Reconstructing fluvial incision rates based upon palaeo-water tables in Chalk karst networks along the Seine valley (Normandy, Northern France)

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Introduction

Determining rates of landscape evolution, river incision and continental uplift are important prerequisites for modelling landscape change over 10^2-10^6 year timescales. However, quantitative estimates of landscape change are often hampered by the lack of datable material or preserved ancient deposits, especially in areas of rapid erosion or weathering. Cave systems are useful tools for reconstructing the landscape evolution because they can record the elevation of paleo-water tables, which are controlled by fluvial base levels in many karst areas (Palmer, 1987). Moreover, cave deposits can be accurately dated using a variety of techniques, notably uranium series (Bischoff *et al.,* 1988), palaeomagnetic dating (Sasowsky *et al.,* 1995) and burial ($^{26}Al/^{10}Be$) dating (Granger *et al.,* 2001). Cave systems also have the benefit that they, and the deposits they contain, can be preserved over long timescales where surface landforms such as river terraces may be degraded by weathering and erosion. Therefore, mapping and dating cave systems can be used to deduce valleys incision rates and continental uplift (Farrant *et al.,* 1995; Granger *et al.,* 2001; Rossi *et al.,* 2016). In this paper, the landscape evolution of the western Paris Basin (France) was investigated through the systematic investigation of relict caves exposed in the sides of the lower Seine River valley around Rouen (Eastern Normandy).

Cave passage morphology can be used to determine palaeo-water table by identifying the transition from a vadose to a phreatic morphology (Palmer, 1987, 1991; Atkinson and Rowe, 1992). Caves formed above the water table are typified by steeply descending narrow canyons and shafts, whilst those formed beneath the water table are characterized by rounded conduits, often with a looping profile (Lauritzen 1985; Ford and Williams, 2007). In a phreatic environment, the palaeo-water table can also be identified from the elevation of concordant phreatic loop crests and phreatic avens and lifts, or where horizontal water table passages cut across dipping strata. However, true water table caves are relatively uncommon (Gabrovšek *et al.,* 2014).

In carbonate terrains, as rivers incise their valleys, the corresponding drop in base level causes the water table to fall and leads to the subsequent abandonment of shallow-phreatic conduit networks, creating new conduit networks at lower elevations (Ford and Williams, 2007; Audra and Palmer, 2013). During phases of static base level, or when cave formation is restricted to certain climatically constrained time periods, the main active conduits tend to concentrate at similar elevations, resulting in a distinct cave 'level' or still-stand (Ford and Williams, 2007). Over time, this process leaves a stacked relict cave levels preserved above the modern active conduit system, creating an inverted passage stratigraphy comparable to that of river terraces (Sasowsky *et al.,* 1995; Stock *et al.,* 2005).

Cave levels can also develop due to lithological heterogeneity. In heterogeneous carbonate sequences such as the Upper Cretaceous Chalk of northern France, caves may preferentially develop along restricted stratigraphic discontinuities or 'inception horizons' particularly susceptible to dissolution within the limestone succession (Lowe, 2000). This may occur even in a dynamic situation with river incision followed by base-level lowering (Palmer, 1987). However, even if passage inception is influenced by lithology, subsequent passage enlargement either upwards in a phreatic environment or down-cutting in a vadose system, or due to sediment aggradation, is typically independent of lithology or structure (Filipponi *et al.,* 2009; Sauro *et al.,* 2013).

Many studies have related the genesis of relict cave levels and their subsequent abandonment to base-level dynamics, driven by river incision in fluvial valleys or sea-level oscillations in coastal areas (Piccini and Landelli 2011; Audra and Palmer, 2013; Calvet *et al.,* 2015; Columbu *et al.,* 2015; Nehme *et al.,* 2016; Harmand *et al.,* 2017; Pennos *et al.,* 2019; Bella *et al.,* 2019). The rate of river incision is influenced by several variables. These include climatic forcing, affecting river discharge and sediment transport, geomorphological evolution as well as geological factors such as lithology, structure and tectonic uplift. Quaternary climatic variations may increase or reduce discharge, affecting sediment flux in fluvial catchments, either due to periglacial/glacial processes in high latitudes or increased rainfall in tropical areas, along with vegetation cover evolution (bio-rhexistasy). This may trigger episodic valley aggradation, causing hiatuses in base-level lowering, or even base-level rise (Laureano *et al.,* 2016). The latter is most likely in karst conduit systems developed at or close to the water table adjacent to major rivers (Granger *et al.,* 1991; Constantin *et al.,* 2001).

In high-latitude areas where periglacial/glacial processes are the dominant influence on Quaternary valley incision, climatically-forced incision and aggradation (Aranburu *et al.,* 2014) influences the development of cave levels. Each phase of fluvial incision and base-level fall increased the hydraulic gradient in the chalk aquifer, causing a reorganization of the conduit system (Harmand *et al.,* 2017). These respond to base-level fall by the development of new phreatic conduits graded to the lower base-level, and/or by vadose incision of the existing passage. The type of response is mainly influenced by local factors (lithology, fracture density, geological structure) and regional factors such as the magnitude of the base-level fall. In the Seine valley, the Chalk has a relative high fracture density (0.1-0.3 m fracture spacing), characterized by frequent regional inception horizons including flint bands, marl seams and hardgrounds, and numerous closely-spaced vertical to horizontal joints (Duperret *et al.,* 2012; Mortimore, 2018). The availability of many potential inception horizons and flow pathways coupled with relatively small magnitude falls in base-level, favors the development of low-gradient, shallow phreatic or epiphreatic conduits close to the contemporaneous base-level rather than a deep vadose incision. The studied caves in the Seine valley are relatively simple, very low gradient phreatic or epi-phreatic branch-work and maze systems fed by recharge from the surrounding plateau, often via discrete sinks known locally as *bétoires,* with little documented vadose development other than shaft drains connecting to the plateau surface. There is no evidence of karst auto-captures across the meander necks.

When defining paleo-water tables from caves, consideration also needs to be given to possible modification of conduits following the main phase of speleogenesis, which may affect the elevation of the water table (Audra and Palmer, 2013). This may be due to sediment aggradation during a subsequent cold phase, or blockage of conduits by external factors (glaciers), or internal collapse or sediment deposition leading to a reorganization of the conduit network (Skoglund and Lauritzen, 2010). Fortunately, such changes can be identified from careful interpretation of cave passage morphology. Passage modification due to sediment aggradation, a process known as cave paragenesis (Renault, 1968) can be identified by several characteristic features including wall notches, roof pendants, anastomoses channels in roofs and phreatic canyons with upwards propagating meanders (Lauritzen and Lauritsen, 1995; Pasini, 2009; Farrant and Smart, 2011; Bella *et al.,* 2019).

To investigate the landscape evolution of the Normandy area, each of the relict caves exposed in the Seine valley was mapped along with detailed geomorphological investigations, passage morphology characterization and sedimentological observations. Ten speleothems and 144 cave sediment samples were collected for uranium series and palaeomagnetic dating to determine the minimum age of caves, the timing of sediment infill and passage abandonment. To create a robust age model constraining the rate of Seine valley incision, eight cave systems spanning a range of elevations 10-100 m above sea-level (asl) were dated.

By combining a detailed geomorphological assessment of each site with chronological evidence from uranium series and palaeomagnetic dating, a regional model for cave development in the Chalk was constructed, linked to the incision of the Seine River. From this, estimates for the rate of valley incision can be deduced. The estimated incision rate derived from this study is compared to the previously published incision velocities of the Seine and Somme rivers based on fluvial terrace sequences.

Geological setting: The Upper Normandy Plateau and the Seine valley

The Upper Normandy region in northern France (Figure 1A) comprises an extensive plateau developed at an elevation of ~100-200 m asl. This plateau is deeply incised by the Seine River, a major river system that drains much of northern France with a catchment area of ~76,000 km^2. The region has a temperate maritime climate, with mean monthly temperatures between 3 and 17 ºC, and 600-1100 mm precipitation.

Around 90% of the studied region is underlain by the Upper Cretaceous Chalk Group, a sequence of flinty coccolithic limestones up to 300 m thick deposited on the western margin of the Anglo-Paris basin (Lasseur *et al.,* 2009; Mortimore 2018). The Chalk Group is divided into six formations (Figure 1C), and contain many stratigraphical discontinuities including bands of flint nodules, sheet flints, marl seams, hardgrounds and sponge beds. These features occur at regular intervals every 0.3-1 m throughout most of the stratigraphic sequence (Lasseur, *et al.,* 2009; Mortimore, 2018). The frequency of these stratigraphic discontinuities is much greater in Normandy than in the more basinal parts of the Anglo-Paris basin east of Dieppe and in southeast England.

The Chalk bedrock is typically very gently deformed (e.g. with flexures, low amplitude anticlines), generally appearing slightly dipping or sub-horizontal, and is locally cut by faults with up to 200 m horizontal displacement. These typically trend NW-SE (Figure 1C) and were active from the Upper Cretaceous, when they influenced chalk deposition to the Miocene (Guillocheau *et al.,* 2000; Duperret *et al.,* 2012; Mortimore 2018). Some of these structures were reactivated again in the Pliocene and Quaternary (Hauchard and Laignel 2008). The Chalk Group is locally overlain by Paleogene sand and clays, and Pliocene-early Pleistocene marine sands (St-Eustache Fm) and fluvio-marine sands (Lozère Fm) (Lautridou *et al.,* 1999; Van Vliet-Lanoe *et al.,* 2002) related to the early paleo-Loire-Seine River (Dugué *et al.,* 2009). Around 90% of the Chalk outcrop is mantled with Quaternary superficial deposits (Laignel *et al.,* 1999), especially on the plateau surface. These include sand and clay-rich weathering residues ('Clay-with-Flints') derived from the overlying Palaeogene sediments as well as periglacial deposits. The latter are mainly represented by Upper Pleistocene loess ('limons des plateaux') up to 5 m thick (Laignel *et al.,* 1999, 2002; Quesnel, 2003; Antoine *et al.,* 2016), soliflucted deposits, and fluvial terrace deposits.

Seine valley terraces.

