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Last interglacial in western Europe: 20 years of multidisciplinary research on the Eemian (MIS 5e) calcareous tufa sequence at Caours (Somme basin, France) – a review

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BOREAS



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The calcareous tufa sequence and associated Palaeolithic site of Caours were discovered in 2002 during a test-pit campaign aimed at identifying last interglacial (MIS 5e) archives in the fluvial terrace system of the Somme basin, northern France. The presence of an outstanding stratigraphical succession with four *in situ* Palaeolithic layers within the tufa sequence has motivated archaeological excavations of the site since 2005. The first malacological studies and U-series ages quickly showed that the sequence was mainly deposited during the Eemian interglacial (MIS 5e). After 20 years of investigations, we propose here a summary of this multidisciplinary research project including stratigraphy, sedimentology, geochronology, geochemistry, malacology, mammals, palaeovegetation and archaeology. By combining 25 dates obtained by U-series, ESR/U-series, TL and OSL methods, the Caours calcareous tufa sequence is securely dated to the Eemian (123.1 ± 2.8 ka). Based on the summary of the whole information, we propose a robust and detailed reconstruction of the modification of the valley environments between the Late Saalian and the Early Weichselian. At the scale of northwestern Europe, Caours provides a reference terrestrial molluscs record for the Eemian interglacial, including the climatic optimum, that is also described in the same layers by $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ analyses on calcite and by mammal remains. Moreover, the 300-m-long transect crossing the fluvial terrace covered by the tufa sequence and the bottom valley formation, combined with the chronology established from U-series and OSL ages, shows that the incision of the present-day valley, leading to the setting of the Very Low Terrace, was achieved during the first stages of the Early Weichselian (MIS 5d–5c). From an archaeological point of view, the configuration of the Caours site is unique at the scale of western Europe and demonstrates the adaptation of Neandertals to a forested environment and to fully temperate conditions during the Eemian.

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In the context of current global climatic change, the reconstruction of past interglacial environments and climates from continental sequences has undergone a major development in the last 20 years. Past interglacial periods are considered to be analogues for the present one, the Holocene (before human impact), and for today's climate and so, they are of critical importance for the modelling and the prediction of future climate evolution (e.g. Sánchez-Goni *et al.* 2000; Berger & Loutre 2002; Tzedakis 2003; Shakun 2015; PAGES 2016; Oliveira *et al.* 2018; Tzedakis *et al.* 2018). Besides, due to their richness in fossils (molluscs, pollen, vertebrates),

interglacial sequences from fluvial terrace systems are fundamental to the reconstruction and dating of the palaeoenvironments in which European Palaeolithic settlements took place (Bridgland *et al.* 2006; Antoine *et al.* 2016b; Hein *et al.* 2021; Laurat & Brühl 2021).

In Europe (Fig. 1), Pleistocene interglacial records are mainly described from lakes (e.g. Beaulieu *et al.* 2001; Tzedakis 2003; Klotz *et al.* 2004; Rousseau *et al.* 2006; Strahl *et al.* 2011; Capron *et al.* 2014, 2017; Helmens 2014; Francke *et al.* 2016; Sirocko *et al.* 2016; Börner *et al.* 2018; Malkiewicz 2018; Kupryjanowicz *et al.* 2021; Laurat & Brühl 2021), speleothems

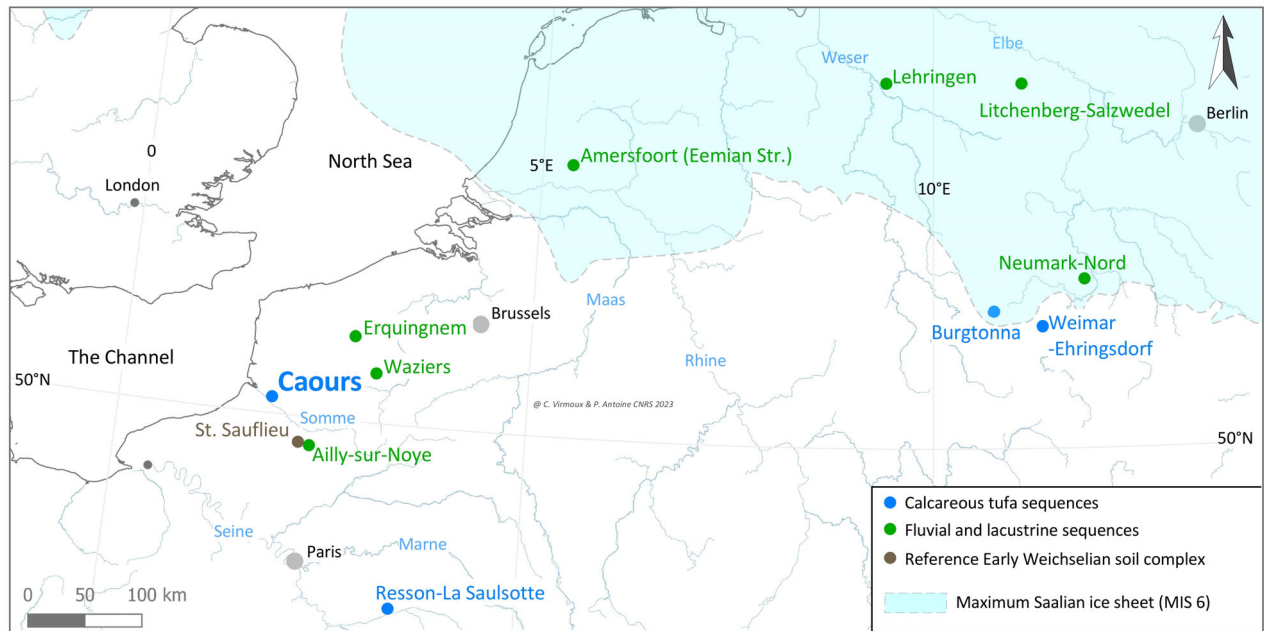


Fig. 1. Location of the Caours site and other Eemian reference sequences and Palaeolithic sites in Europe.

(e.g. Couchoud *et al.* 2009; Genty *et al.* 2013; Moseley *et al.* 2015; Vansteenberge *et al.* 2019) or continental margin sequences (e.g. Sánchez-Goñi *et al.* 2000; Desprat *et al.* 2007). In addition, more discontinuous interglacial records have been observed in fluvial terrace systems from several European rivers, e.g. in the Thames (Bridgland *et al.* 2006), the Saale-Elbe (Mania 1995b), the Seine (Limondin-Lozouet *et al.* 2006) and the Somme rivers (Antoine *et al.* 2000).

For the Eemian interglacial (MIS 5e), reference records were described in western Europe through low energy fluvial and shallow marine sequences preserved in deep basins scoured during the younger Saalian glacial advance (MIS 6) in the central Netherlands (Busschers *et al.* 2008; Kasse *et al.* 2021), where is located the Eemian stratotype at Amersfoort (Zagwijn 1961; Turner 2000). In addition, several famous Eemian sequences with rich large mammal assemblages have been described for a long time from the Thuringian travertines in eastern Germany (Mania 1978; Kahlke 2002; Mania *et al.* 2003).

In NW France (Fig. 1), the Eemian interglacial including its climatic optimum was first described in peat layers from the deepest part of the Lys River Valley infilling at Erquinghem (Sommé *et al.* 1996), and then in the Loon Formation marine deposits occurring at -20 to -30 m b.s.l. near Dunkerque (Sommé *et al.* 2004). Besides, investigations undertaken since the 1990s on the stepped terrace system of the Somme river allowed the reconstruction of the relationship between the fluvial

system and glacial–interglacial climatic cycles during the last 1 Ma, providing a reliable and accurate reference framework for the study of the numerous Palaeolithic sequences (e.g. Antoine 1994; Antoine *et al.* 2000, 2010, 2019). However, from their very beginning, these works on fluvial records raised the issue of the near absence of sediments corresponding to full interglacial conditions, especially to the Eemian (Munaut 1988).

In order to solve this question, research focussing on calcareous tufa sequences from northern France terrace systems (mainly Somme and Seine River systems) was initiated in the early 2000s. This program (SITEP, CNRS, dir. N. Limondin-Lozouet) led to the assignment of several tufa sequences overlying the gravels of a middle terrace of the Somme Valley at St Acheul (Limondin-Lozouet & Antoine 2006), the Seine Valley at La Celle (Limondin-Lozouet *et al.* 2006, 2020) and at St Pierre-les-Elbeuf (Cliquet *et al.* 2009) to the Holsteinian interglacial (MIS 11). In addition, in the Somme Valley, MIS 15 (Cromerian III) interglacial calcareous deposits including layers of oncolitic tufa and large mammal remains were also observed at Carpentier Quarry (Antoine *et al.* 2016b).

In this research context, the Eemian interglacial was first demonstrated at Caours in 2002 in a thick calcareous tufa formation overlying the last fluvial terrace of the Scardon river, a little tributary of the Somme (Antoine *et al.* 2006). Two additional Eemian sequences were later discovered in northern France at Waziers in the

Scarpe Valley (peat deposit; Deschodt *et al.* 2023) and in the Paris Basin at Resson-La Saulsotte in association with a small tributary of the Seine (calcareous tufa sequence; Dabkowski *et al.* 2020; Jolly-Saad & Dabkowski 2021).

