m contour lines). *Circled in white*, the Han and Wellin massifs include karstic systems related to meander cutoff by the Lesse and Ry d'Ave, respectively. Two other massifs at Resteigne and Grignaux-Turmont (west of Han), though also crossed by these rivers, show no significant karstic development. The *dotted blue line* denotes the abandoned surface course of the Lesse upstream of Han. *GB* Gouffre de Bellevaux. *TH* Trou de Han

9.3 The Karstic Network: Morphology and Deposits

9.3.1 Structure of the System

After a ~1 km surface course across the limestones of the Boine hill's southern flank, the Lesse disappears totally in the swallow hole of "Gouffre de Belvaux" and takes a subterranean course across the rest of the Boine massif (Figs. 9.3 and 9.4). At the surface, the valley continues around the hill as a flat, dry valley floor bordered by steep wooded slopes. The subterranean system of caves that cuts this meander off starts with the "Lesse Souterraine" cave immediately downstream of the "Gouffre de Belvaux", essentially a major gallery travelled by the underground Lesse, and goes downstream in the touristic cave of Han, ending in the resurgence of "Trou de Han" (Fig. 9.3). Two other caves, the smaller "Trou des Crevés" and the "Grotte du Père Noël", are disconnected from the main system. The course of the underground river has been explored and followed in its totality by divers (Quinif and Bastin 1986; Quinif 1987a, b, 1988a). Beyond the "Gouffre de Belvaux", the system includes other swallow holes, located more downstream along the margin of the abandoned valley floor, among which the "Trou d'Enfaule" is still active for discharges >25 m^3/s (Quinif 1988a) in high water periods, and the higher lying "Trou du Salpêtre" is the permanently dry entrance of the touristic underground circuit (Fig. 9.3).

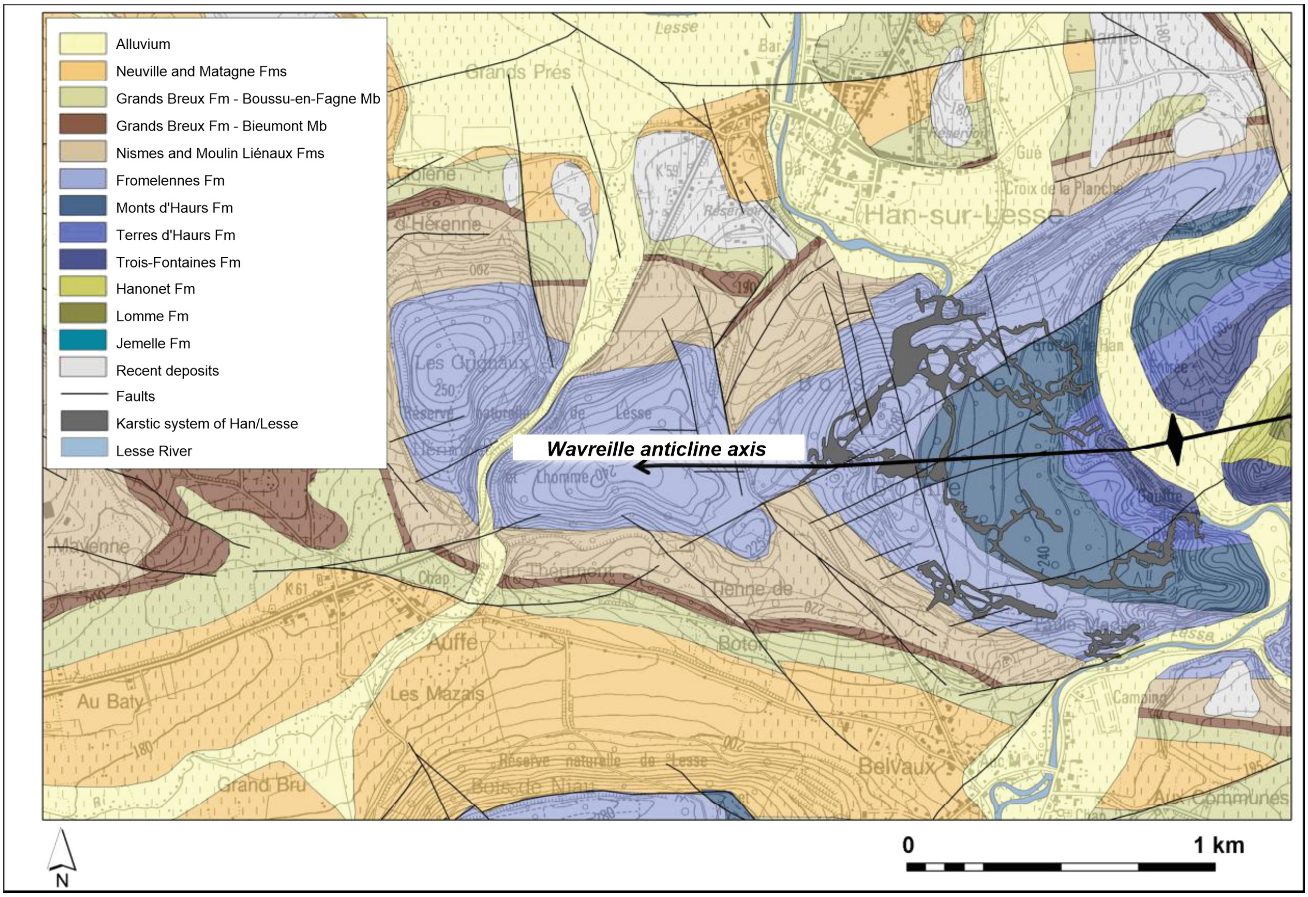

Fig. 9.2 Geological map of the massifs of Boine (in the east) and Grignaux-Turmont (in the west) along the axis of the Wavreille anticline (from Bonniver 2011, modified after Dumoulin and Blockmans 2013). The Givetian limestone formations appear in *blue* tones

These entrances open in distinct gallery systems that finally meet in the “Salle d’Armes” room (Van Den Broeck et al. 1910; Kaisin and de Pierpont 1939). According to Quinif (1988b), the galleries of the Han system extend over a total length of almost 14 km.

From the geological point of view, the karstic system is developed within two main ensembles, the first one encompassing the Lower/Middle Givetian Trois-Fontaines, Terres d’Haurs and Mont d’Haurs Formations, and the second one corresponding to the Upper Givetian Fromelennes Formation. These two ensembles are separated by the watertight Flohimont Member, which marks the base of the Fromelennes Formation and is made of shales and argillaceous limestones. While the “Trou des Crevés” and “Père Noël” caves are developed in the Fromelennes Formation of the anticline’s southern flank (Deflandre et al. 1987), a large part of the Cave of Han, including the “Réseau sud” and the exit gallery of the Lesse (Quinif 1987b), lies in the same Formation on the northern limb of the anticline (Fig. 9.2). The rest of the system, i.e. mainly the “Lesse souterraine” cave and the other galleries starting from the swallow holes in the abandoned meander, extends within the Lower/Middle Givetian limestones, on the other side of the Flohimont barrier.

The main galleries, and obviously the “Lesse souterraine”, develop at or near the river base level. Upper levels consist only of the “Verviétois” gallery (Fig. 9.5), accessed by the “Trou du Salpêtre” and situated ~15 m above the present Lesse, the upper part of the largest collapse rooms, and some cupola systems. The “Père Noël” cave is the only exception. There, a small water flow is observed only very locally at the base level and the main gallery, including the wide and extended, up to 30-m-high “Bivouac” room, is located higher, while a smaller room has still been found ~20 m above this main level (Verheyden et al. 2008).

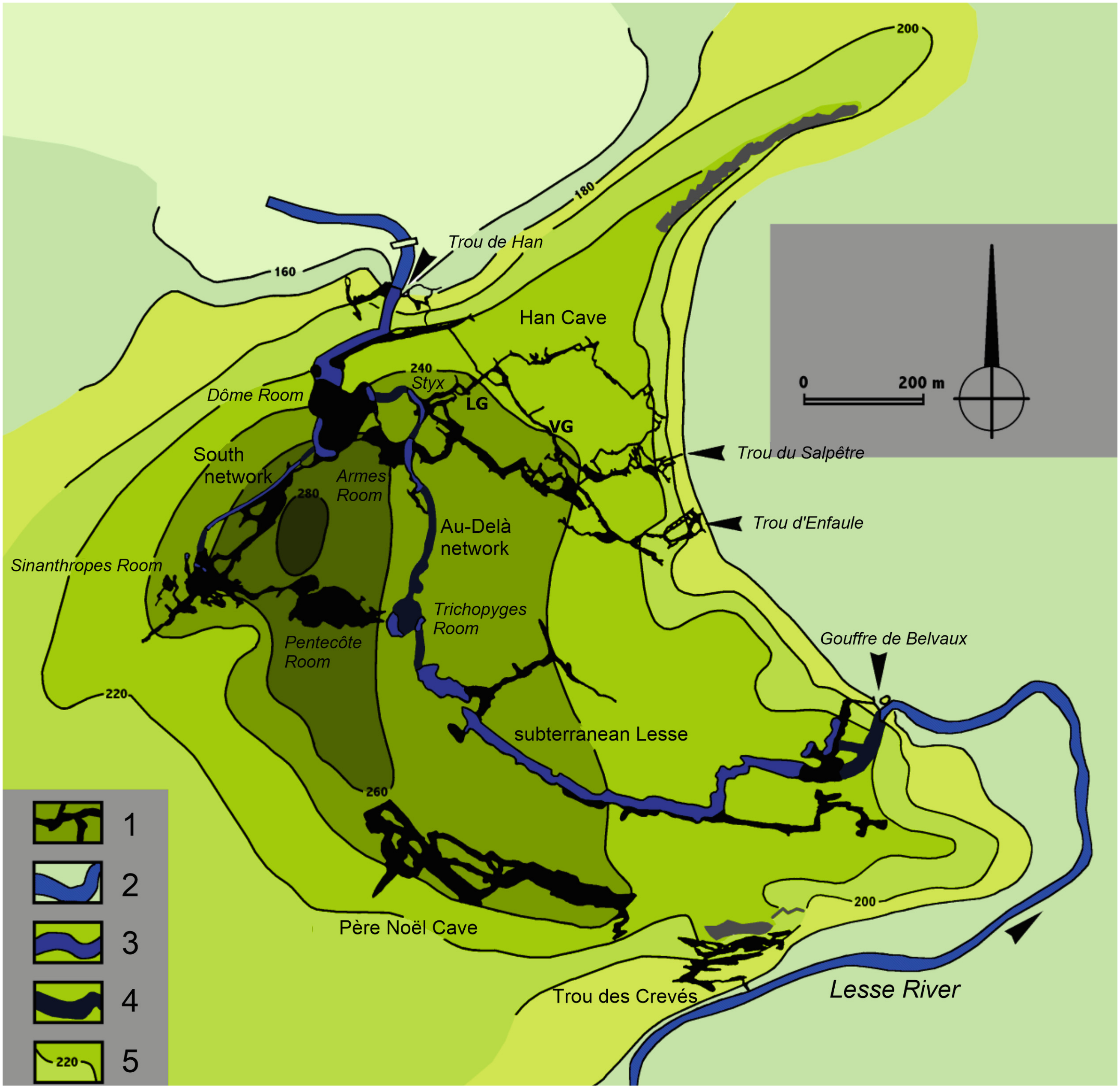

Fig. 9.3 General map of the karstic system of Han-sur-Lesse. *1* Layout of the caves. *2* Subaerial river. *3* Underground river with a free surface. *4* Galleries, including sumps, and rooms. *5* Contour lines of the surface topography. *VG* "Verviétois" gallery. *LG* "Lannoy" gallery. Note the prevailing orientation of galleries following the conjugate N60°E and N150°E joint directions (modified after Quinif 1987)

9.3.2 Morphology and Deposits of the Han Cave

9.3.2.1 From the "Trou du Salpêtre" to the "Styx" Room: A Sedimentary Sequence of the Middle and Upper Pleistocene

The "Trou du Salpêtre" entrance of the cave, an old swallow hole of the Lesse River, is the starting point of the upper level of the karstic system, where the "Verviétois" gallery, connecting successive large ("Scarabées", "Vigneron", "Mystérieuses") and smaller (e.g. "Chaos") rooms, occasionally scattered with fallen roof blocks, is followed by the "Lannoy" gallery leading to the "Salle d'Armes" room (Figs. 9.3 and 9.5). Such galleries and the succession of large rooms they connect are characteristic features of the Han Cave. The higher than large "Verviétois" gallery developed following major N150°E vertical joints.