The Seine River has a well-developed sequence of fluvial terraces (Figure 1B), particularly between Jumièges and Les Andelys (1997; Lautridou, 1983; Lautridou *et al.,*1999, 2003; Lécolle, 1989; Lefebvre *et al.,* 1994; Antoine *et al.,* 1998, 2000, 2007). These terraces correspond to seven phases of incision and subsequent aggradation during periglacial cold-stage periods up to ~95 m above the bedrock floor of the valley. Heights are quoted as Relative Height (RH) based on the elevation above the maximum depth of fluvial incision (rockhead). In the lower Seine River, up to 16 bedrock-steps were identified (Antoine *et al.,* 2007). The lower level terraces downstream of Rouen are graded to former base-levels below present sea-level, and are now buried by Holocene marine, estuarine and alluvial sediments. The terraces above 40 m asl are discontinuous and poorly preserved, and have not been reliably dated (Antoine *et al.,* 2007). In the neighboring Somme Basin, 100 km to the northeast, up to 10 bed-rock steps from +5-6 to 55 m RH above the bedrock floor of the valley. Some of these have been dated using a combination of absolute ages and archeological findings, suggesting that river incision began at *ca.*1 Ma and incised at an average rate of 0.055-0.060 $m \cdot ka^{-1}$ (Antoine *et al.,* 2007).

The scale of post-Pliocene uplift and river incision is evident from the widespread occurrence of the middle Pliocene fluvial Lozère Sand Fm on the plateau surface around Rouen and Le Havre at up to 140 m asl above the current Seine riverbed (Figure 1B). This sand includes ferromagnesian minerals dated around ~2 Ma (Larue and Etienne, 2000) and marks the former northward course of the palaeo Loire-Seine River into the English Channel (Tourenq and Pomerol, 1995; Westaway, 2004; Dugué *et al.,* 2009). In the late

Pliocene, a marine transgression lead to the deposition of the marine St-Eustache Sand Fm in the coastal area around Le Havre to the north-west of the study area (Lautridou *et al.,* 1999). A decrease in fluvial sedimentation in the Seine Valley occurred at this time following diversion of the Loire River to the west. Since the cessation of marine deposition in the early Pleistocene, the current Seine River has incised into the Normandy plateau at an average rate of 0.02-0.05 $mm \cdot a^{-1}$, (Guillocheau *et al.,* 2000; Hauchard and Laignel, 2008).

In the study area, fluvial deposition began with the development of a suite of 'very high' river terraces at ~92-135 m relative height above maximum incision (RH). These contain unweathered augite crystals derived from the French Massif Central volcanism (Tourenq and Pomerol, 1995), indicating that the Loire River still drained into the English Channel. The augite crystals have been dated to *ca.*1 Ma, implying that fluvial terraces are Quaternary, but otherwise the chronology is very poorly constrained. Westaway (2004) assigned these 'very high' terraces to between MIS 26-104 (*ca.* 0.98 to 2.6 Ma).

The highest well-defined fluvial terrace system, the Martot/Madrillet/Bardouville terrace, is at 70-73 m RH, correlated with MIS 22 – *ca.* 1.03-0.86 Ma (Westaway 2004). The Martot Fm can be recognized downstream from Rouen to the Seine Estuary (Figure 1B), but upstream, this formation is not well preserved. At lower altitude, there are up to three poorly defined terraces at 60-64 m (Rond de France), 50-54 m, and 38-40 m RH (Antoine *et al.,* 2007). These terraces probably span much of the MIS 23 to 32 (previously Bavelian complex in Lautridou 1983 and Lautridou *et al.,* 1999).

At Saint-Pierre-lès-Elbeuf near Rouen (Figure 1B), a fluvial gravel terrace (the Elbeuf Fm) at 30-32 m RH is overlain by a sequence of loess and with four interglacial palaeosols (Elbeuf I, II, III, IV) (Antoine *et al.,* 2016). OSL dating of the sequence suggests these soils span much of the Middle and Upper Pleistocene (Cliquet *et al.,* 2009). The Elbeuf I and IV soils have been dated to 164 ± 13 ka and 475 ± 38 ka respectively. A tufa deposit at the top of the Elbeuf IV soil, dated to *ca.* 400 ka (MIS 11), contains a distinctive *Lyrodiscus* malacological fauna. An identical fauna occurs in tufa deposits at Vernon, halfway between Rouen and Paris, which yield uranium series ages equal to or older than 350-400 ka (Lécolle *et al.,* 1989; Rousseau *et al.,* 1992). This characteristic fauna forms a good biostratigraphical marker for MIS 11 and is indicative of humid and warm forested landscape. A similar tufa at La Celle southeast of Paris yielded a uranium series age of 388 ka (+/- 69), coeval with MIS 11 (Dabkowski *et al.,* 2012). The uranium series ages give confidence in the correlation between La Celle and Elbeuf. In both cases, the fluvial terrace underlying the tufa is attributed to MIS 12.
Around 10 m below the Elbeuf terrace another well-defined terrace system, the Oissel Fm, occurs at 22-25 m RH (Figure 1B). This terrace has not been dated. In the Rouen area, the lowest gravel terrace sequence exposed is the Tourville Fm. The base of this deposit is at 17-18 m RH above the maximum incision of the Seine River. It comprises a complex sequence (Lautridou *et al.,* 1999) including three gravel units interbedded with two palaeoestuarine silt beds. These interglacial estuarine deposits, dated by OSL and ESR (Balescu *et al.,* 1991, 1997) give ages of *ca.* 200 ka (MIS 7) for the upper silt, and *ca.* 300 ka (MIS 9) for the lower silt. The upper layer contained an exceptional Saalian-age mammal fauna (Lautridou *et al.,*

1999). The complex Tourville Fm thus comprises two glacial–interglacial sequences spanning MIS 9 to 6. Three further gravel terraces occur stratigraphically below the Tourville Fm (Figure 1B), but as they are close the current floodplain and underlie Holocene deposits, they are not well exposed.

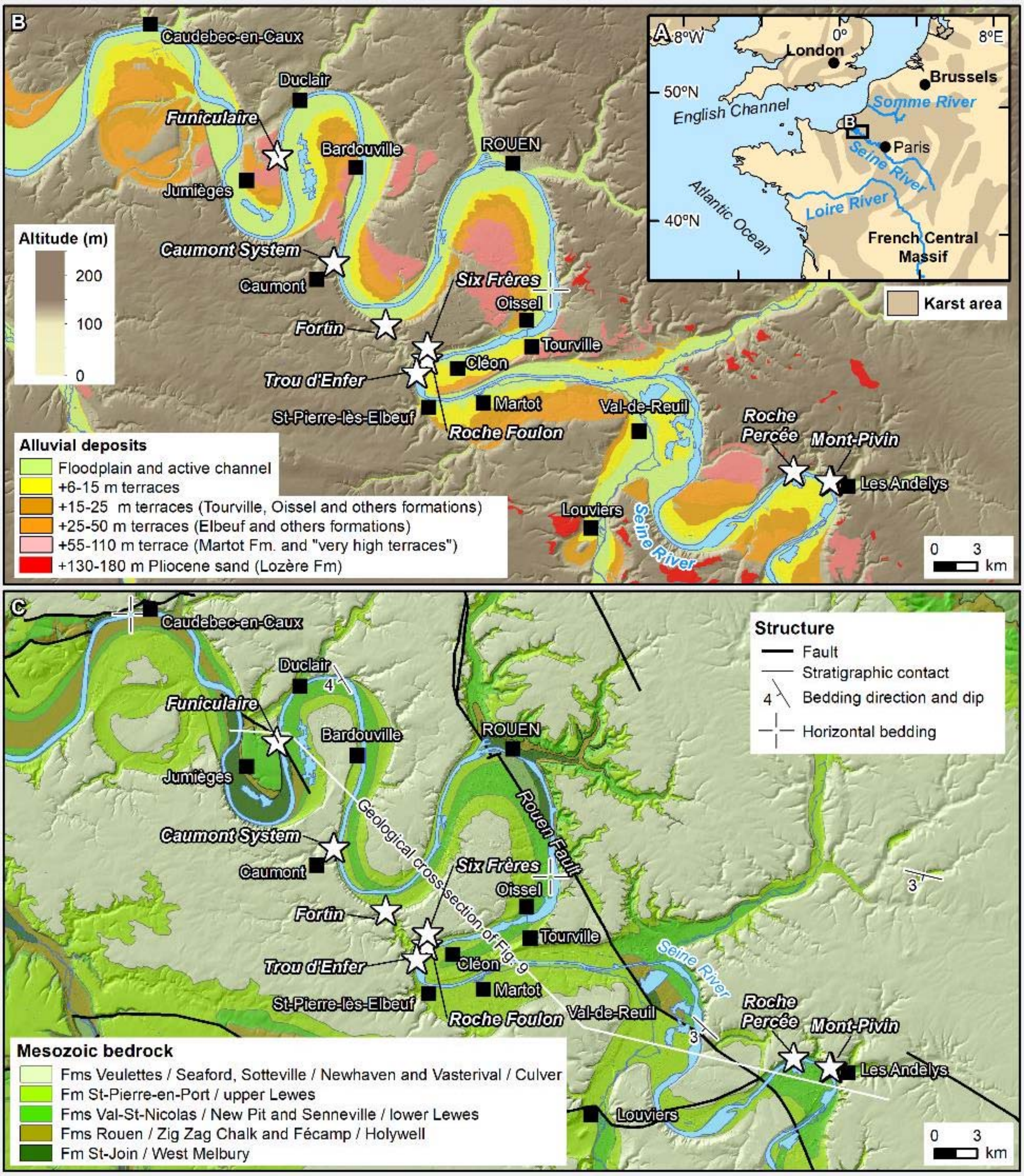

***Figure 1**. Settings of the study area: (A) Situation of the Upper Normandy in the North of France. (B) Digital Elevation Model of the study area (after Institut National de l'Information Géographique et Forestière), showing the position of the eight study caves and alluvial deposits (Antoine et al., 2007). (C) Geological map of the Mesozoic bedrock of the study area, after Juignet and Breton, (1992), Robaszynski et al. (1998), and Lasseur et al. (2009). Alluvial deposits and geological data are after Bureau de Recherches Géologiques et Minières (www.infoterre.brgm.fr).*

Karst geomorphology

Except for the main Seine River and its tributaries, most of the Normandy plateau is characterized by underground drainage within an unconfined karst aquifer. Recharge is predominantly through the Cenozoic semi-permeable superficial formations that cover the plateau (Valdes *et al.,* 2014). These deposits serve to concentrate surface recharge onto discrete points inducing the formation of deep dissolution pipes. These are often infilled by reworked surficial sediments, washed in by infiltrating surface water.