These studies in northern France river basins have definitely established calcareous tufa as key archives of Pleistocene interglacials and especially the Eemian. These tufa routinely show evidence of past environmental conditions through well-preserved floral and faunal (especially mollusc) assemblages (Limondin-Lozouet & Preece 2014). Consisting mostly of pure calcite crystals precipitated at ambient temperature, they are also well suited for direct dating using U-series as well as for geochemical reconstructions of palaeoclimatic parameters, especially from oxygen and carbon isotopes (Andrews 2006; Capezzuoli *et al.* 2014; Dabkowski 2014). Additionally, tufa environments are highly suitable for both the settlement of human populations and the *in situ* preservation of the resulting archaeological levels. Consequently, they have a high potential to be useful in investigating human–environment–climate interactions during interglacial periods, from the Lower Palaeolithic to Antiquity (Dabkowski 2014).

While the geological records of continental sediments that can be securely allocated to the Eemian are not so numerous at the European scale, Palaeolithic remains from the last interglacial are extremely rare and even absent in some countries, such as the UK, raising the question of the existence of Neandertal settlements in the area during this period. The occupation of Europe by hominins during interglacial periods has been long debated and extensive research has been devoted to finding the limits of European hominin occupation, both in time and in space (e.g. Roebroeks *et al.* 1992; Gaudzinski-Windheuser & Roebroeks 2011). This led some authors to promote the ‘green barrier’ theory, according to which Neandertal people were not able to adapt to the forest environments of the last interglacial in northern Europe (Gamble 1986). Hence, in addition to its importance as an Eemian reference sequence for northwestern Europe, Caours is also the first Middle Palaeolithic site that clearly contradicts this assumption (Locht in Antoine *et al.* 2006; Locht 2021).

This contribution is an almost exhaustive synthesis of the abundant stratigraphical, geochronological, environmental, climatic and archaeological data obtained from the last 20 years of research at Caours. It combines some previously published works with a large amount of unpublished data, in order to provide a comprehensive discussion of the palaeoenvironmental evolution at the site and, more widely, in northwestern Europe during the last interglacial. Therefore, it highlights the position of Caours as the best-documented sequence integrating both a robustly dated Eemian interglacial sequence and outstandingly well-preserved traces of human occupations.

Caours: site location, historical data and recent research

The Caours calcareous tufa sequence is located in the Somme basin, 4 km northeast of Abbeville, on the right bank of the Scardon river (latitude 50°07′53″N, longitude 01°52′59″E; Fig. 2A). The tufa formation, outcropping below a thin ploughed topsoil layer, is preserved at the confluence between the Scardon and the small Drucat stream, exhibiting a crescent shape over an area of about 30 000 m² (Fig. 2A). Its surface makes a large and weakly sloping terrace located between about +5 and +1 m above the surface of the present-day marshy valleys of the Scardon (to the northwest) and Drucat rivers (to the north).

Although generally considered to have been discovered in the 1950s (Bourdier 1969; Antoine *et al.* 2006), the Caours tufa formation was most likely first observed at the end of the 19th century by Joseph Prestwich, who mentioned a calcareous tufa deposit overlying the southern slope of the Scardon river: ‘a roadside cutting exposes a section of calcareous tufa or travertine several feet thick’ (Prestwich 1863–1864).

Léon Aufrère rediscovered the site in the early 1950s, but never published any information about it. It was then explored by Breuil (Breuil 1952; Breuil & Barral 1955) and Patte (1953) who produced some short notes focusing on the large mammal remains, in particular cervid antlers, found at the base of the tufa sequence in a former quarry, the ‘Boulangier Quarry’, which is completely filled in today (Fig. 2B). The Caours calcareous tufa was then cited by Agache *et al.* (1963) in their review of the Quaternary of the Lower Somme, by Bourdier (1969, 1974) in several syntheses on the Quaternary in the Somme basin and finally by Sommé (1989) in a review paper on the tufas of northern France. Although it has never been the subject of detailed stratigraphical and sedimentological studies before the most recent investigations reported in the present paper, former authors, especially Bourdier, generally allocated the tufa sequence to the last interglacial (formerly Riss-Würm) due to its position at the top of a Very Low Terrace of the fluvial system, as well as the occurrence of molluscs and large mammal remains indicating fully temperate climatic conditions.

Twenty years ago, at the start of the SITEP research program, the Caours calcareous tufa site was undoubtedly the best (and the only) opportunity to study Eemian deposits in the Somme river basin. New investigations have thus been undertaken yearly at Caours since 2002. Although the Caours area has been heavily urbanized since the 1950s and the former ‘Boulangier Quarry’ totally filled, a few untouched plots of land still remained, close to the Caours village at the western edge of the formation (Fig. 2B).

The archaeological site was re-discovered in October 2002 by P. Antoine during a field survey using hydraulic

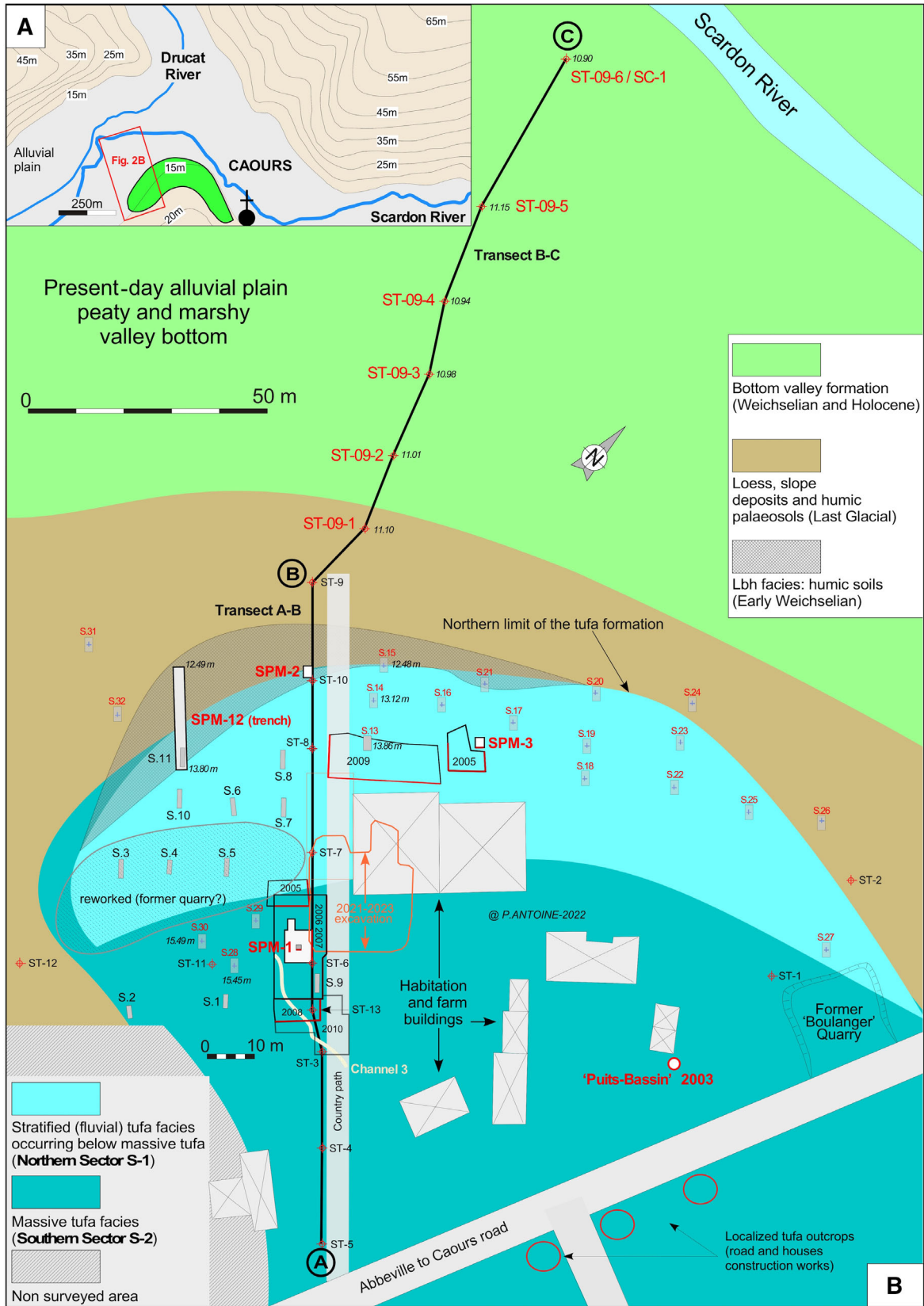


Fig. 2. A. Location of the Caours tufa (green) at the confluence between the Scardon and Drucat River valleys (grey: present-day marshy bottom valley, light brown: chalky slopes with loess cover). B. Location of all survey test pits and excavations undertaken at Caours during the last 20 years.

drilling equipment (SEDIDRILL 150) to establish the stratigraphy of the calcareous tufa formation and to collect the first samples for palaeoenvironmental reconstructions (malacology) and absolute dating (U-series). These investigations resulted in a 170-m-long transect crossing the whole sequence of the low terrace from the Abbeville to Caours road to the left bank of the present-day valley (Transect A–B: 13 boreholes down to ~5-m depth: ST-1 to ST-13; Figs 2B, 3). In two of the boreholes, well-preserved pieces of large mammal bones exhibiting a dark brown patina were discovered at the base of the tufa sequence in a ‘grey tufa level’ at a depth of ~3.5 m.