This upper level contains a sedimentary sequence comprised of a basal detrital unit and a capping stalagmitic complex made of a thick flowstone and stalagmites

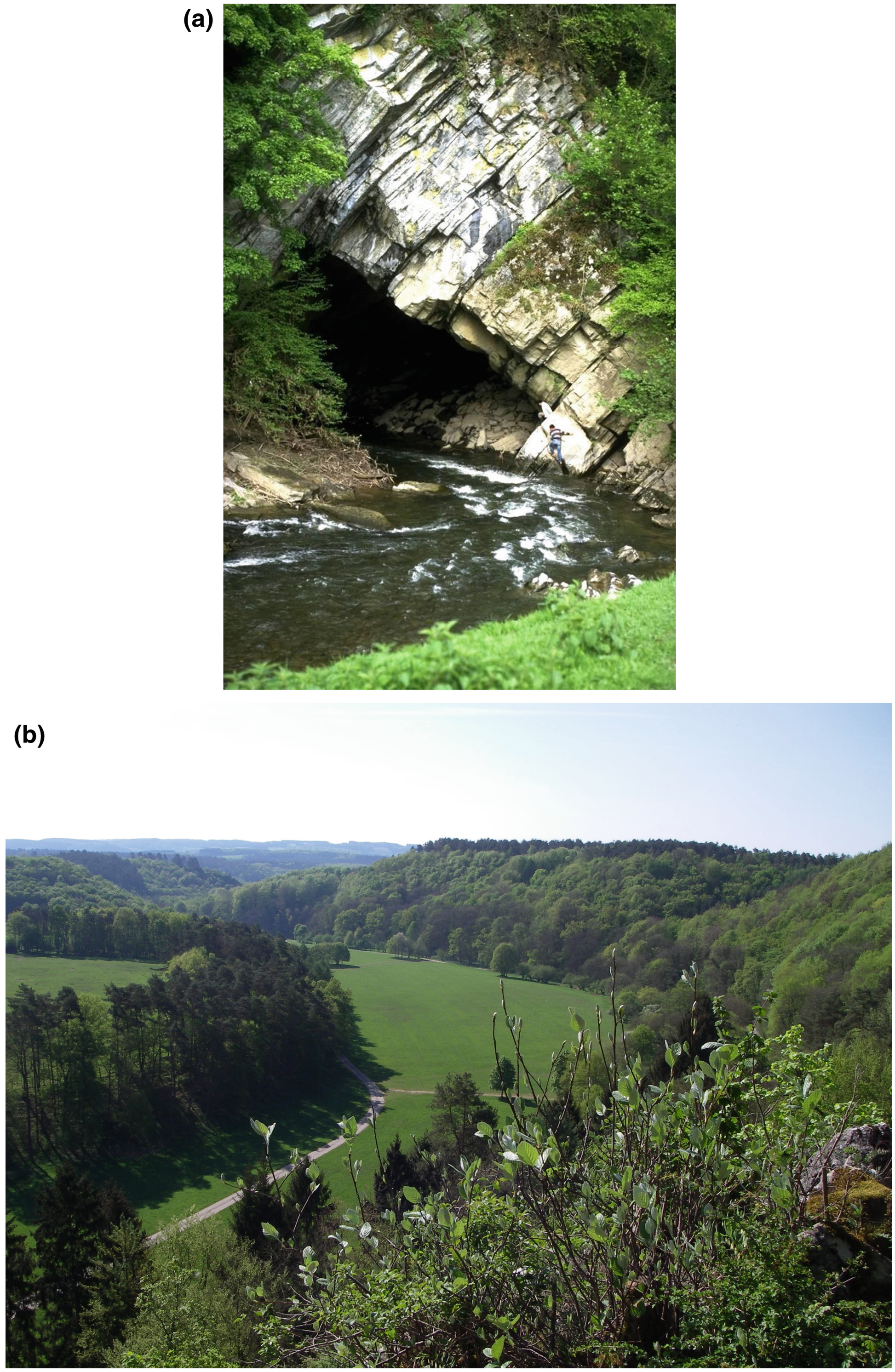

Fig. 9.4 **a** The "Gouffre de Belvaux" swallow hole, where the Lesse River disappears totally. **b** For flow discharges exceeding ~25 m^3/s, the cave is saturated and overflows. The river reuses its ancient subaerial course along the abandoned meander of the "Chavée"

(Fig. 9.6). The several m-thick basal stratified fine sands become more clayey upwards and end in a thin settling facies, bearing witness to a finishing phase of water flow at this level. Small sandy channels within this unit indicate temporary weak resumption of flow. Except for two dates pointing very locally to MIS 7 at the base of the 1-m-thick flowstone, multiple U/Th dating of the stalagmitic complex yielded a consistent set of ages encompassing the whole marine isotopic stage 5 (~128–70 ka) (Quinif 1991). The colder substages 5.2 and 5.4 are identified by variations in

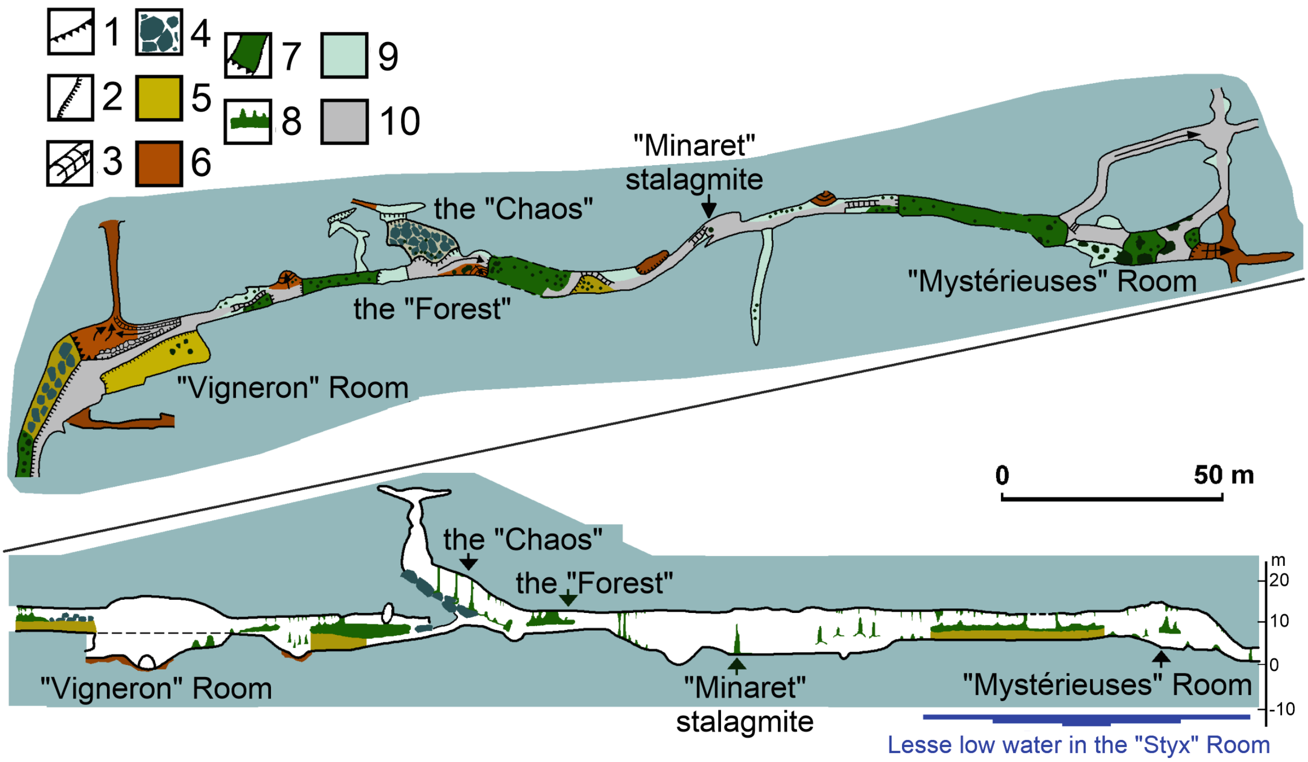

Fig. 9.5 Map (*top*) and longitudinal section (*bottom*) of the "Verviétois" gallery in the Han Cave (the "Trou du Salpêtre" swallow hole is on the *left*, see Fig. 9.3). *1* Escarpment >5 m. *2* Escarpment <5 m. *3* Slope of the ground. *4* Collapsed blocks. *5* Detrital sediment accumulation. *6* Loams deposited during recent high floods. *7* Flowstone. *8* Flowstone and stalagmites in section *9* Limestone bedrock. *10* Touristic path. The successive sections of thick flowstone are at the same elevation and systematically cap a detrital sequence. The deepened parts of the gallery result from either collapses between two superposed karstic levels (e.g. the "Vigneron" room) or decanting into lower voids

the speleothem growth rate without interlayered sedimentation (Quinif and Bastin 1994). The underlying sands and clays are thus attributed to MIS 6.