Over 50 cave systems have been recorded in the Chalk of Upper Normandy, with an aggregate passage length of over 10 km. The caves are typically segments of relict conduits comprising complex anastomotic networks that converge into larger galleries (Rodet *et al.,* 2006), although branch-work systems and divergent conduits are also known (Rodet and Lautridou 2003). The conduits are fed by recharge from the surrounding plateau, often focused on discrete leakage points (*bétoires*) through the superficial deposits. Many of the caves are infilled with sand, silt and clay derived from the overlying superficial sediments (Laignel *et al.,* 2004; Chédeville *et al.,* 2015). Discrete levels of cave development are preserved at elevations up to ~ 90 m above the present Seine River (Rodet, 1992, 2007). Previous studies (Lautridou, 1983; Lécolle, 1989; Rodet, 1992) correlated these relict cave levels to former base levels in the Seine valley (Laignel *et al.,* 2003). The only previously published chronological constraint for cave development is a speleothem in the Caumont cave system at ~13 m asl (21 m RH) dated to 236 ± 75 ka (Rodet, 1992; Lautridou, 2003).

Study caves

Eight relict and active cave systems in the Seine valley around Rouen were investigated in this study (Figure 1), located between Les Andelys in the southeast to Jumièges in the northwest. These include (Figure 1B) from the highest to the lowest in relative height above maximum incision (RH), the Mont-Pivin system (107 m RH) and the neighboring Roche Percée (95 m RH) cave, Fortin (98 m RH), Trou d'Enfer (87 m RH), Roche Foulon (86-94 m RH), Six Frères (85 m RH), Funiculaire (60 m RH) caves and Caumont active system (21 m RH).

The Mont-Pivin System and Roche Percée caves are located on the north side of the Les Andelys meander 30 km southeast of Rouen (Figure 1B). Both caves, situated at the top of cliffs 80 m above the Seine River, are relict branchwork systems. The Mont-Pivin system comprises two caves: l'Hôpital (49°14'51.30"N, 1°23'43.66"E, Z: 98 m) and St-Jacques caves (49°14'52.49"N, 1°23'37.88"E, Z: 94 m) that were connected together by excavating cave deposits that infilled most of the passages (Figure 2G). They have a combined length of 328 m. Both caves are close to the surface of the plateau and contain well-stratified clay, silt and sand deposits reworked from the overlying surficial deposits including loess (Rodet, 1992). Vertical shafts filled with sediment are also present. Prior to excavation, the passage was almost filled to the roof with sediment. Small flowstone deposits are located along the cave wall and close to the cave ceiling. The Roche Percée cave (49°15'20.9"N, 1°21'55.3"E, Z: 93 m), located 2.7 km west-northwest of the Mont-Pivin system (Figure 1B), is 480 m long and comprises a horizontal labyrinthine network of passages (Figure 2H) partially infilled with interbedded silt, sand and clay deposits and flint nodules. Two vertical shafts developed along a minor fault have allowed the introduction of loessic material from the plateau above.

Fortin cave (49º20’23.8"N, 0º57’47.5"E, Z: 90 m) is located near Moulineaux, 18 km southwest of Rouen (Figure 1B). This cave is a small 20 m long branch-work system at an elevation of 98 m RH (Figure 2C). The cave is largely sediment choked. An excavated pit reveals more than 1.5 m of interbedded clay, silt and very fine sand.

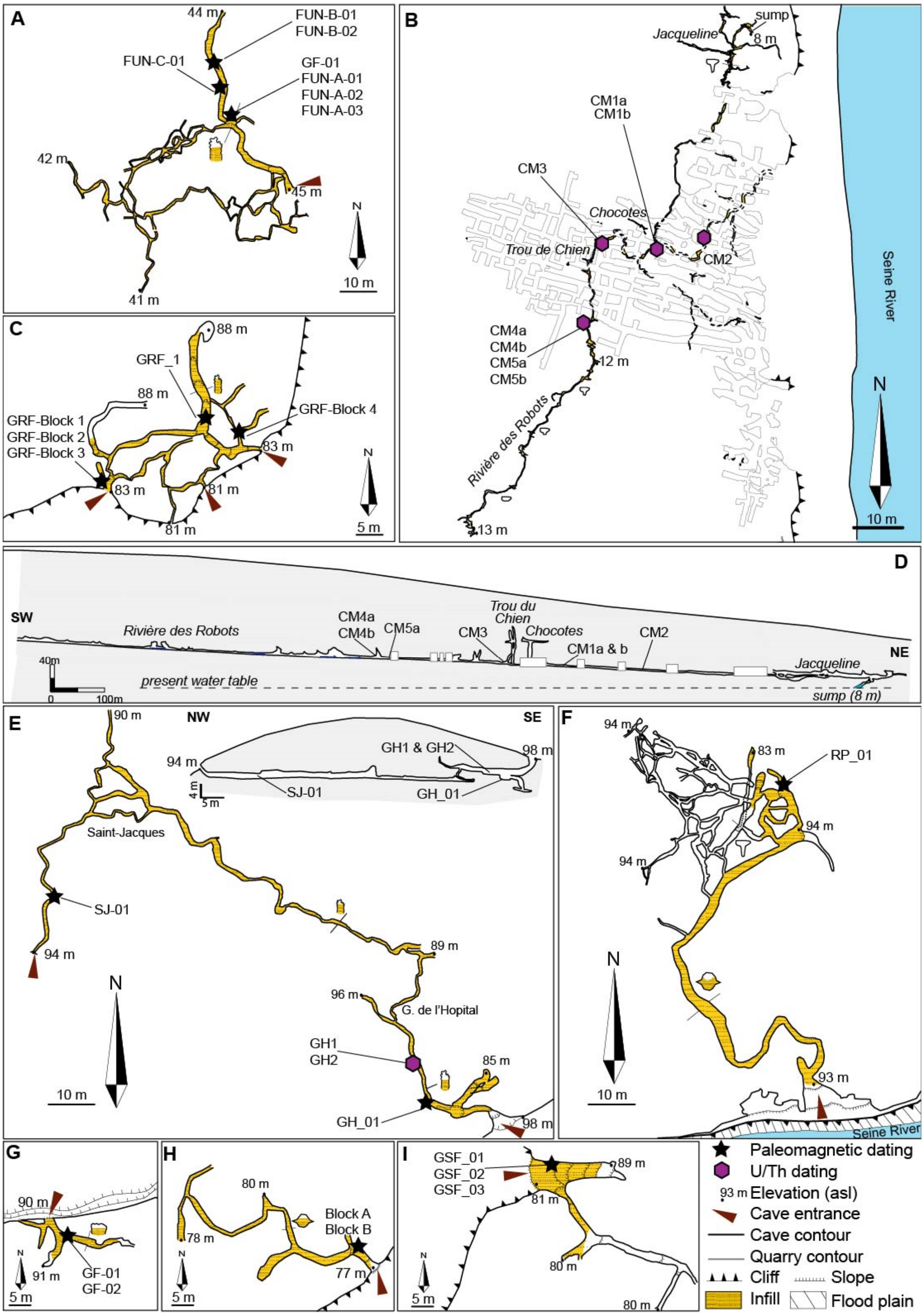

Figure 2. *The plan view and cross-sections of the studied caves: Funiculaire (A), Caumont (B & D), Roche Foulon (C), Mont-Pivin System (E), Roche Percée (F), Fortin (G), Trou d’Enfer (H) and Six-Frères (I) caves. The sampling of clay-silt for paleomagnetism relative dating and calcite for uranium-series dating are indicated on each cave map. The indicated elevation on each cave map is in meter above sea-level (asl).*

The Trou d'Enfer and Roche Foulon caves are located at the Cléon meander 15 km south of Rouen (Figure 1B). The Trou d'Enfer (49º18'35.2" N, 0º59'38.4"E, Z: 77 m) is a small relict cave 87 m long at an elevation of 77 m (Figure 2D). Most of the cave is a network of small passages, with a thick clay-dominated sediment fill preserved at the entrance. The neighboring Roche Foulon cave (49º19'7.5" N, 1º00'13.1"E, Z: 82-88 m) is a complex network of passages 162 m long, developed on two levels between 86 and 94 m RH, connected by small sub-vertical to inclined vadose conduits (Figures 2E). Like most other caves, the passages are largely infilled with clay, silt and sand which have been partially excavated by speleologists (Chédeville *et al.,* 2015). Over 2 m of sediment is preserved in a section at the southern entrance, with several other 0.5 to 1 m sections elsewhere in the cave.

Six Frères cave (49°14'51.30"N, 1°23'43.66"E, Z: 82 m) is situated on the side of a dry valley near Orival at an elevation of 86 m RH (Figure 1B). It comprises a large entrance gallery with sediments exposed in the floor, and a smaller passage leading off, totaling 81 m length (Figure 2F).

The entrance of the Funiculaire cave (49°26'39.70"N, 0°51'14.56"E, Z: 45 m) is located on the outer, north bank of the Jumièges meander, 16 km downstream of Rouen (Figure 1B). The cave is 360 m long and characterized by a quasi-horizontal labyrinthine network of small relict passages that feed into a single larger conduit (Figures 2A). The cave is partially infilled by clay and silt with some sand, and flint derived from passage breakdown, since excavated by speleologists (Coquerel *et al.,* 1993). The sampled section shown in Figure 4C suggests the main phase of sediment infill was followed by an erosional phase and a second phase of sedimentation.

The Caumont cave system (49°22'41"N, 0°54'47"E, Z: 13 m) is developed on the south bank of the Caumont meander 25 km southwest of Rouen (Figure 1B). It comprises a branch-work network of passages 4 km long (Figure 2B) discovered and partially truncated during the excavation of an underground chalk quarry (Rodet and Lautridou, 2003). The main conduit (lower cave-level) is a 2.4 km long stream passage (Rivière des Robots) at an elevation of ~13 m asl (21 m RH) (Figure 2B). This stream passage is largely filled with sediments, predominantly clay silt and sand, capped by speleothem and breakdown deposits. Part of this sediment fill has been removed by the current stream and by the original explorers, leaving remnants of speleothem false pavement in parts of the system between the Trou du Chien and Jacqueline passages (Figure 2B). The downstream end of the stream passage terminates in a sump at 8 m asl (15 m RH) that connects directly with the Seine River which is tidal at this point. The Trou du Chien and Chocotes galleries are higher level relict passages situated at an elevation of ~50 m asl (57 m RH; Figure 2B), and accessed by vertical shafts connecting the two levels.