In April 2003, the first direct observation of the tufa stratigraphy was then possible thanks to the excavation of a deep well through the tufa sequence by the owner of the site at about 100 m to the east of the initial transect (‘Puits-Bassin’, Fig. 2B). A continuous sampling column was performed on this profile for the first systematic malacological study (17 samples collected along ~3-m-long profile). At the base of the sequence, in the upper ‘grey tufa level’ the discovery of a large fragment (≥ 15 cm) of a large mammal bone (aurochs) confirmed the large extent of the Caours archaeological site on a wide surface.

In November 2003, two large test pits were opened with an excavator (SPM-1 and SPM-2; Figs 2B, 4), revealing an exceptionally well-preserved succession of at least three archaeological levels rich in large mammal bones and Palaeolithic flint artefacts. Besides, the first U-series dating results obtained from samples of indurated stromatolites collected both at the surface of the tufa and within the SPM-12003 excavation confirmed the Eemian age of the Caours tufa deposits. On the basis of these early stratigraphical, palaeoenvironmental and dating results, the first archaeological excavation campaign was launched in July 2005 under the direction of J.-L. Lochet. Data collected before this have already been published in Antoine *et al.* (2006).

Additionally, two test-pit campaigns were undertaken in 2006 (12 pits: S.1 to S.12; Fig. S1) and 2009 (20 pits: S.13 to S.32; Fig. S2). They provided an accurate survey of the extent of both the tufa sequence and archaeological layers (Fig. 2B). The most complete section is ~22 m long and was opened in 2006 and 2007 (Figs 2B, 5A). During the 2009 campaign, an 11-m-long trench (SPM-12) was opened at the margin of the tufa formation where humic soils and associated colluvial deposits, directly post-dating the interglacial tufa formation, were especially well preserved (Fig. 2B). Finally, still in 2009, a new mechanical drilling campaign (six drillings: ST-09-1 to ST-09-6, and one continuous core SC-1; Fig. 2B) was undertaken in order to extend the previous transect to the present-day valley floor of the Scardon river. This work provided a 300-m-long continuous cross-section including, for the first time, the lowest terrace sequence covered by the Eemian tufa and the present-day valley sequence

(last glacial gravels, Holocene peat, fluvial silts and colluvial deposits; Fig. 2B Transect A–B–C).

Given the scientific importance of the site and the threat of destruction due to on-going urbanization projects, an attempt to acquire the land by public authorities with the aim of preserving the site for future research was carried out for 10 years in parallel with the annual excavation campaigns. For administrative reasons, the archaeological excavations were suspended for 5 years, then restarted in 2015 after the ‘*Communauté d’agglomération de la Baie de Somme*’ (Abbeville Conurbation authorities) had finally purchased the land. Currently, an initiative to protect the excavation area and the associated stratigraphical profiles and to promote the site to the general public is underway.

Methodology: stratigraphical record and sampling strategy

The stratigraphy of the Caours locality was first established on the basis of the observations made in 2002 from the initial 13 drilling logs supplemented by a 1-m-long core sample (SC-ST-13), then by the small ‘Puits-Bassin’ excavation and test-pit excavations (2003, SPM-1 to SPM-3, Figs 2B–4). These investigations provided detailed stratigraphical observations over several metres long panels on which the definition of the stratigraphical reference labelling still used today in the Caours archaeological excavation is based. They also allowed accurate establishment and naming of the four archaeological levels containing large faunal and Middle Palaeolithic remains, N-1 to N-4 (Figs 4, 5B).

At the same time, the first samples were taken for dating using TIMS U-series on laminated indurated stromatolite tufa, OSL (Optically Stimulated Luminescence) on quartz included in fine tufa layers, ESR (Electron Spin Resonance) from fluvial silts and ESR/U-series on large mammal tooth enamel. Sampling was also performed for sedimentological, malacological, palynological and micro-palaeontological (rodents, ostracods) analyses and palaeoflora remains study (SPM-1, Fig. 4). In the SPM-1 excavation a 2.4-m-thick continuous column (10-cm-thick samples) was sampled for malacology (Limondin-Lozouet in Antoine *et al.* 2006).

Besides, the initial investigations, carried out on a SE–NW axis perpendicular to the present valley, resulted in a 170-m-long profile (Fig. 3). During the first archaeological excavation campaign (2005) and the subsequent campaigns, complementary reference stratigraphical profiles were surveyed and in 2007 a very long (22-m-long) stratigraphical profile, parallel to the main transect, was opened. Additional stratigraphical sequences studied by J. Dabkowski and G. Jamet during post-2008 archaeological campaigns provided complementary information but no significant changes to the stratigraphical record.

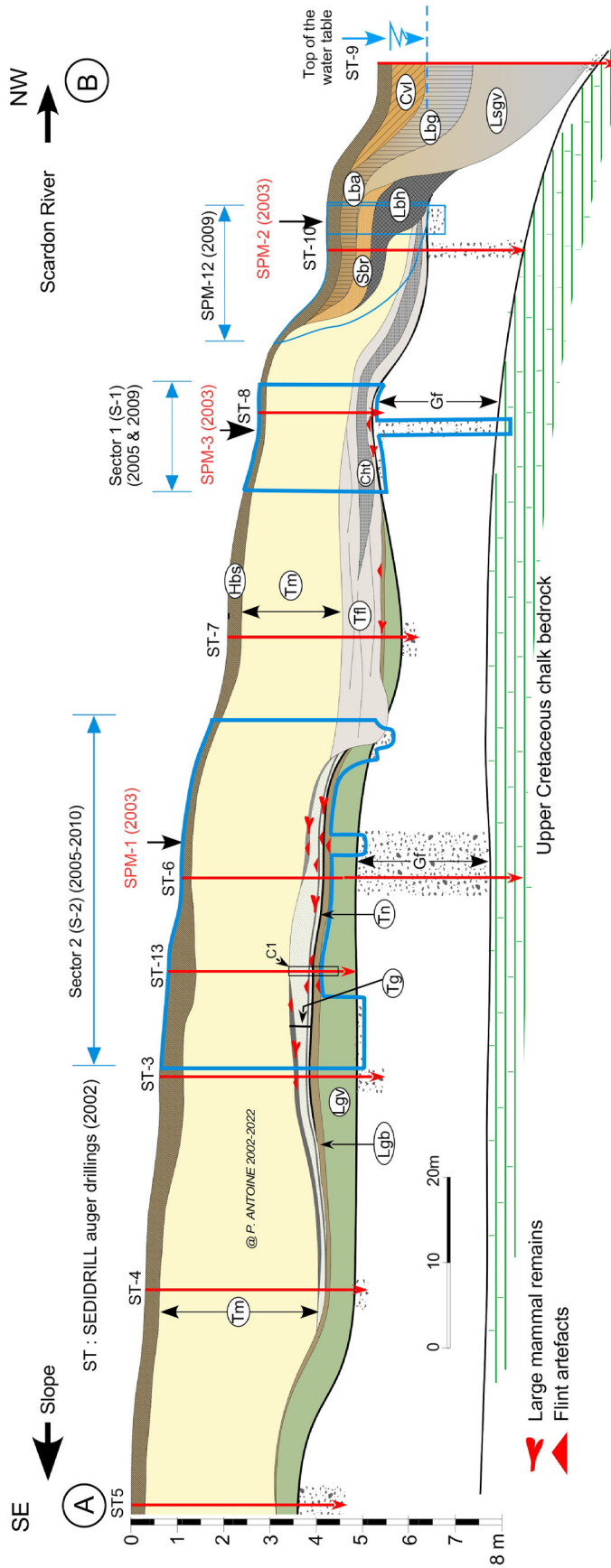


Fig. 3. Geological cross-section of the Caours tufa formation based on mechanical auger drills (ST) and various archaeological excavations (location: see Fig. 2B). Simplified description (detailed description in Table 1): Tm = mainly massive white to beige tufa (U1 to U4); Tg = grey tufa sub-sequence made up of superimposed greyish 'humic' tufa layers including archaeological levels N-1 and N-2 (U5 and U7) and white granular tufa (U6 and U8); Tn = peat layer (U9/archaeological layer N-3); Lgb = grey-brown to greenish marshy soil horizon developed on top of calcareous fluvial silts (U10a & U10b) including archaeological layer N-4; Lgv = calcareous fluvial silts (overbank facies; U11); Gf = periglacial fluvial gravels (U12); Tff = laminated calcareous fluvial tufa; Cht = light grey to dark grey finely laminated fluvial calcareous tufa with abundant aquatic mollusc shells (channel facies); Hbs = topsoil (ploughing Ah horizon); Lbh = loamy colluvial deposits (re-deposited loess and soil products from slope); Lba = brown clayey silts (Bt horizon of the topsoil exhibiting a greyish facies-Lbg-below water table); Lsgv = massive sandy loess with a grey facies below water table towards the present-day valley; Sbr = yellow to brown-red stratified sands with scattered flints; Lbh = complex of colluvial deposits and humic soil horizons (see Fig. 1 and Table 4 for details).

For sedimentological, geochemical and malacological analyses, continuous high-resolution (5 cm) sampling columns were taken from the most complete profile of the southern archaeological sector (Sector 2, hereafter named S-2) in 2005 (Fig. 6) then in 2007 from the long eastern profile (Figs 8, 9). All the geochemical and malacological studies have been produced from these continuous sampling columns (Limondin-Lozouet hereafter in this paper). ESR/U-series analyses and TL (thermoluminescence) dating studies were also realized on teeth and heated flint pieces, respectively.