9.3.2.2 The "Petites Fontaines" Gallery and the Lower Filling

The "Petites Fontaines" is a small dead-end gallery lying a few metres above the current low water level of the underground Lesse, near the exit of the river at "Trou de Han" (Fig. 9.7a). Though at a lower level, the "Petites Fontaines" displays a partial filling fairly similar to that observed in the "Verviétois" gallery, again superposing thick speleothems over several metres of detritic material (Fig. 9.7b) (Blockmans et al. 1999). Here, the basal unit is made of thinly layered clays locally interrupted by centimetric sand layers, evidencing lake deposition occasionally disturbed by temporary water flow. The sedimentological analysis of these deposits assigned them to the Late Glacial (Blockmans et al. 1999), which is confirmed by the 8–9 ka ages of charcoal found at the base of the overlying flowstone (Fig. 9.8). We thus find the same sedimentary sequence in the "Verviétois" and "Petites Fontaines" galleries, except that they refer to two successive glacial–interglacial cycles. Detrital sediments are accumulated under quiet water flow to lake conditions during a cold period before being sealed by speleothems that develop in the temperate conditions of the next interglacial. This scheme, also recognized in Remouchamps (see Chap. 8), may be envisioned within the frame of the biorhexistatic theory of Erhart (1967). In this view, speleothem growth is the subterranean counterpart of soil development at the surface under the chemically driven biostatic equilibrium conditions of interglacials (assuming no tectonic interference), whereas accumulation of river sediments in the cave is the subterranean response to their increased erosion at the surface

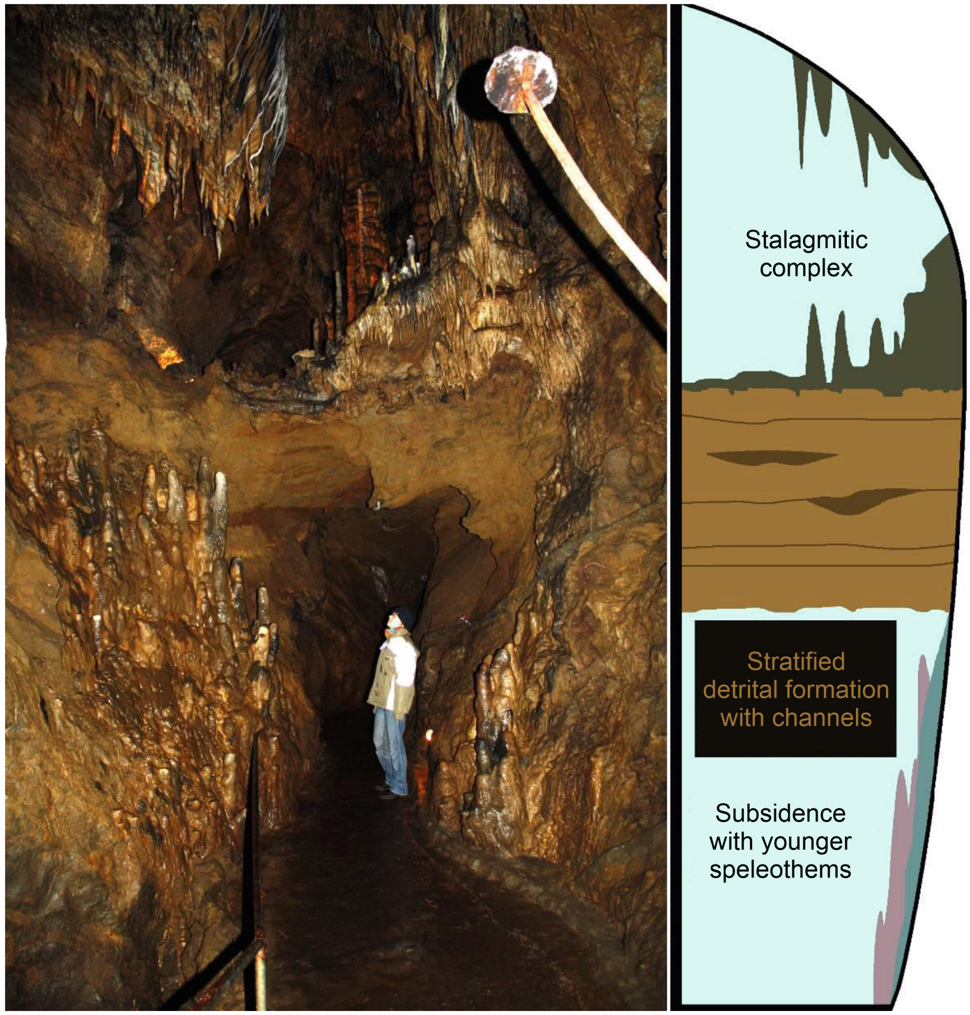

Fig. 9.6 View of the filling in the "Verviétois" gallery observed from a low level caused by subsidence into a lower void. This event may be dated thanks to the speleothems that grow on the flank of the collapse. The flowstone overlying the detrital sequence is dated to marine isotopic stage 5, defining a minimum age of the sediment accumulation

during the mechanically driven rhexistatic episodes induced by the cold periods, which act here as perturbations of the biorhexistatic cycle.

9.3.2.3 The "Dôme" Room

Large collapse rooms are a characteristic feature of the karstic system of Han-sur-Lesse. Most of them are structurally controlled. With the exception of the "Vigneron" room, which results from the collapse of the roof of a lower level, connecting it with the higher lying gallery (Fig. 9.5), they develop in relation with geological discontinuities such as faults, joints, or anticlinal hinges, the initial voids enlarging mainly in the vertical direction by successive breakdowns along bedding planes. In several rooms of the lower level (e.g. the "Dôme", "Antiparos", "Cornet", "Sinanthropes", and "Pentecôte" rooms), the cones of fallen blocks are soaked by the underground water flow.

The "Dôme" room is a representative example of the structure and morphology of such voids (Quinif and Bastin 1987; Fig. 9.9). In its eastern part, it developed within the very brittle argillaceous limestones of the Flohimont Member. In the west, the room is limited by a ~N350°E thrust fault and the associated overturned anticline (Delvaux de Fenffe 1985; Fig. 9.10). Breakdown progression and enlargement of the room occur in the southward direction, up-dip of the stratification, while the Lesse soaks the basis of the large cone of fallen blocks to the N and NE.

9.4 The Subterranean Water Systems

Since 2004, the hydrogeology of the Boine Massif and the Han-sur-Lesse karstic system has been intensively studied (Bonniver 2011; Poulain et al. 2015; Dewaide et al. 2016).

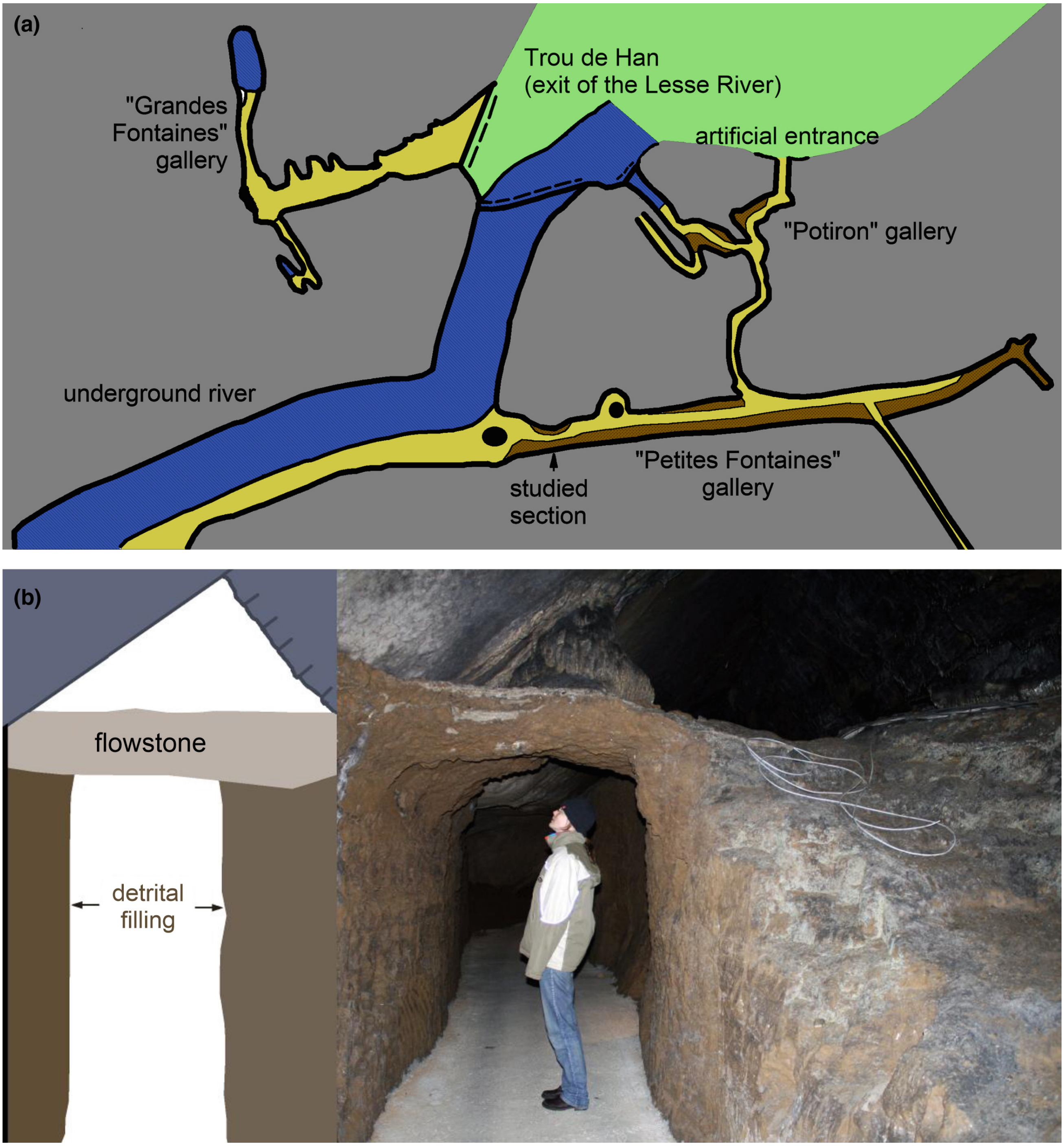

Fig. 9.7 **a** Plan view of the “Petites Fontaines” gallery in its environment close to the exit of the Han Cave. The sedimentary filling appears in *brown*. **b** Sedimentary section observed in the gallery, showing the same superposition of detrital sediments and a thick flowstone also found in the “Verviétois” gallery. Paleoclimatically, this superposition evidences the succession of the cold and warm stages of a glacial–interglacial cycle