Methods

Cave Surveys

Georeferenced cave surveys and geometric parameters were obtained following Ballesteros *et al.* (2015). Each studied cave was re-surveyed at 1:200 scale using the polygonal cave surveying method with 670 stations and 1431 values of distance, direction and inclination. All measurements were taken using a Disto

X2 laser rangefinder. The position of caves entrances was measured using a Garmin GPS (2-3 m precision). The raw survey data was processed using cave survey software (COMPASS) elaborating the digital georeferenced cave surveys in ArcGIS (10.3) plotted against topographical and geological maps, aerial orthophotographs and a digital elevation model (5 m/pixel resolution) of the study area. Four geometric parameters were calculated from the cave survey database: cave entrance altitudes above sea-level, relative altitude on the maximum incision of the Seine (RH), length, vertical range and the elevation of the dated deposits (Table 1).

Geochronology

Palaeomagnetic dating of fine-grained detrital cave sediments and uranium series dating of speleothem were used to derive a robust chronology for the cave systems. Both sediments and speleothems necessarily postdate initial cave genesis, and thus only provide minimal ages for the cave development and later evolution (Ford *et al.,* 1981; Atkinson and Rowe, 1992). Uranium series (U-Th) dating of calcite speleothem provides a minimum age for the commencement of vadose conditions within the caves. Palaeomagnetic dating relies on measuring the magnetic polarity of iron-rich laminated clay and silt deposited in slack water. Abundant evidence of paragenetic cave development indicates that sediment infill and deposition was contemporaneous with cave passage formation at or close to fluvial base-level. Other methods used to date cave deposits such as optically stimulated luminescence (OSL - Ortega *et al.,* 2012) and cosmogenic burial dating of quartz grains (Anthony and Granger, 2007) were not used in this study due to the lack of suitable material to date. There was very little suitable quartz material preserved in the caves, despite the potential for material to have been reworked from the overlying Lozère Fm. Moreover, most caves are located at shallow depth (<30 m) and thus not suited to cosmogenic burial dating.

Palaeomagnetism

Palaeomagnetic analysis of cave sediments can provide an important age constraint on the timing of fine sediment deposition in caves (Sasowsky *et al.,* 1995), especially when different reversals can be identified in a stratigraphic sequence. Magnetic minerals become oriented toward Earth's magnetic pole during deposition in still water. Palaeomagnetic dating involves correlating a local magnetostratigraphic column with the global palaeomagnetic record (Singer, 2014). The chronology of magnetic reversals is well-established, with the last full reversal, the Matuyama–Brunhes, occurring *ca.* 0.78 Ma (Cande *et al.,* 1995). The presence of magnetically reversed sediments therefore indicates a minimum age for cave alluviation of 0.78 Ma. With a stacked series of normal and reversed polarity sediments, this method can be used to date caves back several million years (Farrant *et al.,* 1995; Stock *et al.,* 2005; Hajna *et al.,* 2010; Rossi *et al.,* 2016; Bella *et al.,* 2019). As a dating tool, palaeomagnetism suffers from two main limitations: first, it requires suitable fine-grained sediments within the cave, and secondly, it is correlative tool that cannot yield absolute ages for stratigraphic units except when magnetic reversals are identified and reliably correlated with the global record. Cave sediment magneto-stratigraphy therefore requires extensive sampling of a sedimentary sequence, backed up with either geomorphological or other age dating evidence to correlate any reversals.

Table 1. Elevation of the studied caves (cave entrance altitude, dated deposits' altitude and relative height), geometric parameters (length, vertical range), with the number of samples for geomagnetic relative dating (total, rejected) and the results of the palaeomagnetic analysis. The deposits in Caumont cave system were not subject for palaeomagnetic analysis but were dated by uranium series (see table 2)

Cave	Samples Code	Entrance altitude (m asl)	Deposits altitude (m asl)	Relative Height RH (m)	Length (m)	Vertical (m)	Total (n)	Total (n)	Polarity	Magnetic Chronology	Age (Ma)
Mont-Pivin	MtP	94 & 98	90-91	107	328	12	7	0	N + R	Matuyama 2st reversal to Jaramillo normal	>1.06
Fortin	GF	90	91	98	46	6	14	1	R	Matuyama 2nd reversal	>1.06
Roche Percée	RP	93	95	95	480	18	4	0	N	Jaramillo normal	0.92 to 1.06
Trou d'Enfer	TE	77	79	87	87	3	9	0	N	Jaramillo normal	0.92 to 1.06
Roche Foulon	GRF	81-83	82 (Lower) 88 (Upper)	86 94	172	9	36	6	R+ N	Jaramillo normal to Matuyama 1st reversal	~ 0.92
Six Frères	GSF	81	82	85	81	13	16	0	R + N	Matuyama 2st reversal to Jaramillo normal	~ 1.06
Funiculaire	GF-Fun	45	42	60	406	4	45	5	R	Matuyama 1st reversal	0.78 to 0.92
Caumont	CM	13	15(Lower) 50 (Upper)	23 57	4000	40	--	--	--	--	---

The cave systems exposed in the Seine valley all contain sediments suitable for palaeomagnetic analysis, with extensive deposits of laminated clay, silt and fine sand, deposited in slack water setting, co-incident with cave development under paragenetic conditions (Farrant and Smart, 2011). An assemblage of 144 clay and silt samples was collected from 14 locations in seven caves in the Seine valley near Rouen (Table 1). Up to six subsamples were collected from each individual locality, taking samples from different stratigraphical levels. Samples were collected using cylindrical orientated cores 25 mm diameter to determine magnetic polarities (Table 1). 45 samples were obtained from the Funiculaire cave; 14 from Fortin cave; 16 from Six Frères cave; 36 from Roche Foulon cave; nine from Trou d'Enfer cave; seven from Mont-Pivin system and four from La Roche Percée cave. Samples were oriented in-situ, using a standard magnetic compass. The samples were analyzed using the Geomagnetism Laboratory's RAPID system at University of Liverpool, UK (Kirschvink *et al.,* 2008). Each sample was individually step-wise demagnetized using alternating field (AF) demagnetization. Each AF demagnetization step randomly reorients the magnetic fields of grains with a magnetic coercivity below that of the AF step, effectively erasing their net magnetization. The samples were demagnetized from their initial Natural Remnant Magnetization (NRM) to a maximum AF field of 100 mT in 10-12 steps, with measurements occurring after each step.

Uranium series dating

^{234}U–^{230}Th dating was used to complement the palaeomagnetic analyses in caves where old speleothem was present. Care was taken to identify older speleothem samples based on appearance and relationship to passage morphology and sediments. Samples were collected to constrain a maximum age for the cave development within the last normal Brunhes chron. (780 ka to present). Ten samples were extracted from the Caumont cave system: seven samples from three flowstone layers and one sample from a speleothem growing in small karst voids just above an ancient sediment-filled passage. Two samples were also retrieved in Mont-Pivin system from a thin flowstone layer in the rooftop void capping old fine-grained sediments. The base of each sample was selected for dating.

Uranium series analyses were conducted at the NERC Isotope Geosciences Laboratories at the British Geological Survey, Keyworth (UK). Powdered 100 to 400 mg calcite samples were collected with a dental drill from the base of each sample. Chemical separation and purification of U and Th were performed following the procedures modified from Edwards *et al.* (1987). Isotopes concentrations were obtained on a Thermo Neptune Plus multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) following procedures modified from Hellstrom (2006) and Heiss *et al.* (2012). Mass bias and SEM gain for Th measurements were corrected using an in-house ^{229}Th–^{230}Th–^{232}Th reference solution calibrated against CRM 112a. Activity ratios are calculated using the decay constants of Cheng et al. (2013). Quoted uncertainties for activity ratios, initial $^{234}U=^{238}U$, and ages include a *ca.* 0.2% uncertainty calculated from the combined $^{236}U=^{229}Th$ tracer calibration uncertainty and measurement reproducibility of reference materials as well as the measured isotope ratio uncertainty. Ages were calculated from time of analysis (2016) in years before 1950 with a 2σ uncertainty error. Many of the samples are contaminated to some degree by detrital sediment. The effect of detrital contamination was corrected by calculating activity ratios and dates using a detrital U-Th isotope composition of ($^{232}Th/^{238}U$) = 1.2, ($^{230}Th/^{238}U$) = 1 and ($^{234}U/^{238}U$) = 1 with ± 50% (2σ) uncertainties. We consider the impact of detrital Th to be negligible since the $^{230}Th/^{232}Th$ ratio is greater than three. Whilst there are issues with the methods used to correct for the effects of detrital contamination, the precision of the U-Th method is less critical for landscape evolution modeling than for palaeoclimate studies. Even with 10% error, the age range of the U-Th method amounts to less than half a glacial-interglacial cycle, and still can be used to constrain the age of climatically driven aggradation and incision events.

Results

Palaeomagnetic relative dating

The results of the palaeomagnetic analyses are given in the supplementary data. Of the 144 samples obtained, 132 gave useable palaeomagnetic directions (Table 1). Based on reasonable rates of valley incision and dated river terraces, the lower elevation caves are expected to preserve normal polarity inclination and declination similar to that at present (Declination: 0°, Inclination: 64°). Higher elevation samples are expected to have an antipolar reverse direction. Figure 3 includes the average palaeomagnetic direction for the samples grouped by inferred polarity. The Normal pole is around 8° shifted from the modern pole direction. The Reverse pole is 176° offset, which is within error of being antipolar of the Normal direction. The data present some scatter as the measured sediments are relatively weakly magnetized. There is little evidence of systematic bias in the direction of the remnant magnetization due to water flow.