The 32 test pits, conducted in 2006 and 2009, allowed accurate documentation of the lateral extension of the main tufa facies and the stratigraphical connections between the two excavation areas (Fig. 2B). The reference transect was finally extended to the present-day valley and to a final length of 300 m by six additional auger drillings and a core describing the infilling of the present-day valley and its relationships with to the tufa formation (Fig. 10). Finally, pollen content was tested in various organic facies and in the peat layer (U9) by A. Gauthier (CNRS, LGP-Meudon) and V. Andrieu-Ponel (CNRS-Univ. Marseille) but led to

disappointing results (total absence or very low pollen concentration).

Stratigraphy

Because of the observation of significantly different stratigraphical successions between the various areas studied within the Caours tufa formation, a specific stratigraphical nomenclature was defined in 2002 for each of the two studied areas: southern and northern sectors respectively labelled S-2 (Figs 3–5A, 6, 8, 9) and S-1 (Fig. 7).

Reference stratigraphical succession: southern area (S-2)

In the southern archaeological sector (S-2), the furthest from the Scardon palaeovalley, 11 units dominated by spring tufa facies are defined overlying the terrace gravels (Table 1), whereas the northern sector (S-1) shows only 6 units mainly deposited by fluvial dynamics overlying the same gravel layer (Table 2). Some profiles, such as S-22005 East, show a very rapid transition between the two types of sequences corresponding to the palaeo-Scardon

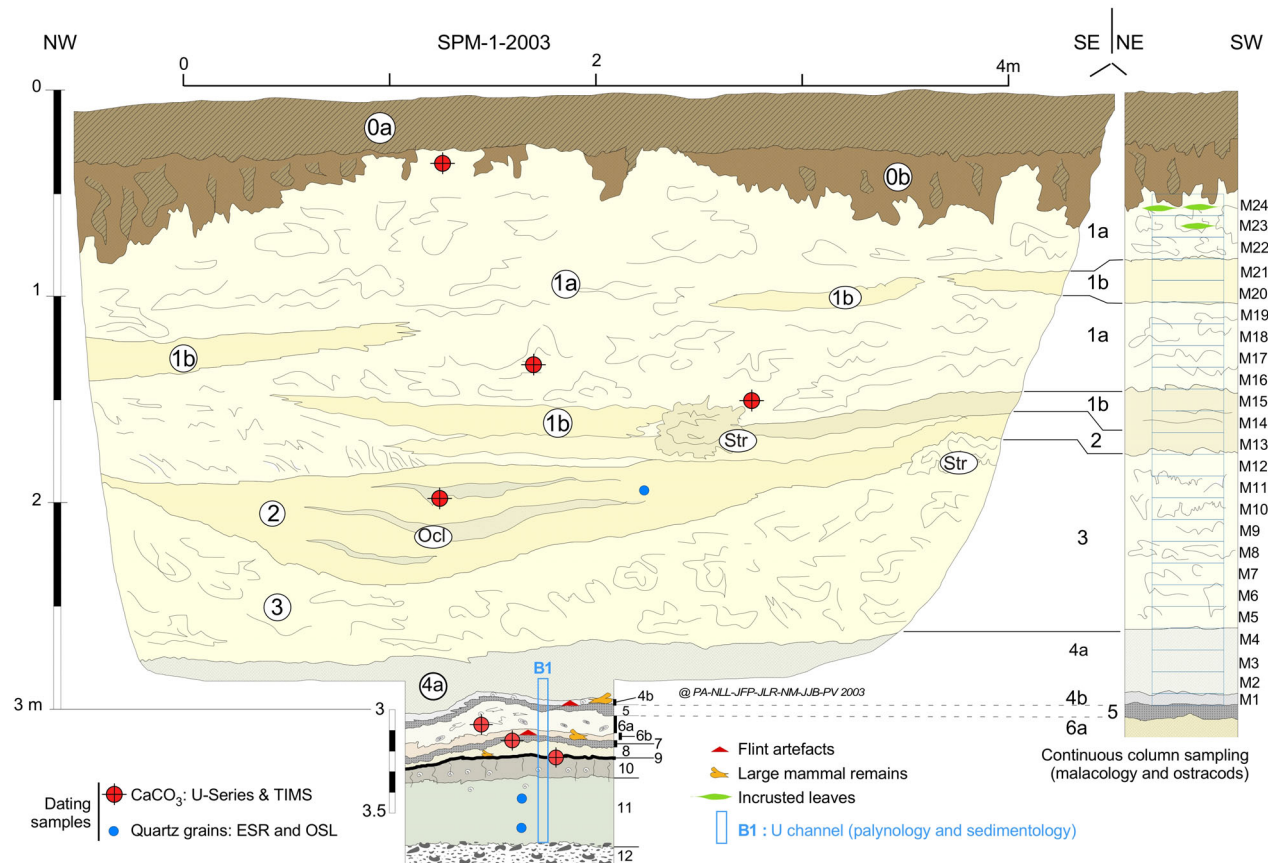


Fig. 4. Stratigraphy of SPM-1 2003 excavation (southern wall) with locations of the various dating samples, and of the first continuous sampling column for malacology (location: see Figs 2B, 3). For a description of the units: see Tables 1, 3.

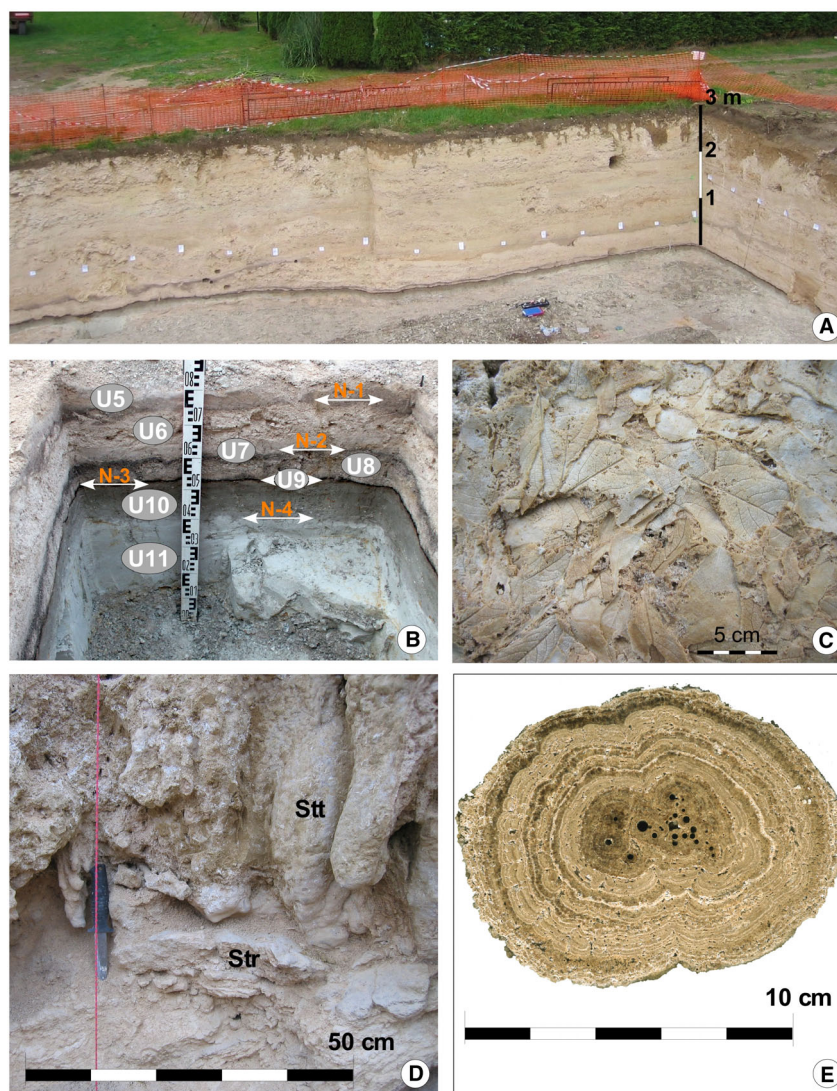


Fig. 5. Stratigraphy and particular facies. A. Full stratigraphy of the southern sector exposed at the end of the 2007 excavation (Profile East: 22 m and Profile South: 10 m). B. Stratigraphy of the base of the sequence exposed in the small ditch at the base of SPM-12003 test pit (location: Figs 3, 4) with the location of the four archaeological levels. C. Encrusted leaves (*Salix* sp.) from facies Tv in section 2007 S-2 (Fig. 8). D. *In situ* large tubular stromatolites (Stt) and subhorizontal stromatolitic crust (Str) in Profile East 2005. E. Polished cross-section of a large tubular stromatolite showing the undulated stromatolitic laminations around the remnants of vegetal stems (2–4 mm in diameter).

riverbank (<3 m: Fig. 6). The most complete stratigraphical sequence being that of the southern sector, it was considered as the reference stratigraphy for the Caours site and completed by sedimentological analyses including total organic carbon and $\text{CaCO}_3\%$ (see Antoine et al. 2006).

However, during successive excavations, specific facies, often lenticular and of limited lateral extent (a few metres at most), were defined in the two different sectors. They are described below using abbreviations independent of the stratigraphical units of the two reference sequences designed by numbers (Table 3). Finally, an additional stratigraphical sequence has been defined for the pedosedimentary facies (slope deposits

and palaeosols) overlying the edge of the tufa in the SP-12 trench (Fig. 11 and Table 4).