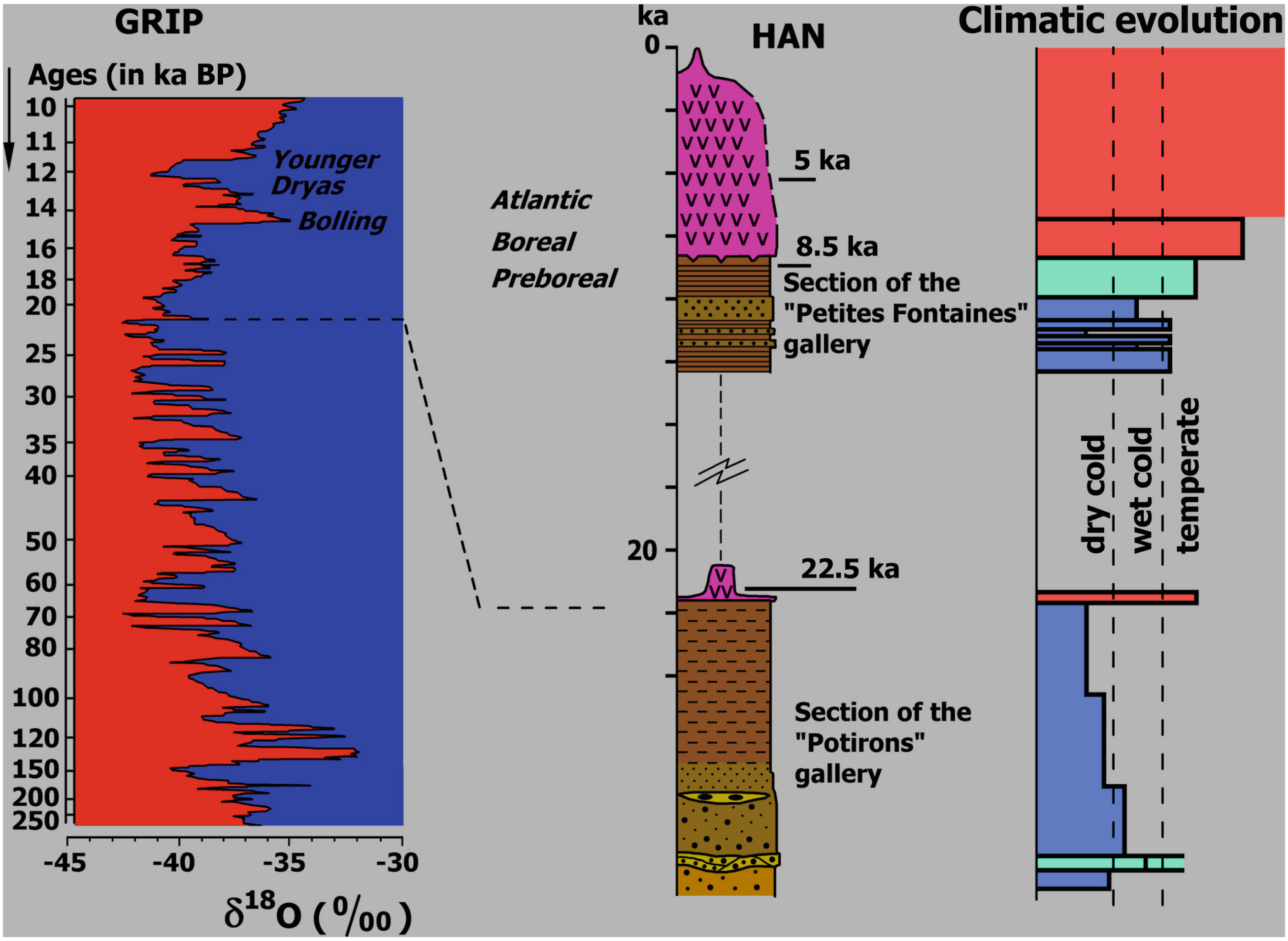

Fig. 9.8 Climatic interpretation of the filling of the "Petites Fontaines" gallery. The stratigraphic column shown in the *centre* is a composite of observations and results in the "Petites Fontaines" and the adjacent "Potirons" galleries. Speleothems are represented in *magenta*, silty (*dashed*) to clayey (*hatched*) sediments in *brown*, sands in *green brown*. The sediments of the "Petites Fontaines" gallery are stratigraphically higher than those of the "Potirons" gallery, both being located in time by dated overlying stalagmites ("Potirons") or flowstone ("Petites Fontaines"). Ages in ka BP are derived from U/Th and pollen analyses on speleothems and radiocarbon on charcoal in the upper fine sediments of the "Petites Fontaines". *Left* excerpt of the $\delta^{18}O$ curve of the GRIP ice core in Greenland sets the climatic background of the sedimentary sequence at Han. The stalagmite developed over the "Potirons" sediments may be linked to a warming peak. *Right* climatic interpretation of the data, evidencing oscillations from dry cold through wet cold to temperate conditions. The *red* colour is for $CaCO_3$ precipitation, *middle blue* for river deposition, *light blue* for quiet water deposition

For example, the groundwater table was monitored across the Boine Massif between 2004 and 2011 and several tracer tests were conducted.

9.4.1 Structure of the Aquifer

Results clearly show that the Boine massif is subdivided in three hydrogeological units that are separated by the ~20 m thick argillaceous limestones and shales of the Flohimont Member, located at the base of the Fromelennes Formation (Figs. 9.2 and 9.11). The three units are the «Trou des crevés (CR)—Père Noël (PN)—Réseau sud (RS)» system (Unit I), the «Lesse souterraine (DA to SA)» system (Unit II), and the «Trou de Han (TH)» system (Unit III), which is the downstream collecting unit of the whole underground system and goes to the "Trou de Han" resurgence (Fig. 9.11). Unit III is limited to the north by the shales of the Nismes Formation.

The piezometric maps (Fig. 9.12) show that, in low water conditions, the water level of Unit I is 2–3 m higher than that of Unit II. The groundwater gradient is ~0.3% to the north in Unit I, against ~0.1% in Unit II. These low gradients confirm the high permeability of the Boine massif in link with its intense karstification. By contrast, in high water conditions, the water level in Unit II is higher than in Unit I,

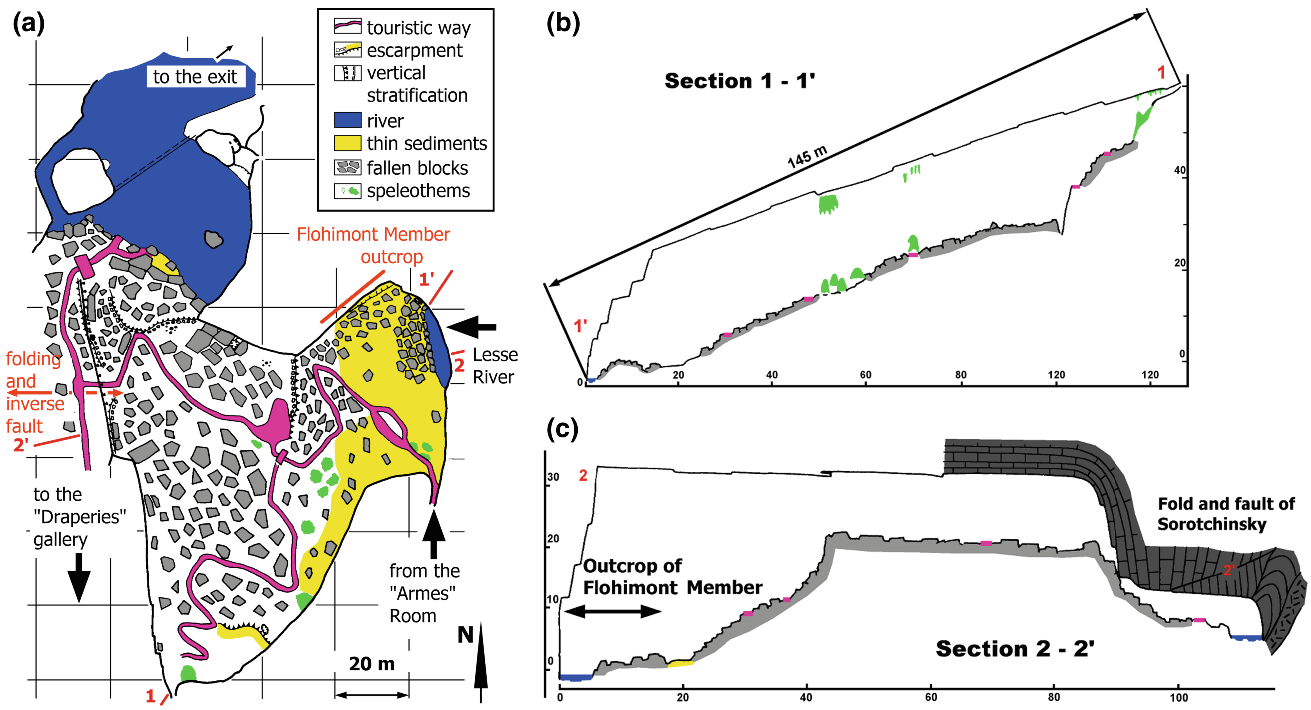

Fig. 9.9 **a** Geomorphic map of the "Dôme" room. This room is located between the argillaceous limestones of the Flohimont Member in the east and the fold and thrust fault of Sorotchinsky in the west (see Fig. 9.2). In the east, blocky accumulation on the sand beach along the river results from a breakdown of Flohimont limestones in 1984. **b** NE–SW section of the "Dôme" Room, following the dip of the strata (see location on the map). **c** ENE–WSW section of the "Dôme" Room, showing the outcrop zone of the Flohimont Member and the geometry of the fold and thrust fault of Sorotchinsky, which control the room position and development (see location on the map)

because of the reactivation of the dry meander in flood events with river discharges exceeding the 25 m^3/s capacity of the "Gouffre de Belvaux" swallow hole. In such events, the subaerial Lesse section acts as an infiltrating river that recharges the aquifer. Low water conditions are by far predominant, as the aquifer is generally drained in less than three weeks after a flooding event. In summer time, the contribution of the Boine massif aquifer to the Lesse base flow is almost nil.

9.4.2 Dynamics of the Underground Lesse

Four tracer tests were performed in various hydrological conditions encompassing discharges between 0.9 and 19.5 m^3/s. The shape of the breakthrough curves shows that transport is mainly by advection (Fig. 9.13). Dispersion effects are low, even if slightly higher in low discharge conditions, and transient storage effects remain poor regardless of flow conditions.

First arrival times of the tracer at the measurement sites (either the "Trou de Han" resurgence or the "Salle d'Armes" room) range from 2.2 h (for $Q = 19.5\ m^3/s$) to 17 h (for $Q = 0.9\ m^3/s$) after injection at the Belvaux swallow hole, corresponding to maximum and minimum flow velocities of 910 and 130 m/h, respectively. Based on the evolution of transfer times with discharge, Fig. 9.14 shows that mean flow velocity increases linearly for discharges up to $\sim 10\ m^3/s$, then tends to stabilize for discharges over 10 m^3/s. This suggests that the understanding of sedimentation processes within the cave should take account of a maximum underground flow velocity of ~ 1 km/h.