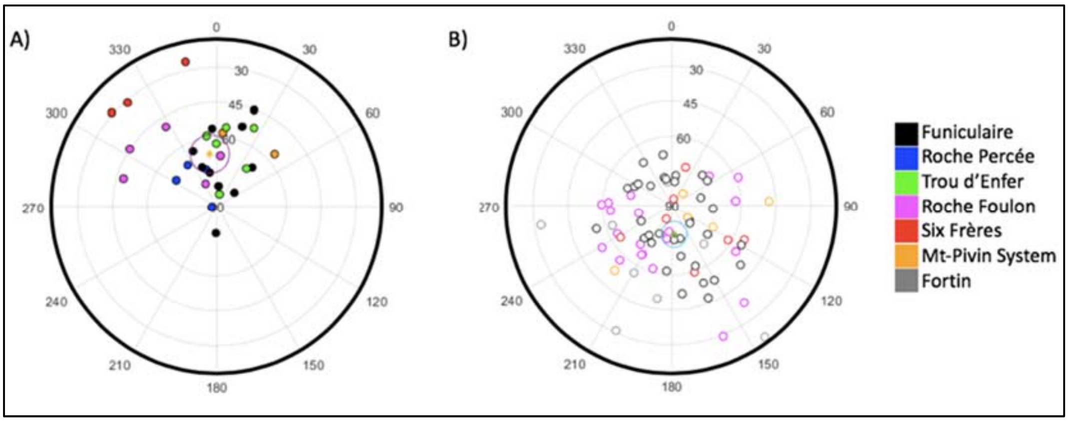

***Figure 3**. Equal area stereographic projections of characteristic remnant magnetization (ChRM) directions for all samples. The mean poles are given by solid circles, with the 95% confidence interval given by the corresponding open circle. A) Normal polarity (filled dots) average direction with a declination of 352.4°, inclination of 61.4°, α_{95} of 10.1° for 30 samples (n). B) Reverse polarity (empty dots) average direction with a declination of 175.5°, inclination of -74.1°, α_{95} of 7° for 75 samples (n).*

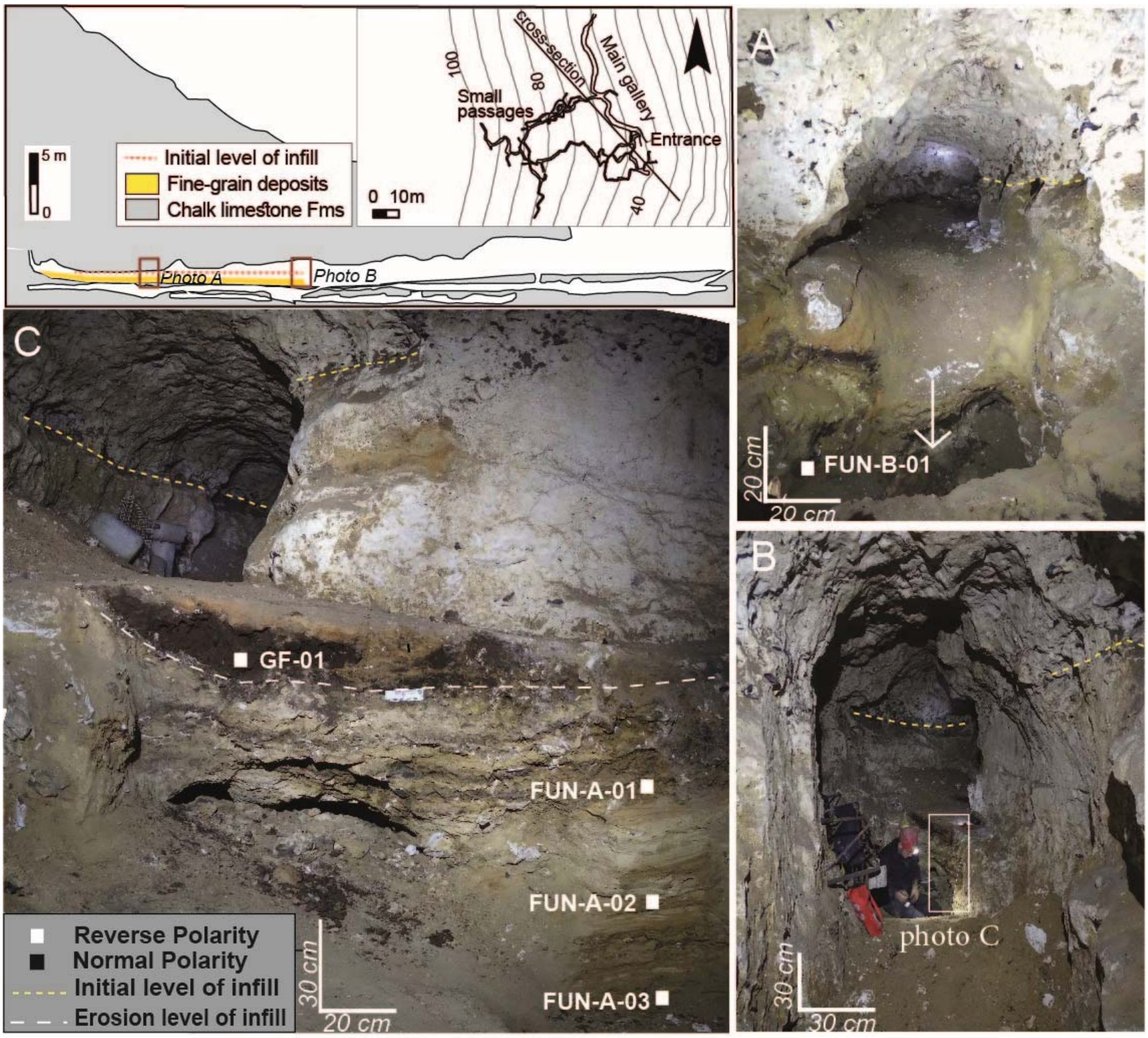

***Figure 4.** Passage profile in the Funiculaire cave showing the location of the sampled sections in the Main Gallery. Image A is the location of Section B (looking into the cave). Image B is a view of Section A, with a close up of the section in Image C, both looking into the cave. Note the initial level of infill indicated on A, B and C marked by the yellow dashed line.*

The lowest level palaeomagnetic samples are from the Funiculaire cave. Three clay and silt layers were sampled from a 1 m sediment section in the main gallery. Here, the palaeo-water table is estimated to be ~60 m relative height (RH) above the base of the maximum incised depth of the Seine River (samples GF-

1, GF-2, GF-3; Figure 4-A, B and C). All these samples show reverse polarity. Using previous estimates of river incision (Guillocheau *et al.,* 2000; Hauchard and Laignel, 2008) these have been ascribed to the youngest part of the Matuyama chron.

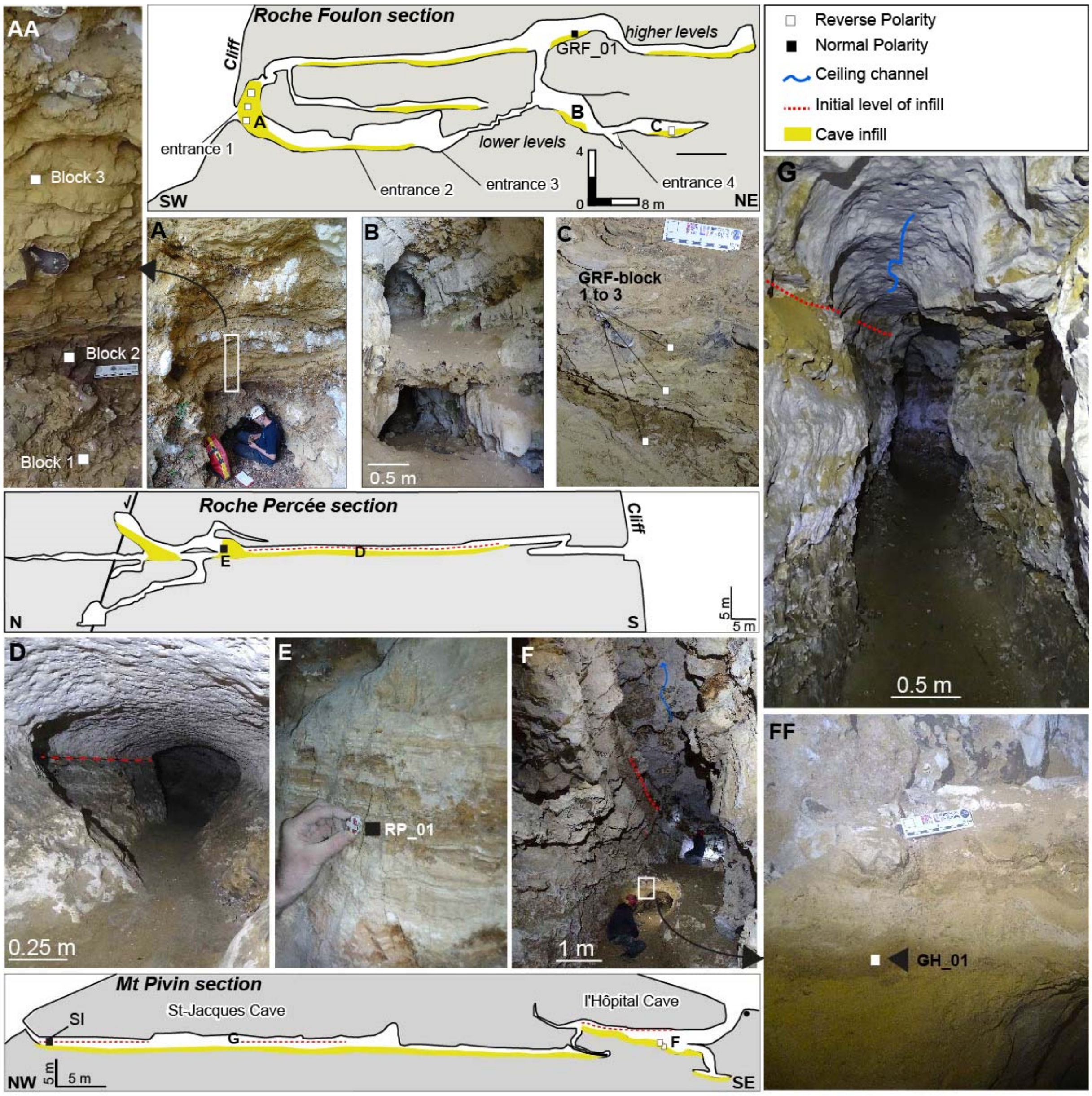

Figure 5. Passage sections in the Roche Foulon, Mont-Pivin system and Roche Percée caves with the photos of conduits and sampled layers in each cave. The sample locations in the Roche Foulon cave section are highlighted in the section, and shown in the relevant image (A, B and C). The sample site A is shown in more detail in image AA. The Roche Percée cave section and samples are indicated in images D and E. The Mont-Pivin system sample site is shown in image F, with a more detailed view in image FF. The St-Jacques cave section is indicated in image G and the sample site (SI) is indicated on the Mt Pivin cross-section. The level of sediment infill is marked by a red dashed line.