Stratigraphical units from the northern area (S-1)

The stratigraphical reference for the northern area of the Caours tufa sequence and archaeological site is illustrated by the 6-m-long profile of the northern area (Fig. 7). Compared to the S-2 area sequence, the stratigraphy of S-1 is quite simple, but it is very important for the interpretation of the whole Caours sequence, its relationships with the palaeo-Scardon river and the connections between the various Palaeolithic occupation layers from the two areas.

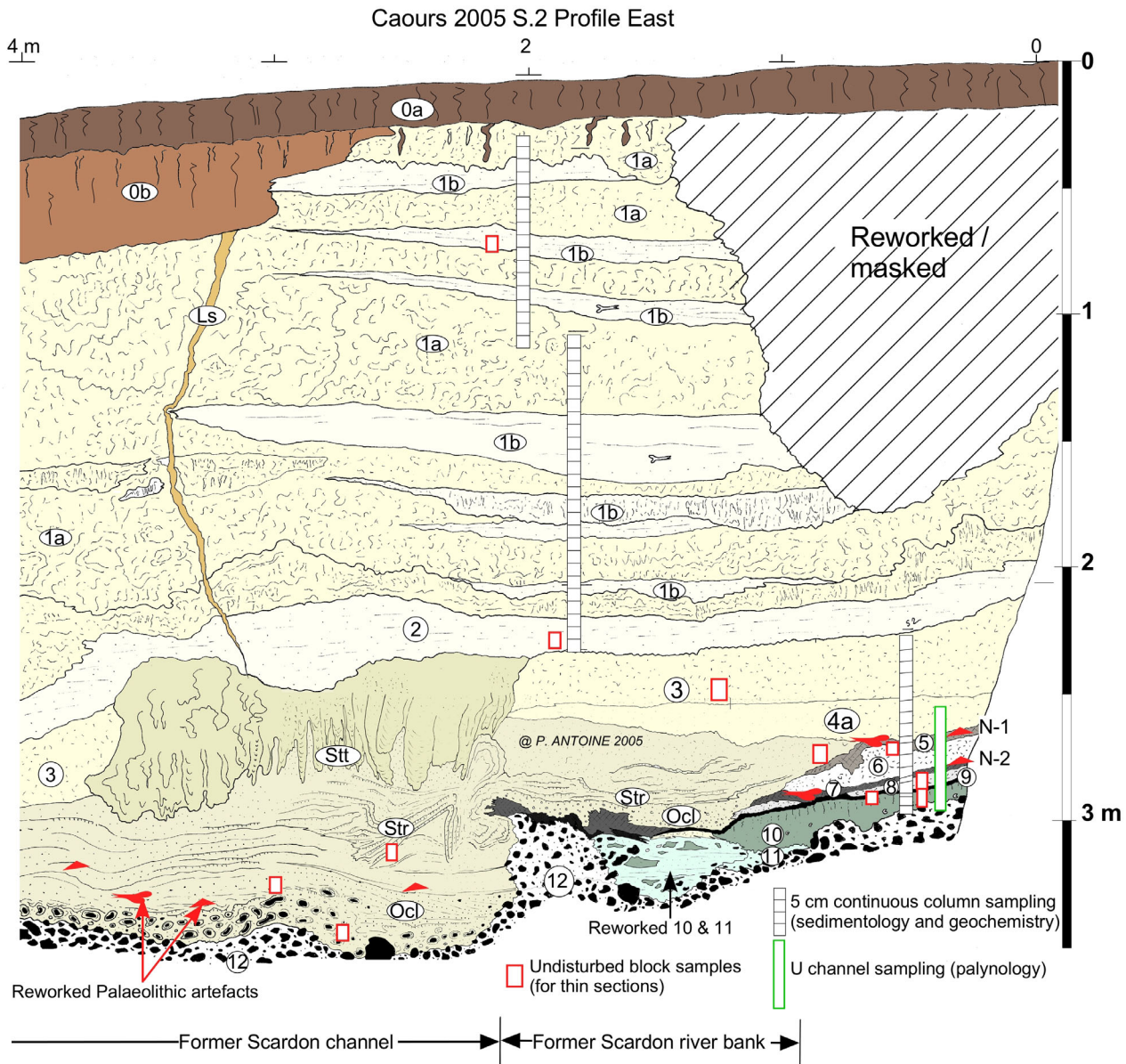


Fig. 6. Caours S-22005 Section East: stratigraphy, location of various samples and of Palaeolithic levels (location: see Fig. 2B; description of the units: see Tables 1, 3).

Particular tufa facies observed in the various profiles

Within the Caours tufa formation some original facies were observed both in the southern and northern areas as well as in the various test pits. As they are not restricted to a specific area they are described below in a separate table (Table 3).

Test-pit trench SPM-12

This 12-m-long profile (Fig. 11, Table 4) allows, for the first time in the Somme basin, the description of a continuous section encompassing the morpho-stratigraphical transi-

tion between the stratigraphical records of the Very Low Terrace and the Bottom Valley Formation. The SPM-12 trench is thus very important for the reconstruction of the environmental changes occurring in relation to rapid climate changes during the end of the Eemian and the Early Weichselian.

Tufa microfacies

The micromorphological study of the Caours sequence was carried out on 34 thin sections from undisturbed blocks extracted from various profiles in excavations SPM1, SPM-3 test pits and archaeological Sectors S-1

Table 1. Description of the units of the southern sector (S-2).

Units	Description
U0a	Humus-brown sandy-clayey silt with scattered flints and granular structure: ploughing (Ap) horizon of the topsoil.
U0b	Brown, non-calcareous sandy loam only preserved in traces of bioturbation (roots) and small depressions at the top of 1a: colluvium.
U0a and U0b combined as Hbs in Figs 3, 10	
U1a	Pale yellow to white, low cohesive, massive tufa with numerous encrusted vegetal remains, large porous indurated blocks and secondary CaCO ₃ precipitation in the voids (mycelium). The upper part of this unit exhibits a level of encrusted leaf remains (Figs 4, 5C).
U1b	Lenses of fine-grained tufa interbedded in level 1a (channels). Fine grey-beige facies with a silty-to sandy texture, low cohesion (no elements greater than 5 mm) and scattered mollusc shells. This facies is made up of encrusted vegetal micro-debris scattered in a homogeneous mass of fine carbonate grains.
U1c	Set of much more porous calcareous tufas with a slightly darker colour and abundant well-preserved encrusted plant remains often <i>in situ</i> (branches, twigs, reed leaves and stems). Local occurrence of indurated finely laminated stromatolite layers a few cm thick (Str) (<i>in situ</i> or slightly reworked).
U2	Massive, beige to light yellow calcareous tufa including oncolith sand beds (oncoliths Ø: 2 to 20 mm) infilling an especially well-developed large channel structure visible in SPM-1 (Fig. 4).
U3	Massive light grey granular calcareous tufa with scattered oncoliths and encrusted twigs (4 to 10 mm), embedded in a fine light beige grey calcareous sandy tufa matrix (Fig. 4). Locally coarser layers made up of <i>in situ</i> encrusted twigs at the base (Tv facies: see Table 3).
U4	Compact light grey fine granular calcareous tufa with fine beige grey matrix, tubular concretions (encrusted small branches and vegetal stems) and scattered <i>in situ</i> encrusted vegetal stems. In the 2007–2008 profiles this unit is subdivided into three subunits: U4a – compact light grey finely granular tufa with silty matrix and <i>in situ</i> encrusted vegetal remains. U4b – compact beige tufa with encrusted vegetal remains and subvertical vegetal stems (Tv facies). U4c – coarse sandy oncolith tufa with rolled twigs (Ocl facies: see Table 3) and erosive basal limit. The erosion preceding its deposition is responsible for the disappearance of U5 in some places of the southern area, is linked to the activity of deep channel structures originating from the lower chalky slope such as the one visible in the southern section 2007 (Fig. 9A, B). Following their incision, the banks of these channels were covered by a porous and well-laminated stromatolitic coating (cement) a few centimetres thick ('biscuit facies', Fig. 9A). The channel is then infilled by stratified oncolitic sands (Ocl) including, at their base, Palaeolithic artefacts and large mammal bone remains reworked from the underlying archaeological level N-1 (Fig. 9B).
U2 to U4 combined as Tm in Figs 4, 10	
U5	Grey granular calcareous tufa layer with abundant silty to sandy matrix, abundant mollusc shells, numerous large mammal bone remains and teeth, rodent remains, earthworm calcite granules (≤1 mm) and Palaeolithic flint artefacts (main archaeological level N-1). To the south of the site this unit shows a much more irregular geometry characterized by significant variations in thickness (5 to 20 cm) and an irregular upper limit with involutions (load casts?). In the 2007 and 2008 profiles it is fully eroded by fluvial activity linked to the overflow of small lateral channels originating from the lower slope (Figs 8, 9). U5a – Uppermost facies of U5 made up of a very homogeneous grey silty tufa.
U6	Compact white tufa with numerous encrusted twigs and locally large tubular oncoliths formed around longer twigs (3–5 cm; Figs 3, 4). This unit thickens in Profile 2007 where it shows a more complex facies including a channel infilling extremely rich in encrusted leaves (Unit 6'; Tm facies; Fig. S3C).
U7	Fine dark grey compact granular silty tufa with abundant matrix mollusc shells, bone remains and <i>in situ</i> Palaeolithic artefacts (archaeological level N-2, Fig. S3C). U7' – Lateral facies observed in the southern part of the excavation 2007–2008 (Fig. 9), where it is characterized by a markedly finer texture passing to a dark grey-brown humic calcareous silt directly overlying the peat layer U9.
U8	Light grey granular calcareous tufa with centimetre-sized oncoliths, numerous encrusted branches and scattered mollusc shells (Figs 4, S3C).
U5 to U8 gathered as Tg in Fig. 4	
U9	Thin (≤1 cm generally <5 mm), but continuous, compact black silty-peat horizon (TOC: 4.4 to 9%) making up the interface between the uppermost part of the silty sequence (U10) and the first calcareous tufa deposits (U8). The surface of this silty peat layer yields a lot of <i>in situ</i> large mammal bone and teeth remains (Figs 4, 5B, S3A) associated with flint artefacts (archaeological level N-3). U9 = Tn in Figs 3, 10.
U10a	Compact grey-greenish calcareous brown clayey silt (CaCO ₃ : 15–25%), with orange oxidation patches and tubes (former root tracks) lightly humic (TOC: 0.2–0.4%), diffuse prismatic structure, scattered mollusc shells and shell fragments. A rich archaeological layer including large mammal remains and flint artefacts locally associated with heated and burnt elements (bones and flints) occurs at the base of this unit at the boundary with the underlying silts of U10b or 11 when facies 10b is not present (archaeological level N-4; Figs 5B, S3A).
U10b	Light grey-green compact calcareous clayey silt with oxidation patches and numerous large and well-preserved terrestrial molluscs (<i>Cepaea</i>) often concentrated (by floatation processes) at the top where they make up a 1–2 cm thick ' <i>Cepaea</i> layer'.
U10a and 10b gathered as Lgb in Figs 4, 10	
U11	Compact, homogeneous, light green-grey to light grey fine calcareous silts with subvertical ferruginous oxidized root tracks, scattered small mollusc shells and fragments in the upper part (Figs 5B, S3B). U11 = Lgv in Figs 3, 10.
U12	Heterometric coarse fluvial gravels (flint and chalk) with abundant sandy-calcareous matrix (Fig. 4).
U13	Weathered chalk bedrock (Upper Cretaceous).