The underground Lesse consists of a succession of free surface river and siphon segments (see Fig. 9.3). In order to test how flow velocity and transport process behave in these successive sections, a spatial multisampling tracer test was performed during low water conditions ($Q_{Lesse} = 0.7\ m^3/s$). The obtained breakthrough curves confirm that advection is the main transport process, especially in the open surface section, while dispersion and, to a lesser extent, transient

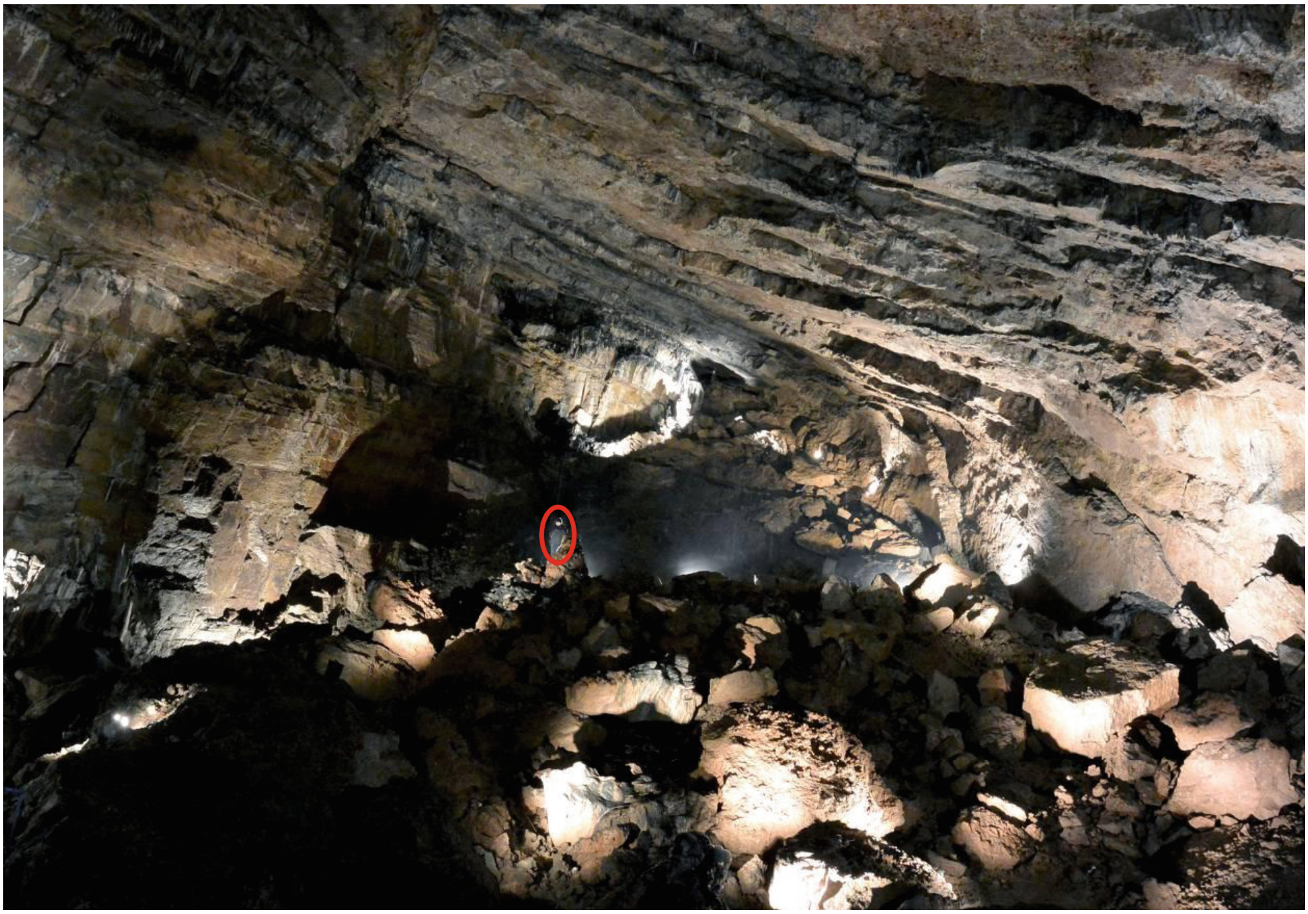

Fig. 9.10 View of the “Dôme” Room, taken from the middle of the room and looking north. People *circled in red* for scale. The stratification of the Fromelennes limestones, which dip gently toward the Sorotchinsky fold hinge in the *right*, is clearly visible

storage occur mainly in the flooded sections (Fig. 9.15). Based on these experimental data, the Lesse karstic network was modelled with the OTIS software (Dewaide et al. 2016; Fig. 9.16). The volume of the “Gouffre de Belvaux” siphon has been estimated to 15,400 m^3 (or 57 m^3/m of section), from which 35% are used as transient storage zone (Fig. 9.16, Box 2). The volume of the second siphon, downstream of the underground Lesse, has been estimated to 31,200 m^3 (or 52 m^3/m of section), from which 11% are used as transient storage zone (Fig. 9.16, Box 4). These volumes are thrice that measured and calculated in the free surface water section (18 m^3/m of section, no transient storage).

9.4.3 Dynamics of the “Trou Des Crevés—Père Noël—Réseau Sud” Network

Two tracer tests were conducted in the system of Unit I. In the first test, fluorescein was injected in the “Trou des Crevés” and a monitoring station was installed in the “Père Noël” cave. In the second test, fluorescein was injected in the “Père Noël” cave and the monitoring station was installed at the “Réseau sud” outlet (Fig. 9.3). The breakthrough curve observed in the “Père Noël” (Fig. 9.17), clearly shows that the transport process within the “Trou des Crevés” and “Père Noël” caves is essentially advective, with low dispersion and almost no transient storage effect. First

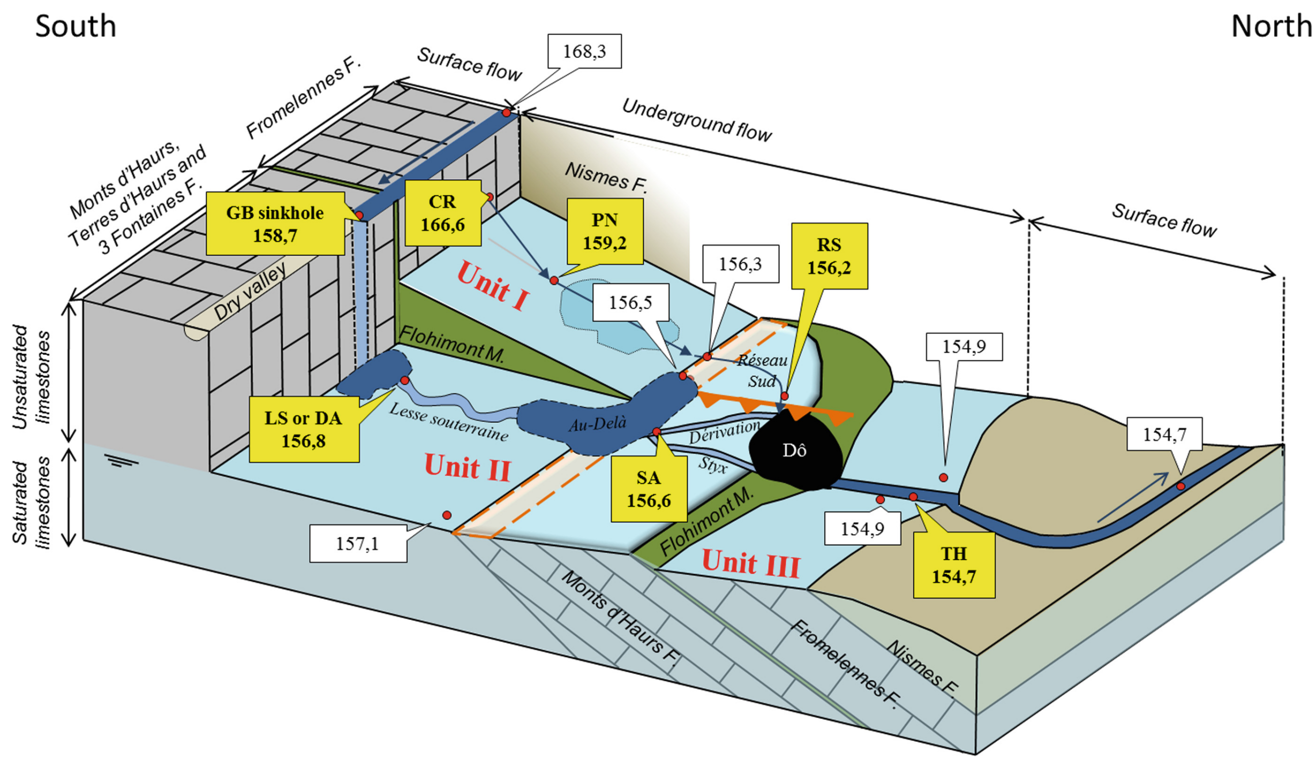

Fig. 9.11 Sketch of the hydrogeological units of the Han-sur-Lesse karstic system, evidencing the role of the argillaceous limestones and shales of the Flohimont Member as a barrier between these units. Water levels are indicated in m asl (modified after Bonniver 2011). *GB* "Gouffre de Belvaux". *LS or DA* "Lesse souterraine" or "Daniel Ameye". *SA* "Salle d'Armes". *TH* "Trou de Han". *CR* "Trou des Crevés". *PN* "Père Noël". *RS* "Réseau sud". *Dô* "Dôme room"

arrival of the tracer in the "Père Noël" was observed ~2.8 h after injection, corresponding to a maximum velocity of 115 m/h. An OTIS model run showed a homogeneous narrow conduit (Fig. 9.18). The breakthrough curve observed in the "Réseau sud" shows a completely different transport process downflow of the "Père Noël" (Fig. 9.19), with strong dispersion and transient storage effect. Observed 75 h after injection in the "Père Noël" cave, the tracer's first arrival indicates a maximum velocity of 13 m/h. Results of an OTIS run point to a ~25 m^2 flow section and a bigger storage zone section of ~40 m^2 (Fig. 9.20).

9.5 Speleogenesis

9.5.1 Ghost-Rock Karstification

This new karstogenetic theory suggests that the origin of many cavities is not directly linked to the present flow dynamics (Dubois et al. 2014; Quinif et al. 2014). The classical view about cave initiation considers that it begins with the enlargement of fissures by chemical dissolution of bedrock, followed by geometrical structuration of the growing system according to the laws of irreversible system dynamics. The fundamental assumption therein is that all products of chemical dissolution, i.e. not only the dissolved species (ions, colloids, molecules) but also the solid residue (e.g. clay, sparitic calcite and quartz grains) leave the system together in a process we call "karstogenesis by total removal".