The next lowest cave in the sequence, Roche Foulon, comprises two passage levels between 86 and 94 m RH that show more complex results. The lower sediment layers sampled (Figure 5-AA and C) located at the more southerly entrance have a reverse polarity (Figure 5), whereas the higher layers (Figure 5-Roche Foulon section) located in the upper level (GRF_1) have a normal polarity. The latter is ascribed to the Jaramillo subchron. The passage morphology suggests the sediment fills were deposited within two closely-spaced, but separate cave levels, and are thus separated in time (ie higher = older), spanning the end of the Jaramillo normal subchron. The samples from the Trou d'Enfer cave at 87 m RH are a similar elevation above base-level and also have normal polarity, ascribed to the Jaramillo subchron. Samples from the Six

Frères cave at 85 m RH also show a magnetic reversal. The lower layers (GSF_03 & GSF_02) have reversed polarity whilst the samples from higher in the sequence sediment fill (GSF_01) record normal polarity and are ascribed to the Jaramillo subchron (Figure 6B). Unlike Roche Foulon cave, these samples are from the same sediment sequence and record a phase of paragenetic alluviation, and thus the higher samples are younger. They record the polarity change at the start of the Jaramillo normal subchron.

Figure 6. *Sampled deposits and flowstone in Fortin cave, Six Frères cave and the Caumont quarries. A is the section of the sampled deposits in Fortin cave. B is the entrance section of Fortin cave showing passage morphology, C is the section sampled in Six Frères cave. D to H show the passage morphology in the Rivière des Robots in the Caumont system. I shows flowstone preserved in dissolutional pockets associated with relict conduits in Caumont system. The survey shows the location of the images. White squares indicate layers with normal polarity and black squares represent layers with reverse polarity.*

The Roche Percée cave is at a similar elevation above base level (96 m RH) to the Six Frères cave, and contain wholly normal polarity sediments from the Jaramillo subchron (Figure 5F). Just upstream, the sampled clay and silt layers in the Mont-Pivin system (107 m RH) show reverse polarity, indicating a level prior to the start of the Jaramillo subchron at *ca.* 1.068 Ma. Fortin cave at 98 m RH show that three clay and silt samples have a reverse polarity (Table 1, Figure 6A), within the latter part of the Matuyama Chron, but prior to the Jaramillo subchron.

Uranium series dating

Eight speleothem samples were collected for uranium series dating from the Caumont cave system, and two samples from the Mont-Pivin (l'Hôpital cave) system, from which ten dates were obtained (Table 2). All the samples from the Caumont system are younger than ~300 ka. The oldest date, 301 ± 20 ka BP (Figure 6F) was obtained from a flowstone (sample CM2) lining the inside of an alcove on the wall of a relict conduit at ~21-22 m RH. Nearby, a flowstone in the lowest level at site directly below the Chocotes conduit (Figure 2D, CM1a and 1b), approximately 2 m lower grew between 274 ± 7 and 250 ± 14 ka BP. A younger dated flowstone retrieved in the lowest level of Trou du Chien conduit (Figure 2D; sample CM3) was dated to 127.6 ± 0.7 ka BP. Two flowstones were obtained from the 'Rivière des Robots' stream. A stalagmite growing on boulders in a vadose rift ~2-3 m above the present stream (CM4a and 4b, Table 2) grew between 102 ± 16 and 79 ± 6 ka BP. Another speleothem capping a sediment bank 1.2 m above the stream (Figure 6E; samples CM5a and 5b) grew between 10 ± 3 to 7 ± 1 ka BP.

In the Mont-Pivin cave System, two thin flowstone layers deposited between the top of the sediment fill (since excavated) and the cave wall and ceiling (Figure 5D) near the l'Hôpital cave entrance give ages 570 ± 52 and 495 ± 25 ka. BP. These much older ages provide a minimum estimate of the timing of passage abandonment. However, they are considerably younger than the sediments dated using relative palaeomagnetic polarity, implying a significant time gap between sedimentation, abandonment and speleothem growth.

Table 2. *Summary of U-Th data from Caumont (CM1 to 5) and Mont-Pivin (GH1 and 2) caves in the Seine Valley. All uncertainties are reported at the 2σ level. Activity ratios calculated using the decay constants of Cheng et al. (2013). 1 – corrected activity ratios and dates calculated using a detrital U-Th isotope composition of ($^{232}Th/^{238}U$) = 1.2, ($^{230}Th/^{238}U$) = 1 and ($^{234}U/^{238}U$) = 1 with ± 50% (2σ) uncertainties. 2 – uncertainty includes 0.2% external reproducibility. 3 – uncertainty includes 0.1% external reproducibility.*

Cave name	Sample ID	^{238}U (ppm)	^{232}Th (ppm)	($^{230}Th/^{232}Th$) measured	($^{230}Th/^{234}U$) Corrected[1,2]	($^{234}U/^{238}U$) Corrected[1,3]	$\rho_{08\text{-}48}$	Age un-corrected (ka)	Age corrected (ka BP)1	($^{234}U/^{238}U$) initial
Caumont lower level										
Chocotes & Trou du Chien lower levels	CM2	0.07	0.063	3.52	1.2 ± 0.1	1.18 ± 0.08	0.99	325 ± 8	**301 ± 20**	1.4 ± 0.2
	CM1b top	0.08	0.065	4.49	1.18 ± 0.09	1.24 ± 0.07	0.97	268 ± 4	**250 ± 14**	1.5 ± 0.2
	CM1a base	0.04	0.014	9.46	1.25 ± 0.04	1.28 ± 0.03	0.98	282 ± 4	**274 ± 7**	1.59 ± 0.07
	CM3	0.11	0.001	178.8	0.793 ± 0.002	1.129 ± 0.002	0.38	128.0 ± 0.6	**127.6 ± 0.7**	1.185 ± 0.003
Robots stream	CM4b top	0.54	0.152	6.34	0.55 ± 0.04	1.07 ± 0.03	0.71	86.8 ± 0.4	**79 ± 6**	1.08 ± 0.04
	CM4a base	0.15	0.106	3.27	0.7 ± 0.1	1.11 ± 0.09	0.78	122.8 ± 0.7	**102 ± 16**	1.2 ± 0.1
	CM5a top	0.3	0.016	4.66	0.07 ± 0.01	1.094 ± 0.007	0.32	8.43 ± 0.03	**7 ± 1**	1.096 ± 0.008
	CM5b base	0.24	0.031	3	0.10 ± 0.02	1.08 ± 0.02	0.35	13.81 ± 0.05	**10 ± 3**	1.08 ± 0.01
Mt-Pivin system										
G. Hôpital	GH2	0.17	0.002	332.92	1.041 ± 0.002	1.037 ± 0.001	0.05	495 ± 25	**495 ± 25**	1.151 ± 0.009
	GH1	0.13	0.007	64.15	1.058 ± 0.003	1.045 ± 0.002	0.45	571 ± 52	**570 ± 52**	1.22 ± 0.03

Discussion

A model of speleogenesis in a fluvial context

Groundwater flow and cave development in the Chalk aquifer is intrinsically linked to river incision by the Seine River which forms the regional base-level, and climatic variability. The Quaternary evolution of the Seine valley is driven by glacial-interglacial climatic variations, with active incision interspersed with phases of fluvial gravel aggradation. These cycles of incision and aggradation are superimposed on regional scale Plio-Quaternary uplift leading to the sequential development of cave levels and river terraces. Dating of the terrace deposits in the Seine and the Somme basins (Lautridou *et al.* 2003; Antoine *et al.,* 2007) suggested that each terrace represents generally a single glacial-interglacial cycle. Models of terrace formation propose that each cycle is characterized by short period of bedrock incision during the transition from a temperate to a (peri)glacial climate (Antoine *et al.,* 2007), followed (with a variable lag time lag, Tofelde *et al.,* 2019) by a phase of gravel aggradation (Bridgland, 2000; Bridgland and Maddy, 2002) as sediment liberated during the climatic deterioration phase feeds into the major river systems. These periods of climate driven incision, sediment production and ensuing gravel aggradation influenced conduit systems in the adjacent aquifer, both in their initial development but also subsequent evolution of the system.

A sequential model of conduit inception, enlargement, paragenetic modification and abandonment is proposed. Initial conduit development occurred following fluvial incision and base-level lowering at the onset of a glacial episode. Cave passage morphology indicates these were low gradient systems developed under phreatic or epiphreatic conditions at shallow depths (<10 m) beneath the contemporary water table. These are typically developed on one of the many potential inception horizons present in the Chalk sequence. Which inception horizon is utilized depends on its geometry and position relative to the local base-level. A complicating factor is the time needed to develop karstic conduits. Geomorphological response times can lag behind changes in environmental parameters (Tofelde *et al.,* 2019). The time required for conduit development from inception to a passage c. 1 m in diameter is ~10^3 -10^4 years. Consequently, new conduit systems initiated during the transition from warm to cold climate and graded to the new lower River Seine base-level are typically not developed enough to take all the flow before groundwater circulation is curtailed during the peak of the subsequent glaciation. Consequently many of existing conduits systems were still active, at least during periods of high flow, for a considerable time after base-level fall whilst the lower level conduits continued to enlarge.

In the later stages of the transition from a temperate to a glacial climate, a decrease in surface vegetation and increased erosion and sinkhole collapse led to periodic influxes of sand, silt and clay into the aquifer. These sediments, derived from the overlying Clay-with-Flints, loessic deposits and the Lozère Fm (Chédeville *et al.,* 2015), often infilled existing cave passages, forcing further dissolutional enlargement upwards towards the water table. This process left distinctive paragenetic features on the cave walls and ceiling. These include pendants and half tubes, anastomoses, 'drainage grooves' (Palmer, 2007), bedrock fins, notches, flat solutional ceilings ('laudecke'), and paragenetic solution ramps (Farrant and Smart, 2011). The latter feature, also termed 'oblique limit benches' (Jaillet *et al.,* 2011) form below the water-table by lateral dissolution just above the sediment fill, and may be horizontal, inclined or undulating, depending on the nature of the sediment surface. Notches can also form in vadose environments by lateral erosion by a stream flowing over a sediment fill.

Paragenetic development led to the development of complex sedimentary fills, with multiple phases of sediment injection, deposition and erosion. The low discharge and shallow gradients of most of the conduits studied, coupled with the predominance of clay, silt and fine sand from the overlying superficial deposits favoured the deposition of fine-grained sediments in a low-energy environment. Climatic fluctuations drove the periodic influx of sediment followed by long periods of quiescence and ponding. Localized breakdown and collapse generated more angular, coarser breccias with chalk and flint clasts. Continued upwards dissolution reduced the hydraulic flux and generated the accommodation space for continued sediment accumulation. In this way, stacked sequences of locally cross-bedded loessic silts and fine sands, interbedded with laminated silty clay and localized chalk & flint breccias accumulated.