and S-2 from 2003 to 2006. The extended descriptions and interpretations of microfacies have already been published in a dedicated paper (Dabkowski *et al.* 2010) and are summarized below. They are distributed into two groups (Fig. 12): (i) predominantly quartz silt detrital facies representing the fine fluvial deposits prior to the formation of the tufa sequence (U10 and U9), and (ii)

calcareous tufa, including stromatolitic and massive tufa facies.

Fluvial formation microfacies (U10 and U9)

In thin sections, stratigraphical units U10 and U9 mainly consist of coarse silts to fine sands of quartz, rounded to

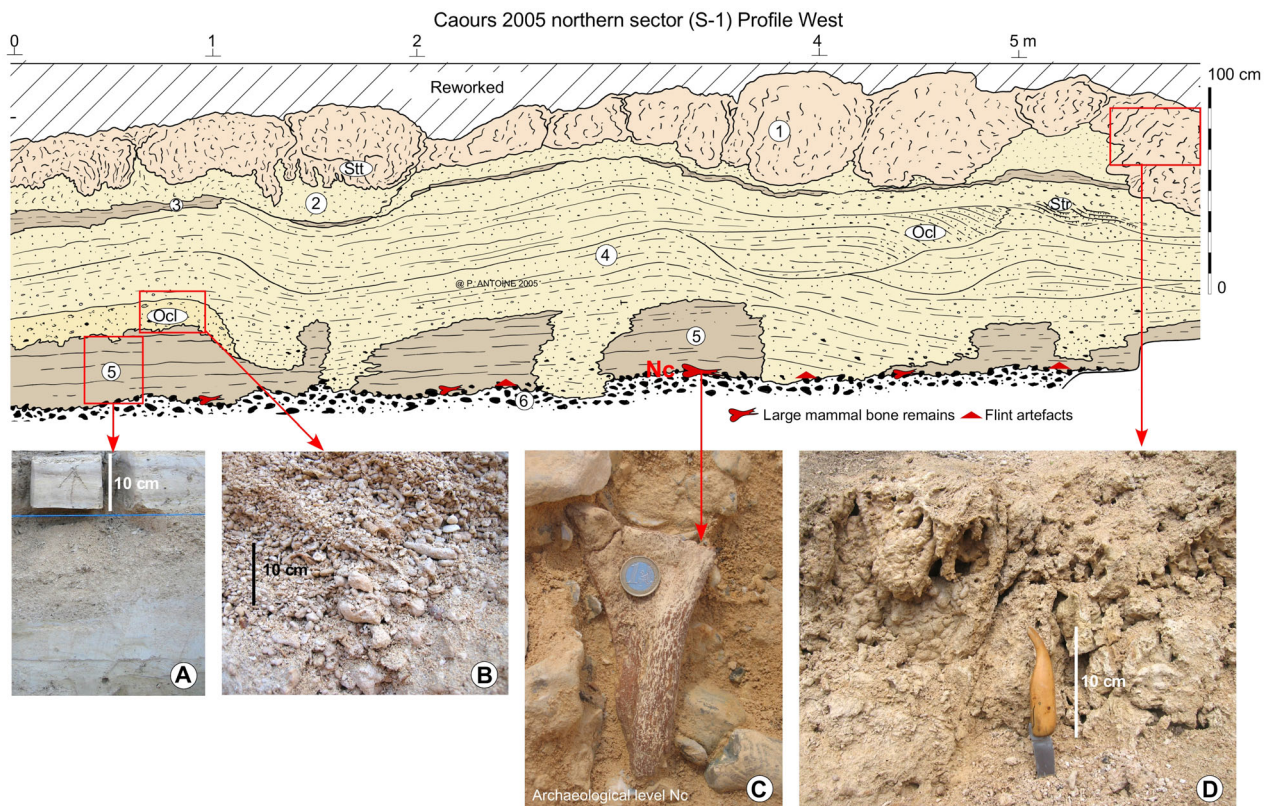


Fig. 7. Caours 2005 northern sector (S-1), stratigraphy of the western profile and location of the Palaeolithic level (location: see Fig. 2B; description: see Tables 2, 3). A. Fine calcareous tufa facies (from U5). B. Close up of the oncolith sands at the base of U4. C. Large mammal bone remains from archaeological level Nc. Close up of on *in situ* tubular stromatolites from the massive tufa layer U1.

subangular, poorly sorted (Fig. 12A, A', B, B'). Some orthopyroxenes were also observed.

In U10, this detrital facies is relatively homogeneous but locally includes small carbonate beds, a few millimetres thick, characterized by a micritic matrix and fragmented gastropod shells. These levels frequently show root impressions. In agreement with field observations, the grain size, grain morphology and facies homogeneity show that U10 corresponds to a fine fluvial deposit during flooding events. These observations reflect a deposition by suspension in the alluvial plain in connection with episodic floods fed by a single meandering main channel (overbank deposits). The fine detrital calcite layers are bioturbated, intersected by root tracks, and contain shells. These bioturbation processes result from the development of a small alluvial plain soil within the upper part of U10 (organic Gleysol).

U9 appears finely laminated and highly fragmented. It is distinguished from the previous one by a very dark, black-brown matrix background, opaque in polarized light, corresponding to organic matter (Fig. 12A, A'), which gives it a black colour. This facies also contains small bone remains, angular flint fragments and charcoals exhibiting preserved fibrous structure and blurred contours. The morphology of these charcoals

attests to an anoxic environment characteristic of a peat bog. The fragmentation of the peat is probably linked to a desiccation event and then to the compaction during the deposition of the following 4 m of sediments. These transformations do not affect the disposition of the Palaeolithic remains present in U9 (flint fragments – absent in U10 – and faunal remains constituting archaeological level N-3). Thus, the archaeological remains making up this archaeological level are probably undisturbed.

Locally, at the top of this unit, phosphate deposits, containing highly fragmented bone remains, and characterized by a high porosity and a chequerboard structure, are observed. They are similar to coprolites attributable to carnivores and seem to have been deposited at the same time as U9. They illustrate at least one episode of land stabilization and temporary draining, allowing the passage of animals and the occupation by humans.

The top of U9 is affected by an erosion surface that can be observed both in thin sections and on the field. It is overlain by the tufa facies (Fig. 12A, A'). This abrupt transition results from the activation of springs at the foot of the slope delimiting the palaeovalley in relation to a general rise in the water table (chalk water table), and at the origin of most of the tufa precipitation at Caours.