However, a substantial body of evidence from paleokarsts in the Carboniferous limestones of the Hainaut Province, W Belgium, has shown that, in the first stage of karstogenesis, only the dissolved species actually leave the system. This typically happens during a biostatic stage (Erhart 1967), when flat landscapes provide no significant hydrodynamic potential. Limited water circulation in the phreatic zone does not allow for exportation of the solid particles, which stay in place and constitute a porous residual alterite of low density impeding the formation of voids in the rock. Such alterite

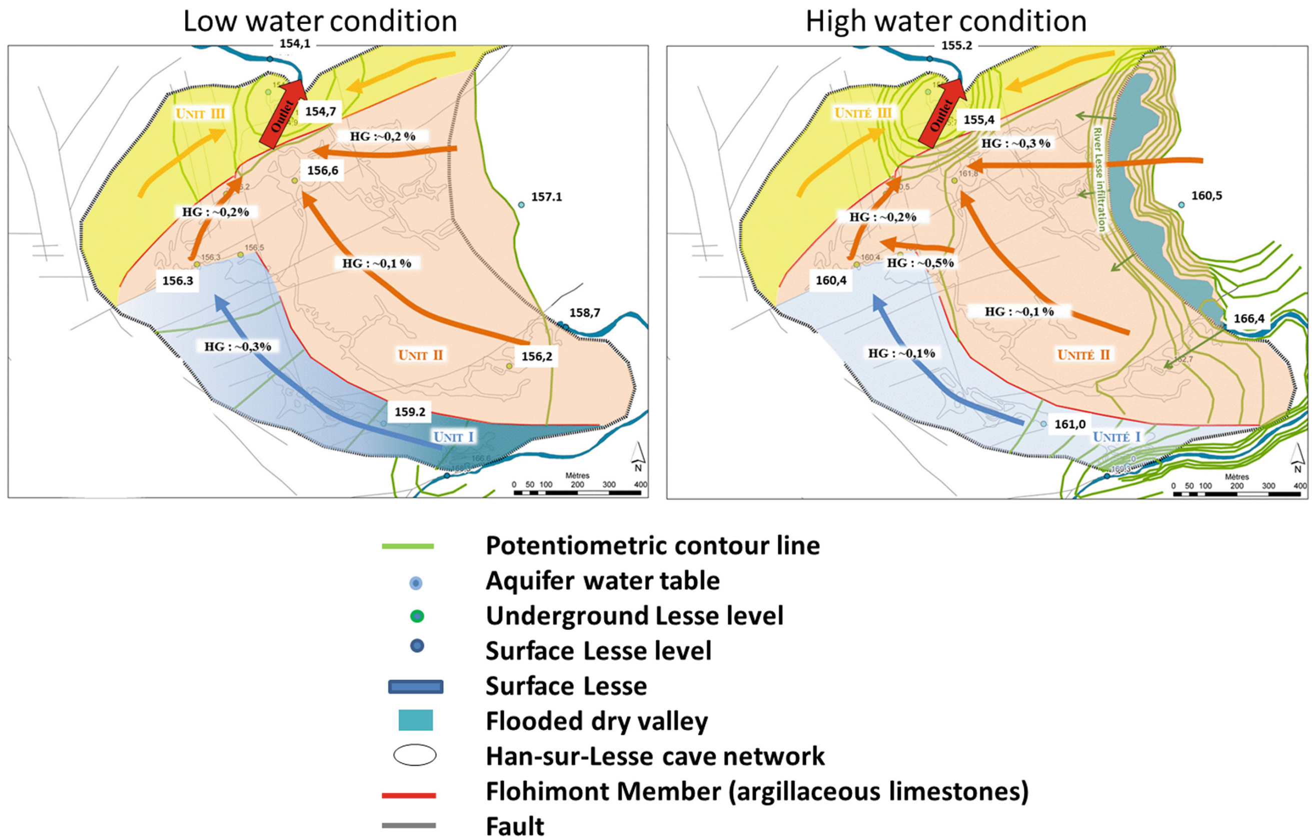

Fig. 9.12 Piezometric maps of the Boine massif at low (*left*) and high (*right*) water conditions

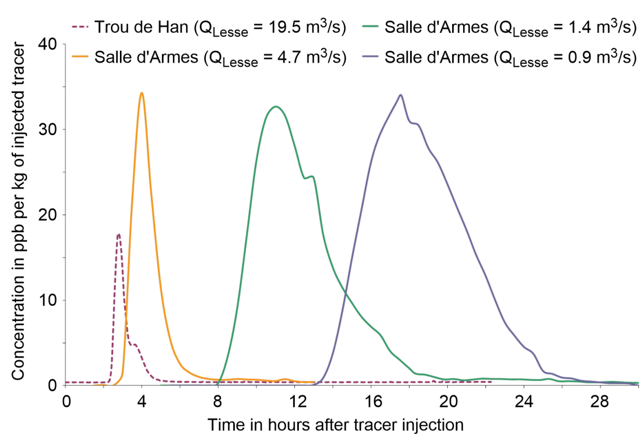

Fig. 9.13 Tracer tests performed in hydrogeological Unit II of the Han karstic system (injection at "Gouffre de Belvaux", measurement at "Salle d'Armes" or "Trou de Han"). Breakthrough curves for different hydrological conditions

bodies within the fresh massif are named ghost rocks and generally form networks whose overall geometry mimics the initial flow pathways through the fresh rock. They thus typically feature alterite chimneys starting from the top and going deep into the limestone massif. Other such bodies are pseudoendokarstic forms totally included in the bedrock, whose shapes may resemble never emptied galleries (Fig. 9.21). The porous, more or less soft material of the residual alterite is made of sparitic calcite grains derived from fossils, calcite veins or clasts, and less soluble to insoluble minerals (clays, quartz). Many ghost rock occurrences exist in western Belgium because this low-elevation region has not undergone any significant change in hydrodynamic potential since the time of ghost-rock karstification. However, if this potential increases for geodynamic (regional uplift, marine regression) or any other reasons (for instance, a climatically induced turn toward rhexistasy), the enhanced underground water circulation, which is still located mainly in the readily infiltrated alterite of the ghost rock network, will remove this soft material from vadose and epiphreatic zones that progressively deepen with uplift, thus opening the cavities formerly filled by the alterite and creating caves in the classical meaning of the term. This erosion process obviously allows then the development of typical

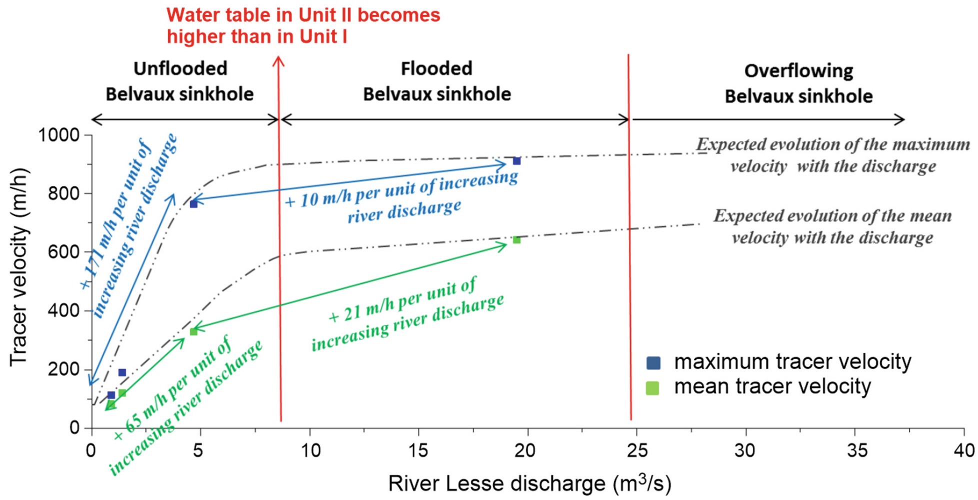

Fig. 9.14 Tracer tests performed in hydrogeological Unit II of the Han karstic system (injection at "Gouffre de Belvaux", measurement at "Salle d'Armes" or "Trou de Han"). Evolution of flow velocities against discharge of the underground Lesse

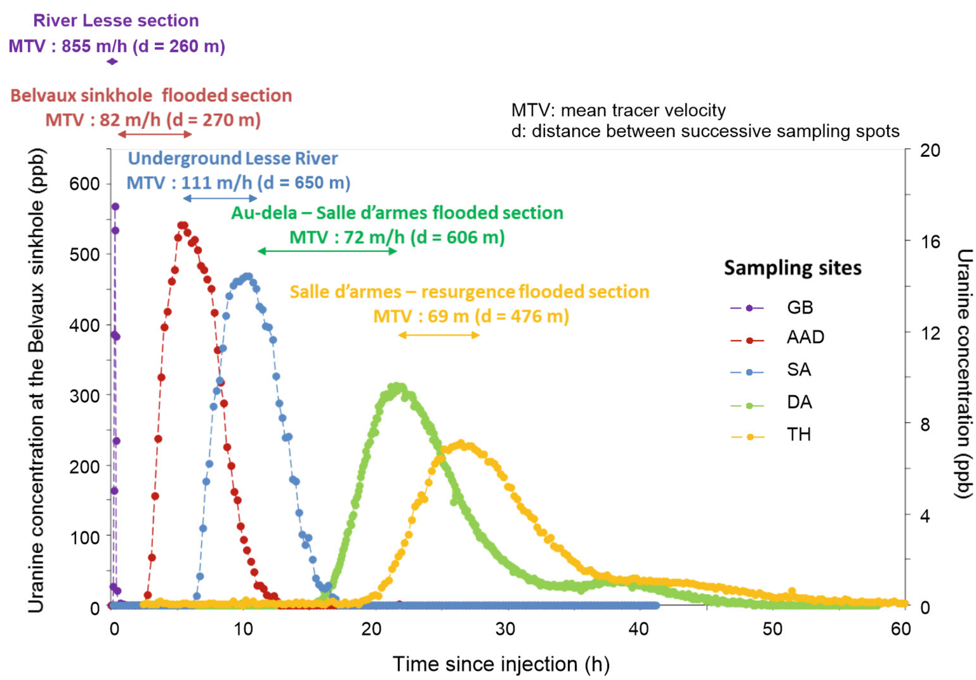

Fig. 9.15 Tracer tests performed in hydrogeological Unit II of the Han karstic system (injection at "Gouffre de Belvaux", measurement at "Trou de Han"). Spatial evolution of the breakthrough curves and flow velocities along the successive sections of the underground Lesse River at low water conditions (Q_{Lesse} = 0.7 m^3/s) (see Figs. 9.3 and 9.11 for location and Fig. 9.11 for site abbreviations)

water flow forms such as potholes, scallops, meander niches, or overdeepenings, whereas other microforms like, e.g. cupolas have also been found in a ghost-rock environment (Quinif 2010; Dubois et al. 2014). In brief, the ghost-rock karstification paradigm highlights that the chemical dissolution and mechanical removal stages of limestone erosion may be disconnected but it makes no prediction about their isolated or common occurrence in each particular case.