During peak glacial events, groundwater circulation was largely curtailed and sediment influx reduced. Renewed groundwater circulation in the subsequent interglacial led to the continued enlargement of the immature conduits initiated during the pre-glacial phase of base-level fall. This enabled the water-table to fall to the level of the previous terrace aggradation. As these lower conduits enlarged, the older, now largely sediment filled higher level conduits became defunct. Some modification of these older relict conduits by invasive vadose inlets led to localized washing out of sediment and the development of vadose trenches and shafts.

The combined result of aggradation and incision of the Seine River is a stacked suite of relict quasi-horizontal phreatic conduit systems at discrete levels, each developed at or just below the contemporaneous water table in a shallow phreatic zone. Models of terrace and cave formation suggest that although each relict cave level reached maturity during interglacial conditions, they are graded to the level of sediment aggradation from the preceding cold phase (Bridgland and Maddy, 2002; Häuselmann *et al.,* 2008), and thus can be linked to terrace levels. Dating of sediments and speleothem deposits within these relict cave systems gives a minimum age for passage abandonment and hence base-level fall. Comparing the altitude and age of alluvial river terraces with dated cave levels can help constrain rates of river incision and the evolution of the karst system.

Figure 7 shows conceptual model scenarios for karst conduit development in the Seine Valley, using three representative caves as references. In the Funiculaire cave (Figure 7), paragenetic features including half tubes, pendants and anastomotic channels (Farrant and Smart, 2011) suggest the cavity was partially infilled when the cave was still an active conduit (Figure 4), leaving an open phreatic tube above the sediment fill. Many small, largely sediment filled paragenetic conduits feed up into a larger horizontal passage with an open phreatic tube above the sediment fill and scallops indicating flow to the south. The passage morphology suggests that sediments were deposited under shallow phreatic or epiphreatic conditions, probably at or close to the level of the water-table. Localized chalk and flint breccias indicate localized breakdown when the conduit was active. Later erosion and sediment compaction following base-level fall led to the partial removal and reworking of the sediment fill. Similar features are observed in Fortin cave with paragenetic half-tubes, anastomoses and abundant scalloping on the ceiling (Figure 6). Other caves such as Roche Foulon (Figure 5D) and Mt-Pivin (Figure 5F and G) show half tubes and large scallops on the ceiling with sediment infill levels reaching the cave ceiling.

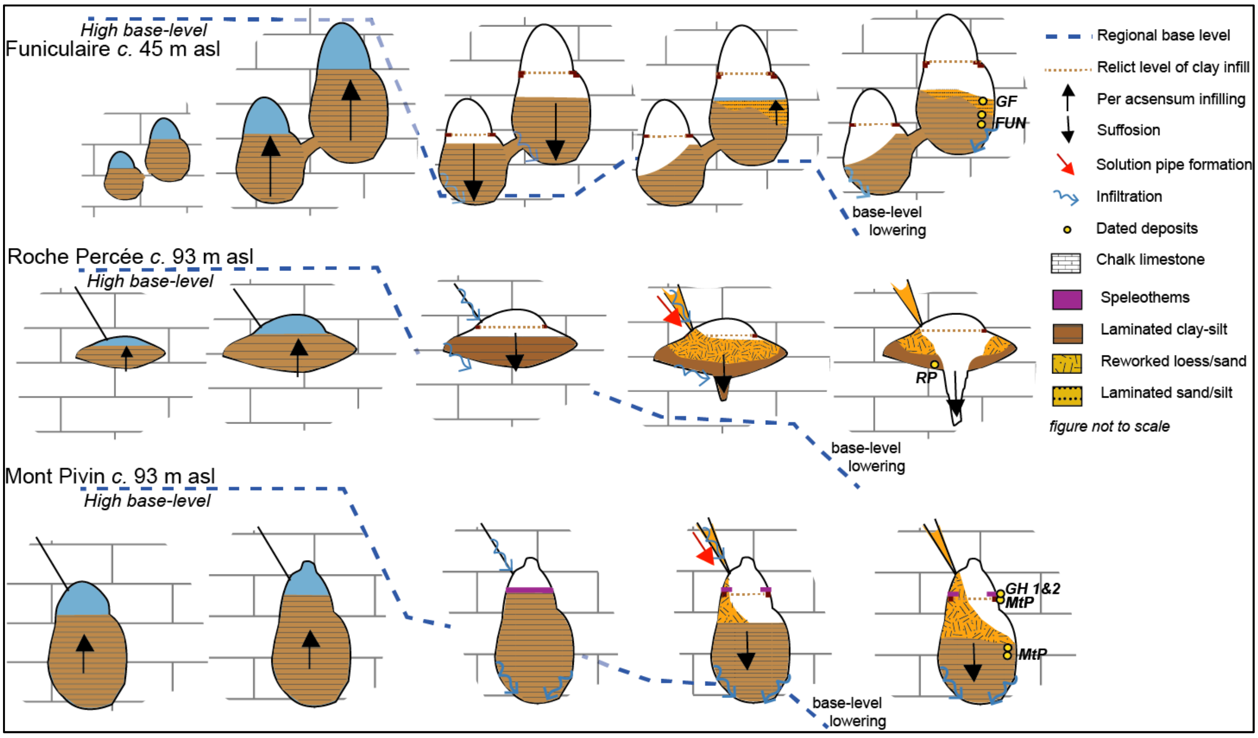

Figure 7. *Synoptic model for the evolution of the studied caves along the Seine valley. The development stages for each cave run separately from left to right. The yellow circles refer to dated deposits (Palaeomagnetic sample) and dated speleothems (uranium series). The dated samples are referred with their codes in Table 1 and 2.*

The Roche Percée system provides a slightly different model of conduit development. Initial phreatic enlargement and localized minor paragenetic modification was followed by passage abandonment. Late stage invasive vadose inflows via shaft drains cut vadose trenches and shafts, documenting continued readjustment to base-level lowering along with sediment evacuation (Figure 7). By contrast, the Mont Pivin system, initial phreatic development followed by paragenetic enlargement created a sediment filled canyon. Following passage abandonment, speleothem deposits were able to grow over detrital infill. Later invasive influxes of sediment and water entering via shaft drains removed and redeposited some of the sediment.

The Caumont system also displays clear evidence of paragenetic development. The present conduit (Rivière des Robots) is a c. 2 m deep paragenetic canyon with localized roof pendants (Figure 6F) and a wider solutional notch at roof level, creating a flat 'laudecke' ceiling above the sediment fill (Figure 6D and H). This epi-phreatic notch marks the water-table prior to base-level fall. Several high-level rifts attest to an earlier phase of phreatic development (Figure 6G). Much of the sediment has been recently flushed out by the stream following breaching of the conduit by the quarry, aided by the early explorers, revealing the canyon form. Small speleothem deposits occur on top of the sediment fill indicating the epi-phreatic zone, and have been left as "false floors" (ancient pavement) after the sediment was removed. These morphological observations coupled with the sediment infill indicate that most of the cave passages were formed under paragenetic conditions with sedimentation occurring when the cave conduit was functioning.

Landscape evolution model of the Seine valley

Figure 8 displays the reconstructed paleo-water table in the Seine Valley for the last million years, showing regional levels inclined at *ca.* 0.06% toward the Seine estuary which represents the current base-level. This represents the foreshortened gradient across the meanders rather than the actual river gradient. The highest and therefore oldest cave system in the Seine valley is the Mont-Pivin system formed when the water table was at or higher than ~107 m RH. Both this and Fortin cave probably predate the Jaramillo subchron, so these cavities are likely to be older than 1.071 Ma. These most likely developed during MIS 33 or 35 and were infilled at the onset of the following glacial phase. The commencement of the Jaramillo subchron is recorded by the sediments in the Six Frères cave, which was probably active during MIS 31. Later, three cave systems were developed during the Jaramillo subchron. The Trou d'Enfer, Roche Foulon (upper part) and Roche Percée caves contain sediments deposited during the Jaramillo subchron between 1071 and 990 ka, suggesting the caves developed during MIS 27 or 29. Although the Roche Foulon (upper) and Roche Percée caves are at different elevation above sea-level, they are at similar relative elevation (70-80 m) above the Seine River, indicating that they are coeval. The transition back to reversed polarity sediments is recorded in the lower part of Roche Foulon cave (MIS 25). The Funiculaire cave (Figure 7) was active during the late Matuyama Chron, probably during MIS 21 at around 860 ka.

The lowest cave level is the Caumont cave system. Here, an initial system of phreatic conduits developed when the water table was higher than ~57 m RH. Following based-level fall, a lower level conduit system developed at ~21 m RH (Figure 2- Caumont section). The system has now been partially drained. Speleothem deposits overlying sediments and debris falls in the lower levels dated to 274 ± 7 ka imply that the upper cave level was drained prior to MIS 7. By implication, this shows the Caumont caves system has been active for >300 ka, and the water table was at or below 23 m RH during MIS 7 and 5 (Figure 9). Fluvial aggradation in the lower Seine valley driven by a marine high stand during the last interglacial stage did not affect the Caumont cave system, as active speleothem growth was occurring at this time.