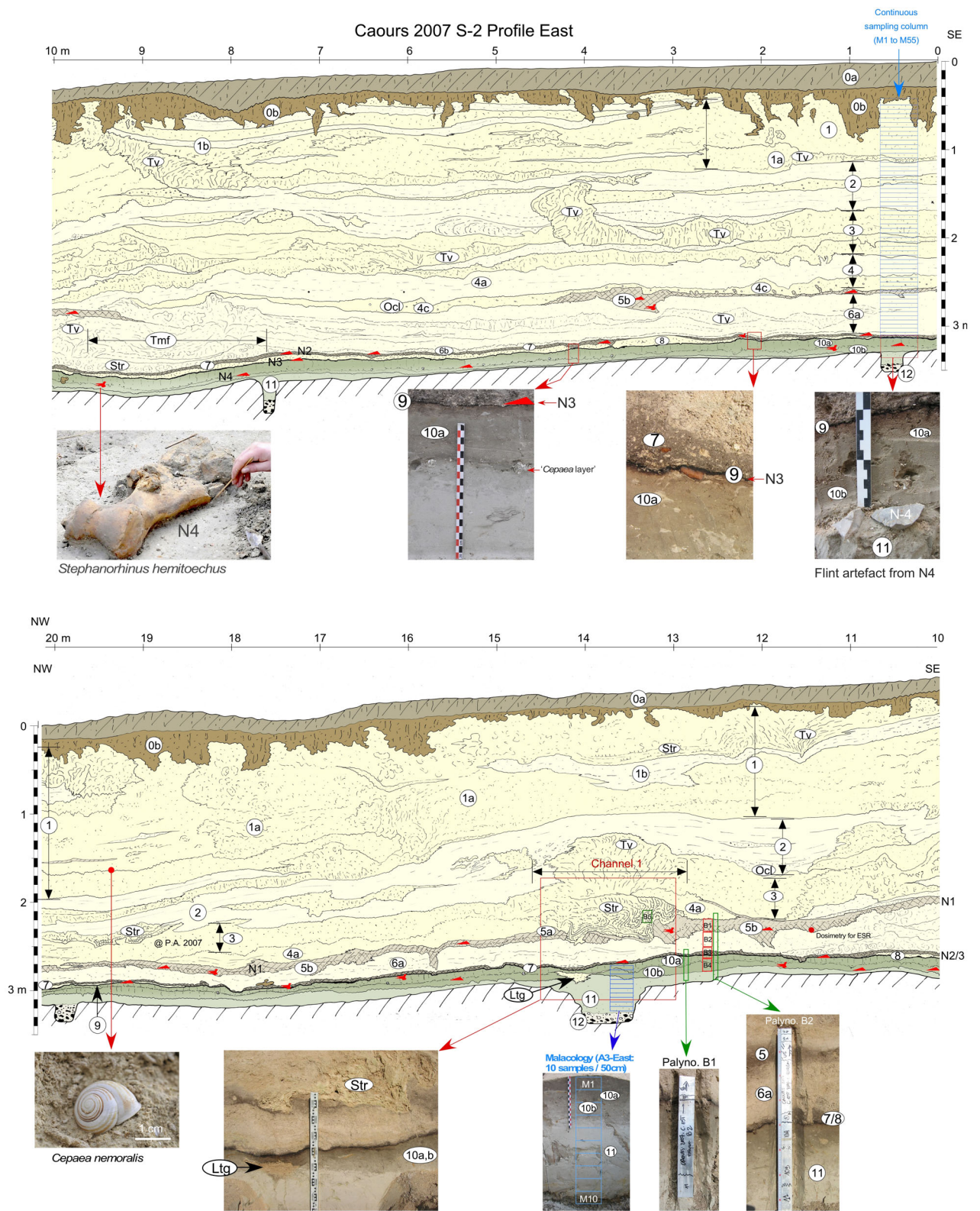


Fig. 8. Caours Profile East 2007 (location: see Fig. 2B; description: see Tables 1, 3).

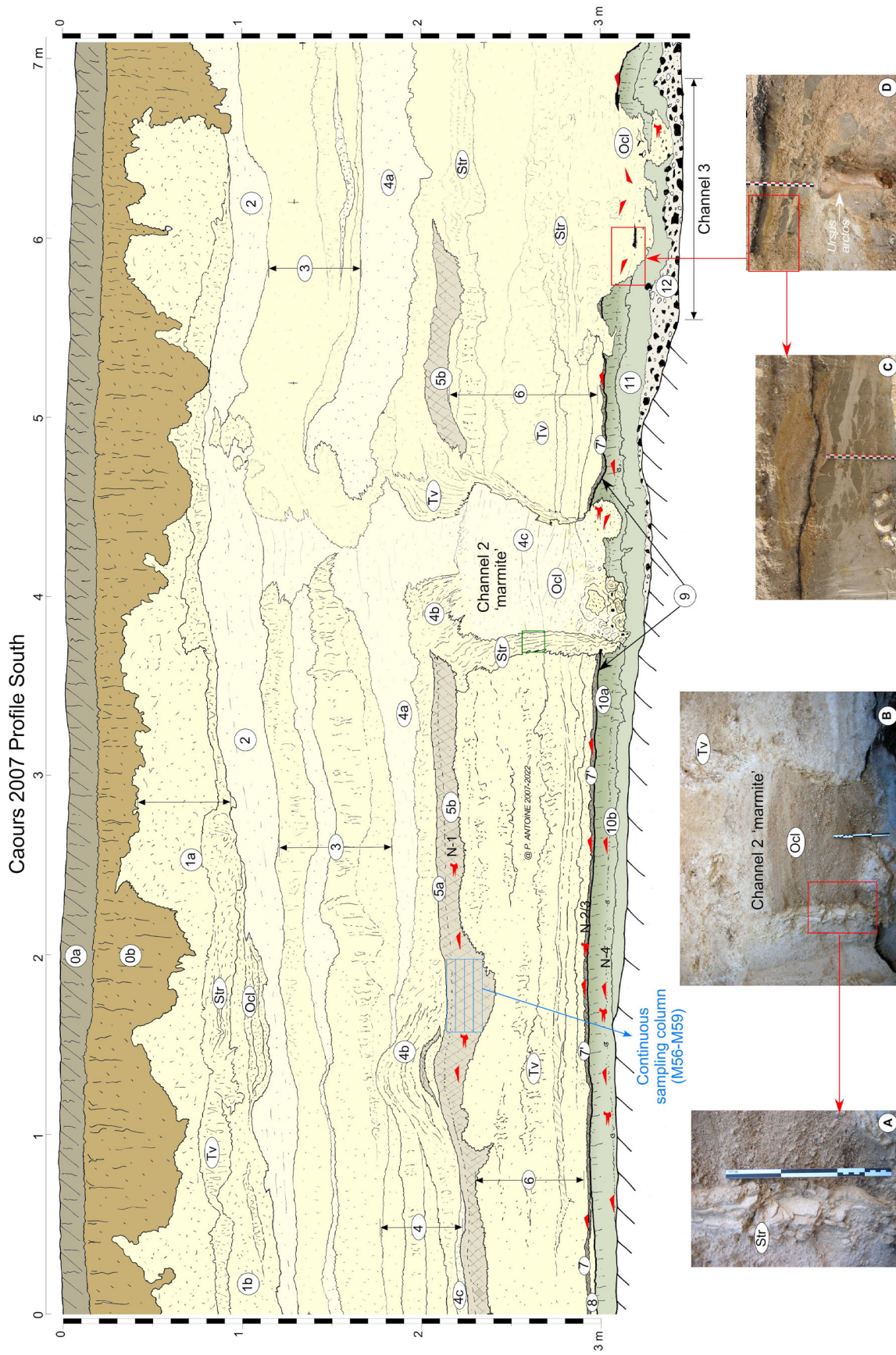


Fig. 9. Caours 2007 Profile South (location: see Fig. 2B; description: see Tables 1, 3).

Table 2. Description of the units of the northern sector (S-1).

Units	Description (Fig. 7 mainly)
U1	Beige, massive and strongly indurated porous tufa including very large concretions, cemented stromatolite 'slabs' and tubular stromatolites (Stt facies, Fig. 7D, Tm in Figs 3, 10), with, locally, secondary carbonate coatings and pseudomycelium in the porosity.
U2	Set of light beige to white sandy low cohesion porous tufas with diffuse bedding. This unit contains numerous <i>in situ</i> calcified tufts of mosses and small twigs. Locally, porous laminated stromatolite floors (Str) and rounded stromatolite forming 'balls' are observed.
U3	Large lens of light grey to beige finely laminated calcareous tufas (silty texture) exhibiting some millimetre-thick dark grey beds including abundant plant micro-remains and mollusc shells (U3b). The upper part of this unit (U3a) shows coarser (centimetre-thick) beds and layers with a coarser granular facies. Tfl in Figs 3, 10.
U4	Low cohesion beige granular calcareous tufa made up of rolled encrusted twigs and oncoliths (average ϕ : 5 mm, locally 2–3 cm towards the base, Fig. 7B) exhibiting large-scale low angle fluvial bedding. Its lower contact is strongly erosive and shows deep overburden features reaching the top of the underlying gravels. Tfl facies in Figs 3, 10.
U5	Low cohesion beige calcareous sandy to silty 'soft' tufa with diffuse stratification, including small flint gravels reworked from U6 at its base (Fig. 7A). Tfl facies in Figs 3, 10.
U6	Heterometric coarse gravels (U12 in the southern area), the upper part of which is impregnated by grey-green calcareous silts identical to those visible in the southern area (U11 and U10) and then by the fine tufa of U5 (over approx. 5 cm). The archaeological level labelled Nc (Fig. 7C), excavated in this area between 2005 and 2009, is located at the top of the gravels on which the larger ones are found. Nevertheless, flint flakes and smaller large mammal bone remains are also spread over a few centimetres into the tufa matrix that permeates the top of the gravels and a few pieces were found in the first 5 cm of U5 (reworked bone fragments). U6 in S-1 = U12 in S-2 and Gf in Figs 3, 10.