9.5.2 Ghost Rocks in the Han System

Finding ghost-rock evidence after large underground flows have travelled through a cave is difficult because the alterite has been more or less completely removed by the hypogeal river. Traces are found only in sheltered areas such as, for example, the highest part of the Antiparos Room of the Han Cave, where the residual alterite of weathered strata has been

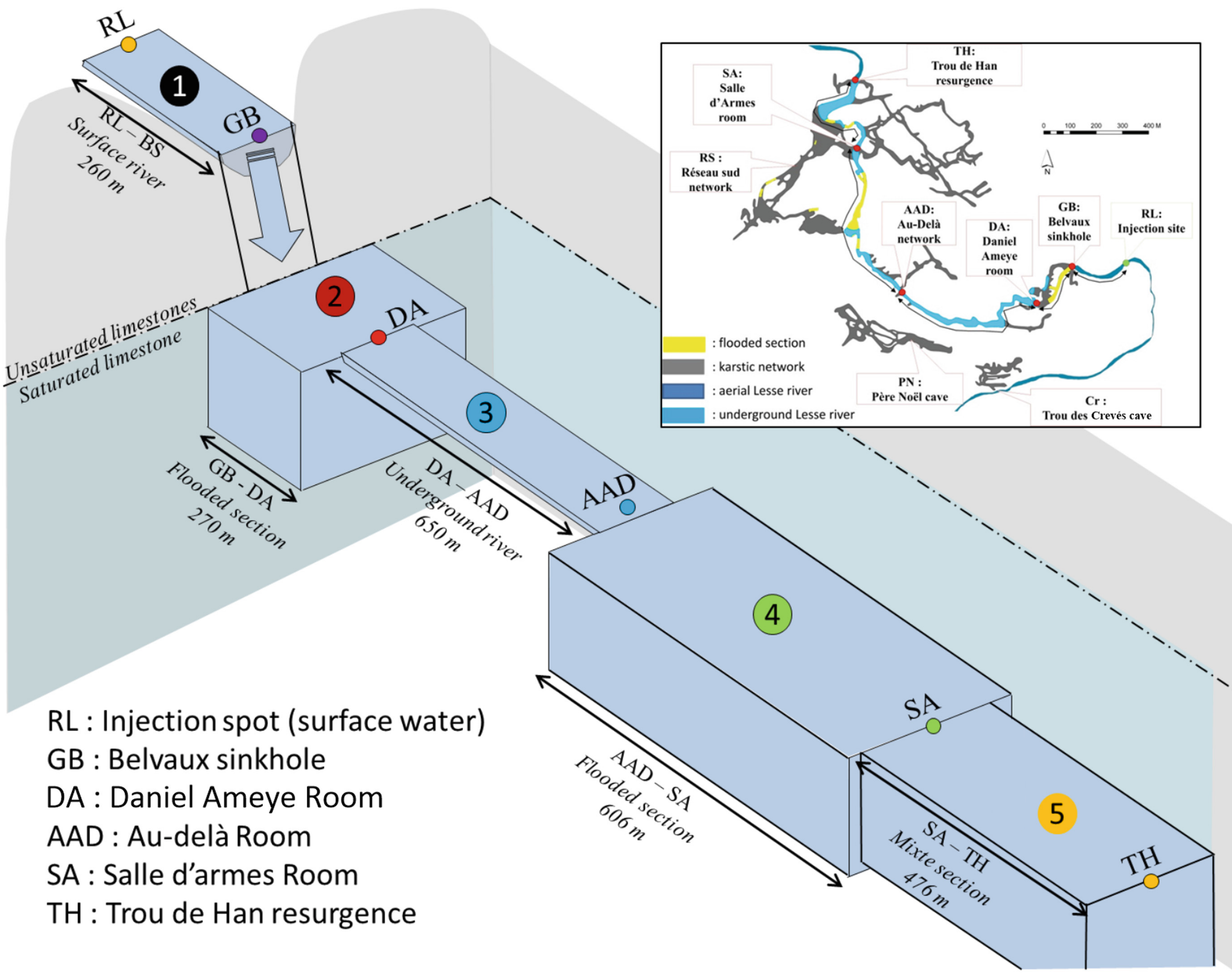

Fig. 9.16 Flow section dimensions along hydrogeological Unit II of the Han karstic system estimated from an OTIS modelling based on the experimental data of the tracer tests (see text for explanation)

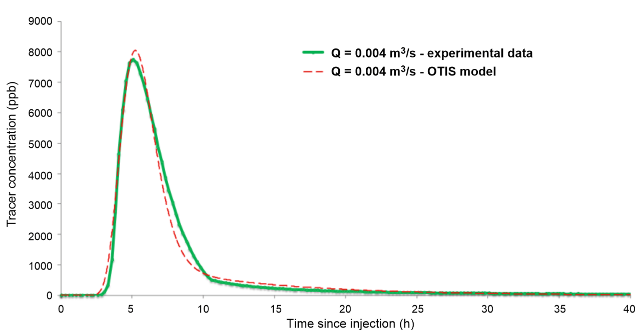

Fig. 9.17 Breakthrough curve obtained from a tracer test performed in the first section of hydrogeological Unit I of the Han karstic system (injection at "Trou des Crevés", measurement at "Père Noël") and best fit OTIS simulation

exposed by the collapse of blocks (Fig. 9.22). This suggests that ghost-rock karstification was indeed the first stage in the evolution of the Han karstic system. In this view, we admit that the structurally controlled geometry of the system, which follows N60°E and N150°E joint directions inherited from Mesozoic and Early Cenozoic extensional tectonic episodes (Fig. 9.3), was foreshadowed by a ghost-rock network that was formed during the Cretaceous and probably also the Paleogene. The warm humid climates of the time in the Han area allowed intense chemical weathering to create a system of "pseudoendokarstic" features preserving a residual alterite in the phreatic zone because the flattened topography and the subsequent absence of hydrodynamic energy robbed close-to-zero water flow in this zone of all mechanical erosive power.

It was only when rivers began to respond by active incision to the Ardenne uplift from Pliocene times onward that a new hydrodynamic potential was created and more efficient groundwater circulation became capable of removing the alterite from the pseudoendokarsts and opening the caves. This was a multistage process progressing downward

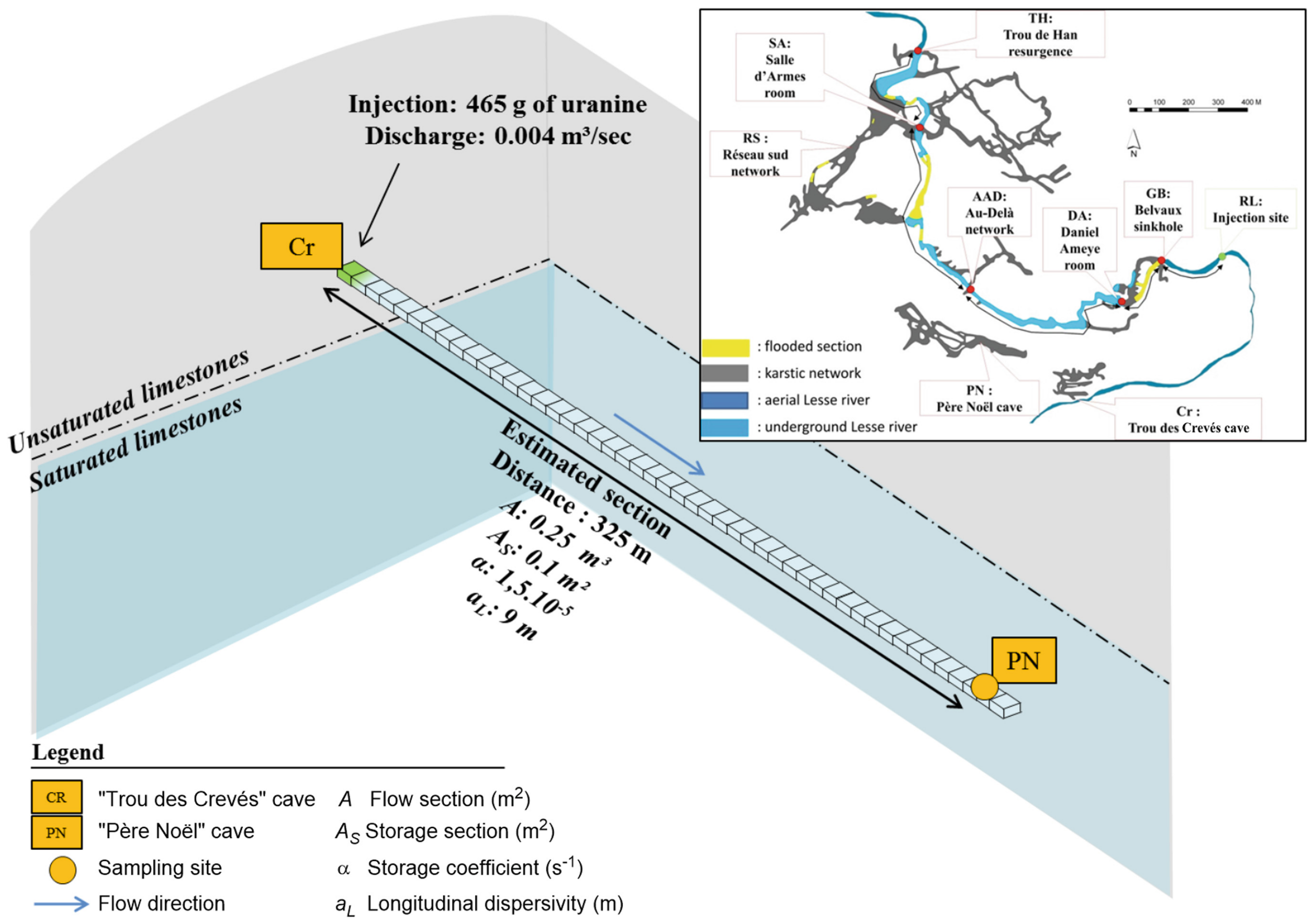

Fig. 9.18 Flow section dimensions along the first section of hydrogeological Unit I of the Han karstic system ("Trou des Crevés"—"Père Noël") estimated from an OTIS modelling based on tracer test data (see text for explanation)

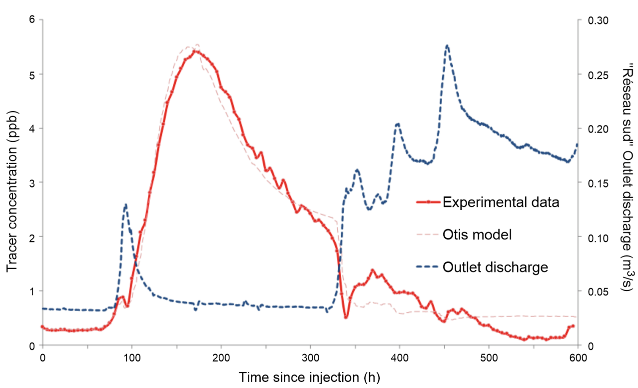

Fig. 9.19 Breakthrough curve obtained from a tracer test performed in the downstream section of hydrogeological Unit I of the Han karstic system (injection at "Père Noël", measurement at "Réseau sud") compared to the best fit OTIS simulation and measured discharge at the outlet of the system

and emptying successive karstic levels at the pace of valley downcutting. Currently, seepage and the underground course of the Lesse continue to shape the cave.