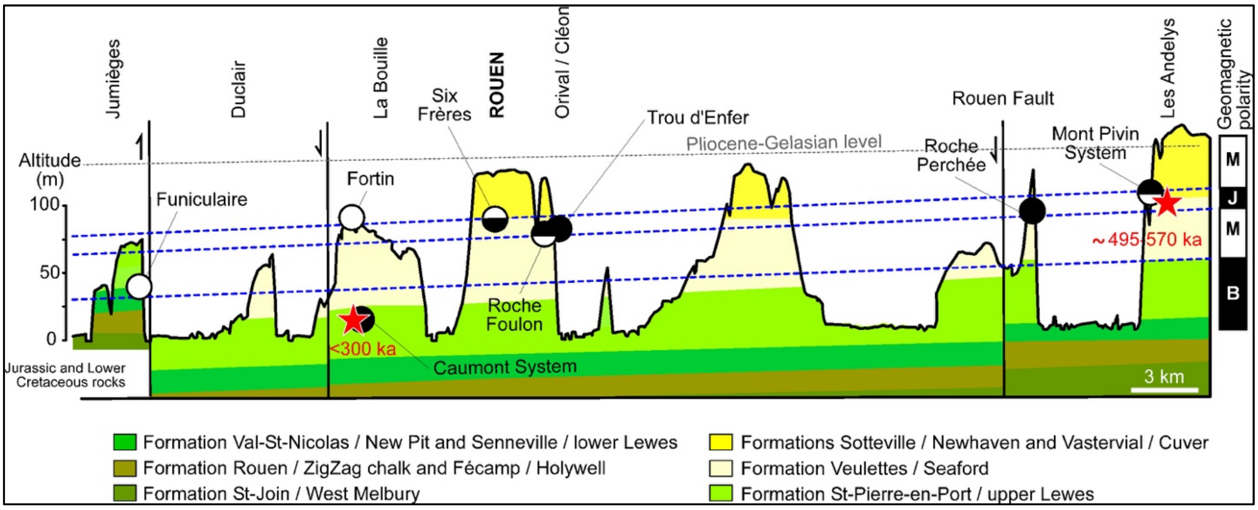

Figure 8. *Synthetic stratigraphical log for the middle section of the lower Seine Valley with the relative height of the studied caves, the projection of the palaeo-water table gradients. The palaeo-magnetic relative dating of the sediment infilling is marked in white (inverse) and black (normal) circles and the U-Th dating of speleothem representing the abandonment of the caves by the regional drainage system, are marked in red stars. The altitude (vertical axis) of the log is exaggerated.*

The dating evidence from the cave systems, after accounting for the gradient of the Seine valley, suggests they can be correlated with the dated alluvial terrace sequences (Figure 9). The results from the dating indicate most of the higher-level cave systems predate the development of most of the well-preserved terrace sequences and suggests that incision began before *ca.* 1.1 Ma. The onset of valley incision is constrained by the presence of late Pliocene marine sand (St-Eustache Fm) and the La Londe clay of

Gelasian age (1.8-2.58 Ma) on the Upper Normandy plateau (Van Vliet-Lanoe *et al.,* 2002). The highest-level cave systems probably developed around MIS 33 or 35, just prior to the deposition of the highest terraces at ~95 m RH (Figure 9), and may be attributed to the palaeo-Seine-Loire river catchment (Westway, 2004).

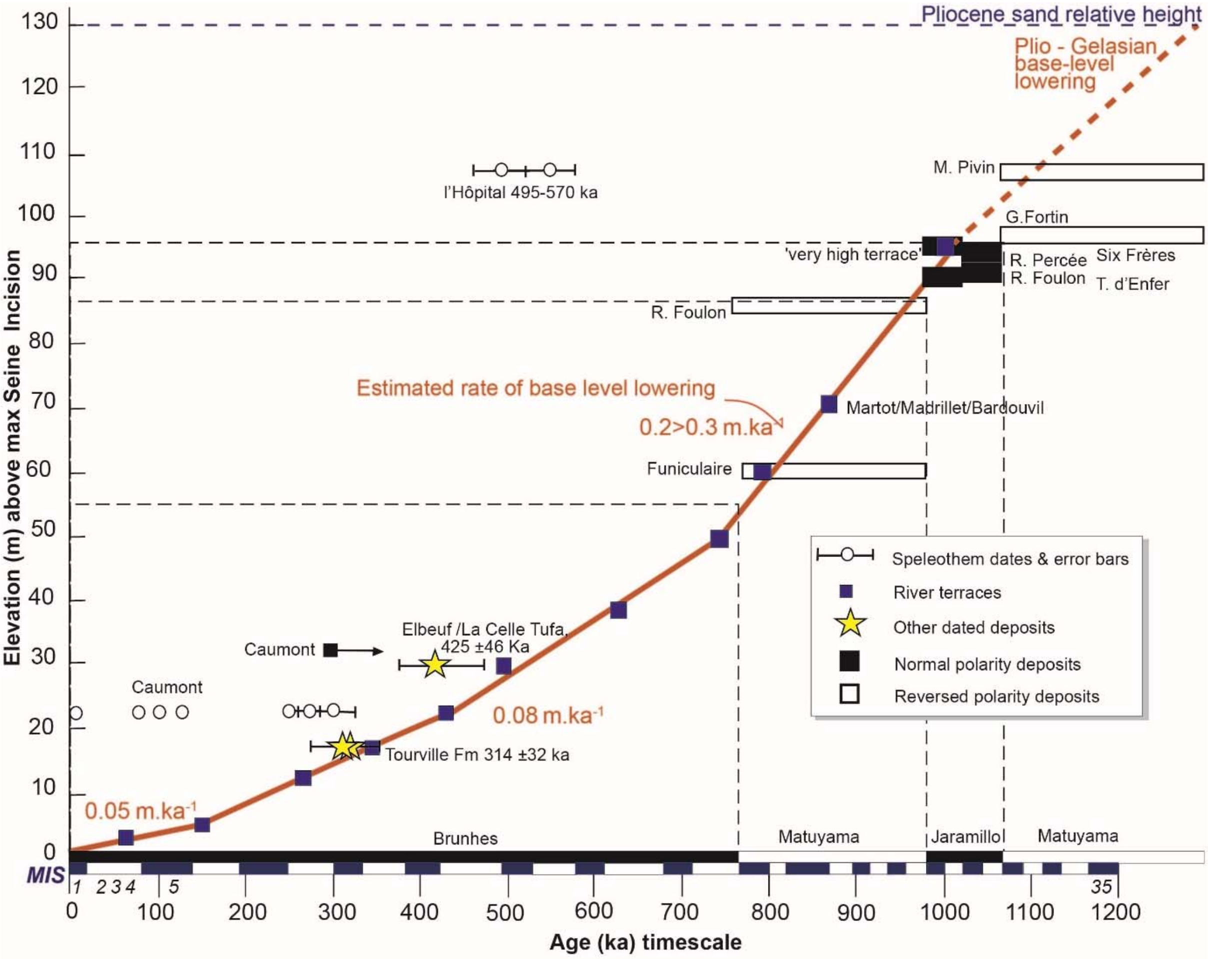

Figure 9. *Estimates of the incision rates for the Seine valley from fluvial terraces and tufa deposits and caves (speleothems and sediment deposits- this study). The terraces positions are based on their elevation above maximum incision (Present relative height - Base-level above Seine bedrock) as well as on dating performed on fluvial sediments and tufas from previous studies (Lautridou et al., 1999, Antoine et al., 2000, 2007, Cliquet et al., 2009) for Rouen, Oissel, Tourville and St-Pierre les Elbeuf-la Celle Fm. The Martot/Bardouville/Madrillet and Rond de France are less-well dated but correlate with other dated terraces (Westway et al., 2004; Lautridou et al., 1999, Antoine et al., 2007). The 'very high terraces' with an average RH (Antoine et al., 2007) dated to about 1 Ma (Tourenq et Pomerol, 1995) define the onset of the River Seine incision after separation from the Loire Basin. The black square with an arrow for Caumont presumes a speleogenesis onset of this karst system earlier than ca. 300 ka.*

The dating of the various cave levels, coupled with estimated ages of fluvial terraces and cave levels based on correlations with marine isotope curves enable rates of river incision to be calculated (Figure 9). Magnetic polarity data suggests there has been ~58-60 m of incision since Brunhes-Matuyama transition, implying an average rate of river incision of 0.074-0.076 $m \cdot ka^{-1}$ over this time, and up to 90 m since the start of the Jaramillo subchron (equivalent to an average of ~0.084 $m \cdot ka^{-1}$). The evidence from the cave and terrace sequences indicate that river incision was initially slow during the early Pleistocene, followed by a phase of more rapid river incision from MIS 28 to 19 (*ca.* 1 to 0.7 Ma), with rates reaching a maximum of ~ 0.30 $m \cdot ka^{-1}$. This phase was probably triggered by the incision of the English Channel River (Gibbard and Cohen, 2015) and matches the onset of widespread erosion within the Paris Basin (Guillocheau *et al.,* 2000; Lagarde *et al.,* 2000; Robin *et al.,* 2003). Bridgland and Westaway (2008) suggest there was a global acceleration of uplift at the time of, and perhaps in response to, the Mid-Pleistocene Revolution. Later, incision rates dropped to ~0.08 m·ka^{-1} from MIS 19 to 5 (Middle Pleistocene), and 0.05 m·ka^{-1} from MIS 5 to present-time (Upper Pleistocene).

Obtained rates are comparable with rates estimated by Lagarde *et al.,* (2000) and Westaway (2004). Antoine *et al.* (2000) derived average rates of 0.055-0.060 m·ka^{-1} since the end of the MIS 19 from the fluvial terrace sequences. Pedoja *et al.,* (2018) reported apparent uplift rates of 0.04 ± 0.01 mm·a^{-1} since MIS 5e (~122 ± 6 ka), and mean Middle Pleistocene eustasy-corrected uplift rates of 0.09 ± 0.03 mm·a^{-1} from marine terraces on the Cotentin Peninsula northwest of the Seine valley. The latter are similar to the rates derived from this study. The similitude between the marine, fluvial terraces and cave data suggests that incision of the Seine River is controlled by gradual long-term tectonic uplift of the region, superimposed by shorter timescale eustatic variations, rather than localized variable incision. There is little evidence from the data of any impact of the catastrophic breaching of the Dover-Artois ridge and opening of the Dover Strait during the Elsterian–Anglian glaciation (Gupta *et al.,* 2017).

Conclusion

Stacked sequences of relict cave levels, combined with river terraces can provide valuable quantitative evidence for landscape change during the Quaternary. This example from the lower Seine valley demonstrates multiple phases of phreatic groundwater circulation and conduit development linked to progressive river incision. These cave levels were graded to contemporaneous base-levels dictated by the incision of the Seine River and can be correlated with fluvial terrace sequences. The evolution of the conduit systems is influenced by climatic changes during the Quaternary. Dating of detrital deposits and speleothems preserved within these caves enables the timing of cave development, and hence fluvial incision to be constrained, particularly during MIS 28-19 when the fluvial terrace record is poorly constrained. Paleo-magnetic dating of sediment infills indicate that the highest-level caves were formed and being actively infilled prior to the start of the Jaramillo subchron at 1.068 Ma, probably in relation to the ancient Seine-Loire River. The evidence from the cave and terrace sequences suggest incision was initially slow during the early part of the Pleistocene, but accelerated from MIS 28 to 19 (*ca.* 1 to 0.7 Ma), with rates reaching a maximum of ~0.30 m·ka^{-1}, dropping to ~0.08 mm·ka^{-1} from MIS 19 to 5 (Middle Pleistocene; *ca.* 0.78-0.12 Ma), and 0.05 m·ka^{-1} from MIS 5 to present-time (Upper Pleistocene). This approach can be used in other karst regions and is particularly valuable where the river terrace record is absent or fragmentary.

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