9.5.3 Consequences of Ghost-Rock Karstification

The most important implication of the Han system origin by ghost-rock karstification is that its overall structure is inherited. The Quaternary caves and galleries and the present subterranean water circulation follow a network of channels created in a remote past, when the Cretaceous and Paleogene climate and topography favoured the development of pseudoendokarsts. Therefore, the directions of the galleries are mostly dictated by those of past tectonic episodes, in this case Mesozoic and Early Cenozoic extensional phases. As the location of the present caves depends on that of the zones where ghost rocks developed, the pre-existing system structure has determined the present hydrogeology much more than the opposite. Sedimentological studies have shown that separate connections exist between the "Trou des Crevés"—"Père Noël"—"Réseau sud" sectors (Unit I) on one hand and the "Lesse souterraine"—"Salle d'Armes"—"Dôme Room" axis and the "Trou d'Enfaule" axis on the other hand.

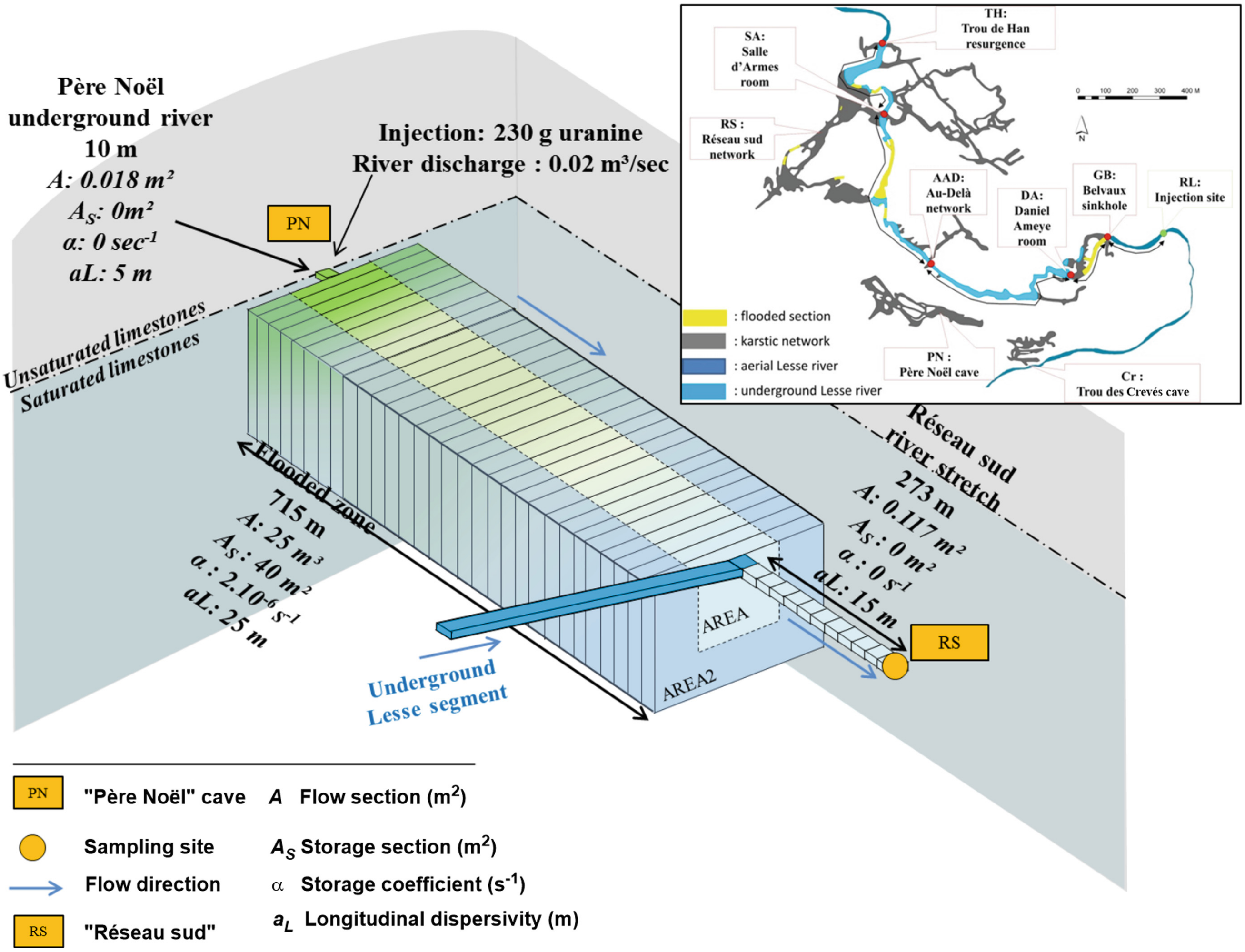

Fig. 9.20 Flow section dimensions along the downstream section of hydrogeological Unit I of the Han karstic system ("Père Noël"—"Réseau sud") estimated from an OTIS modelling based on tracer test data (see text for explanation)

9.6 Conclusion

In this brief overview of the karstic system of Han-sur-Lesse, we showed that this system, developed in Givetian limestones, is the archetype of a subterranean meander cutoff. Secondly, we emphasized how the underground features, their geometry, and the analysis of speleothems and sediments allow for the reconstruction of past environmental and, especially, climatic conditions. Three distinct hydrogeological units have been distinguished, separated by the less permeable shales and argillaceous limestones of the Flohimont Member. While water flow and transport processes are essentially advective in Unit II (with velocities up to ~0.9 km/h in the "Lesse souterraine" system) and the first section of Unit I ("Trou des Crevés"—"Père Noël" connection), dispersion and important transient storage effects in the latter unit between "Père Noël" and "Réseau sud" suggest the existence of a large groundwater volume so far undiscovered.

Finally, scarce but unquestionable traces of ghost rocks in the Han Cave allowed us to reconstruct the history of the karstic system of Han-sur-Lesse within the ghost-rock karstification frame of karstogenesis. This implies recognizing the long geological past of the system, which was initiated by ghost rock formation under warm humid climate and low topography conditions of the Late Mesozoic and Early Cenozoic before being freed from residual alterite and acquiring its present cave status in relation with Plio-Quaternary valley downcutting through the uplifting Ardenne massif. Unknown local conditions during the Mesozoic may explain that ghost rocks (and their evolution into modern caves) intensely developed in the Boine massif but are almost absent in the nearby Resteigne limestone massif. Pre-existence of ghost rock probably also determined the vertical position of the karstic levels, which thus would not have the usually assumed straightforward correlation with river terrace levels. All this attests the high geomorphic and

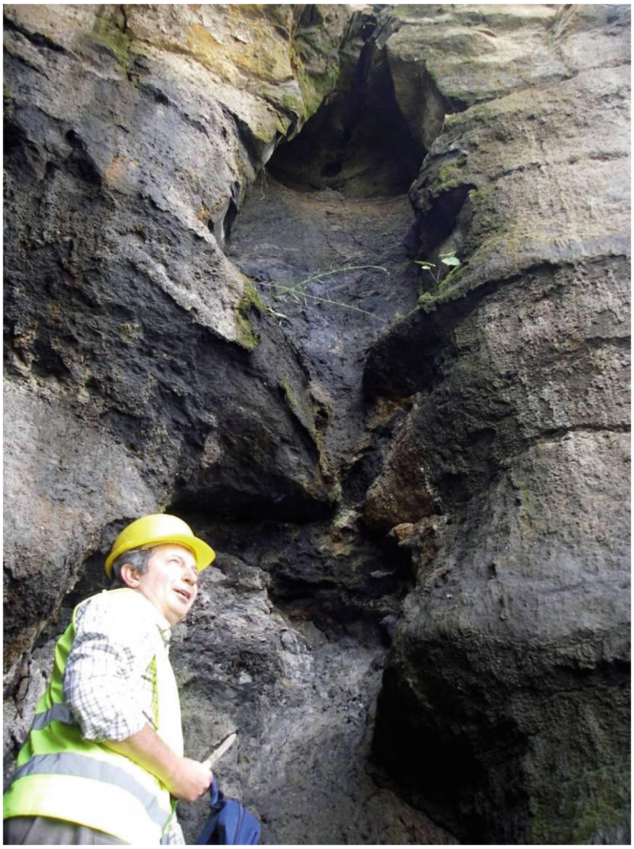

Fig. 9.21 Typical pseudoendokarst feature in the Lower Carboniferous limestones of the Clypot quarry, Soignies, W Belgium. The crumbly matter within the cavity is not detrital filling but the residual alterite of a ghost rock after partial dissolution of the limestone bedrock. This kind of karst results from chemical action alone, without mechanical erosion component, and occurred under biostatic conditions of warm humid climates and lowland topography

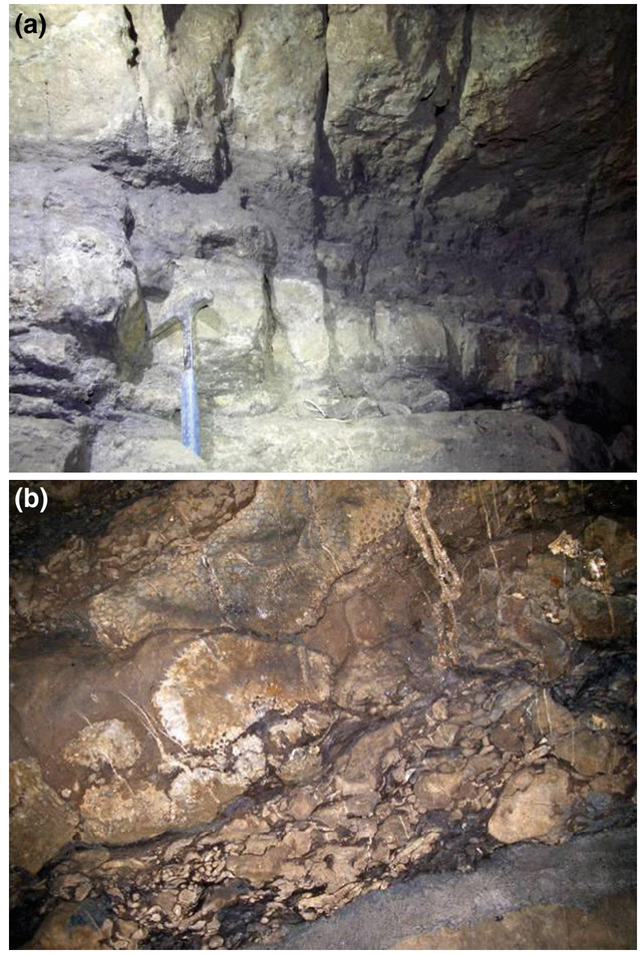

Fig. 9.22 Ghost-rocks in the Han Cave. **a** Limestone layer weathered to *violet-blue* residual alterite still preserving the original structures (hammer for scale). **b** Ghost-rock weathering of the micritic matrix, leaving the sparitic calcite of fossil stromatoporoids and corals intact (*photo* width ∼1 m)

karstic value of the Han-sur-Lesse site and thus amply justifies its exploitation as a highly visited (∼0.5 million visitors per year) touristic site where a pedagogic approach of the local natural wealth is cleverly combined with adapted leisure activities.

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