Calcareous tufa microfacies (U8 to U1)

The Caours tufa formation presents two types of carbonate deposits with very distinct macro- and microscopic structures: (i) Indurated stromatolitic constructions (Fig. 12C, C'–F), well crystallized, that show a succession of light and dark undulating millimetre-thick laminae. At Caours, they are locally observed and form large mamelonated (Str units) or tubular structures (Stt units). (ii) Microfacies corresponding to the predominant massive tufa (Fig. 12G, G'–L) that mostly consist of micrite to spar calcite included fragments of indurated tufa, granules, shells, bones, etc.

The calcite organization in laminated micrite or in crystals often including the traces of filaments, arranged in more or less arborescent clusters, demonstrates that both the stromatolitic and massive tufa facies result from biological, algal or algo-bacterial activity (Adolphe 1981; Freydet & Plet 1991). According to the work of Freydet (1997, 1998), it is possible to determine in Caours three genera of fossil algae: *Ponsella*, *Broutinella* and *Ponsinella*. Their equivalence with present-day genera is complex: a fossil genus, described in thin sections using morphological features, can be assimilated to several modern taxa, themselves defined according to biological criteria, observed by scanning electron microscope or by DNA extraction (Pentecost & Riding 1986). Anyway, Freydet (1997, 1998) proposes some comparisons between fossil and present-day taxa, based on facies convergence, which allow some palaeoecological reconstructions (Dabkowski et al. 2010): *Ponsella* and *Broutinella*, building stromatolites (Fig. 12C, C'–F), belong to cyanobacteria. Specifically, *Broutinella* might be equivalent to present-day *Schizothrix* and *Phormidium*. Cyanobacteria are widely distributed in fresh water and grow below 0.5 to 30 cm of water. Cyanobacterial constructions are usually characterized by the alternation of light and dark laminae, as observed here, generally

interpreted as a record of seasonal climatic variations (Adolphe 1981; Weisrock 1981; Freydet 1992; Andrews & Brasiers 2005). This seasonality has been confirmed in Caours by geochemical analyses at high resolution (infra-laminae sampling) showing 'cycles' of cooler/warmer conditions (Dabkowski et al. 2015).

The genus *Broutinella* is also present within massive tufa where it constitutes a 'cauliflower' facies (U4 and 3, samples 3 and 4, S-1-SPM3 and U8, 6, 4, 3 and 1a, samples 1, 4, 7 and 9, S-2-SPM1) characterized in thin sections by the abundance of tufa fragments, sometimes including the imprint of encrusted plants (stems, leaves), generally in a living position (Fig. 12A', G, G'–I). The 'cauliflower' facies has generally very little micritic matrix and no laminated structure. On the other hand, porosity can be high (up to 20%). These features observed in thin sections are consistent with the macroscopic description of U8, 6, 4, 3 and 1a: granular, more or less compact, they contain indurated blocks (centimetric to multi-decimetric depending on the unit) and/or encrusted stems and branches in place (millimetric to centimetric diameter).

The 'cauliflower' facies alternates with the micritic 'mille-feuille' facies, due to *Ponsinella* (Fig. 12J, J'–L) and typical of U5 and U3 (also 1b). The fossil genus *Ponsinella* can be compared with several present-day genera belonging to different groups or families of algae (Cyanobacteria, Chlorophytes – green algae, etc., Freydet 1998). The large number of hypotheses makes it difficult to provide a reliable actualist palaeoecological interpretation. However, in Caours, *Ponsinella* rarely presents its maximal development in erect clusters and the 'mille-feuille' facies also exhibits diffuse laminae with various embedded detrital elements (quartz, fragments of *Broutinella*, shells, flint fragments, bones, etc.; Fig. 12K, L) that suggest dynamic flow. Conversely, numerous thin layers of organic matter are observed,

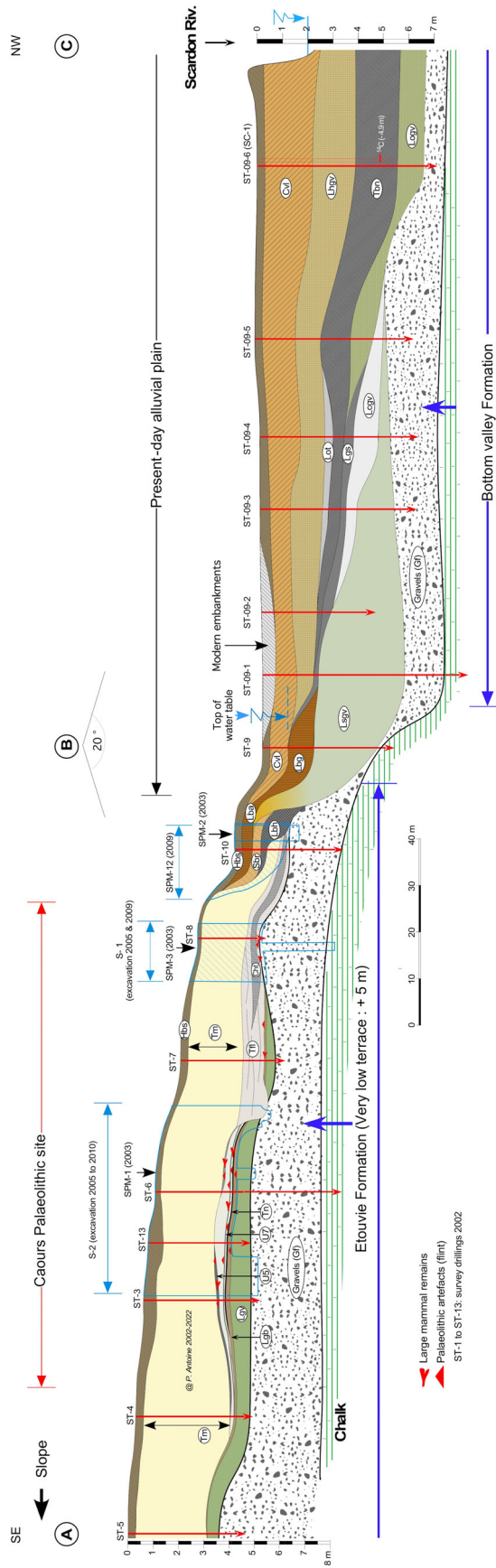


Fig. 10. Full geological cross-section (350 m long) of the Caours Formation and the bottom valley sequence up to the left bank of the Scardon river. Description: see caption of Fig. 3 and below for the Holocene sequence of the present-day valley. Lhg = hydromorphic grey-green clayey stratified silts including centimetre-thick organic layers; Lot = dark grey silty peat; Tbn = typical massive black peat with numerous vegetal remains. A radiocarbon age of 24288 ± 38 a BP has been obtained for this unit at -4.9 m depth in Core SC-1 close to the Scardon river; Logy = laminated organic grey-green (bronze) silts with interstratified peat layers; Lgs = dark grey to black plastic organic silt (gyttja); Lcgv = homogeneous light grey green calcareous silt.

Table 3. Description of specific facies found both in S-2 and S-1.

Units	Description
Ltg	(S-2 southern area only) – Thin and discontinuous layer of granular to sandy calcareous tufa including encrusted twigs and small oncoliths preserved in small channels (≤ 5 cm depth) incised between U10 and U11 (2002–2006) or between U10a and U10b (2007–2010) where they are distinguished (Fig. 8: +14 m). A few flint artefacts allocated to archaeological layer N-4 have been found in this unit in 2007.
Cht	(S-1 northern area only): laminated fine tufa mm thick dark (grey) organic layers preserved in a channel structure (Figs 3, 10).
Ocl	Low cohesion oncolith sandy gravels (average 5–10 mm in diameter) with encrusted twigs exhibiting large-scale low angle fluvial stratifications.
Str	Laminated and lightly undulating porous stromatolite crusts up to 6–10 cm in total thickness (locally ‘balls’ facies). These facies show well-marked laminations (up to 5–8 mm thick, Fig 9A, B) resulting from alternating beige (sparite) and brown (micritic) layers. The structure of the thickest layers exhibits fibrous CaCO_3 crystals orthogonal to the stratification.
Stt	Mainly found in the area of the former riverbank this facies corresponds to massive indurated calcareous tufa forming large blocks (50–100 cm) and exhibiting special subvertical ‘columns’ structures hereafter called ‘tubular stromatolites’ (1–8 cm in diameter for and 10–40 cm in length) separated by fairly large cavities. Stt pieces are found <i>in situ</i> in ‘live’ position (vertical) and often exhibit a final glossy CaCO_3 coating. Polished cross-sections show that Stt are made up of concentric millimetre-sized stromatolite layers (up to 40–50 cm long and 15 cm in diameter for the biggest) resulting from a rapid <i>in situ</i> calcification of small bushes of vegetal stems (ϕ 1–2 mm).
Tv	Porous tufa horizon distinguished by abundant well-preserved <i>in situ</i> encrusted plant remains (rushes, twigs, leaves, stems) with discontinuous laminated stromatolitic layers (Str) (Fig. 4).
Tmf	Massive calcareous tufa layer with subhorizontal encrusted leaf beds corresponding to a channel fill (Fig. 8).

revealing several periods of drying out. This facies therefore appears to have been established in a very thin layer of water. The waterflow revealed on these ‘mille-feuille’ facies is diffuse and non-permanent, probably comparable to seepage, as shown by the absence of channels or micro-channels, the predominance of terrestrial malacofauna, earthworm bio-spheroids, the

remains of terrestrial micromammals and the human settlements (N-1 and N-2; Fig. 12L).

Geochronology

The geochronological framework of the Caours sequence was established using different dating methods:

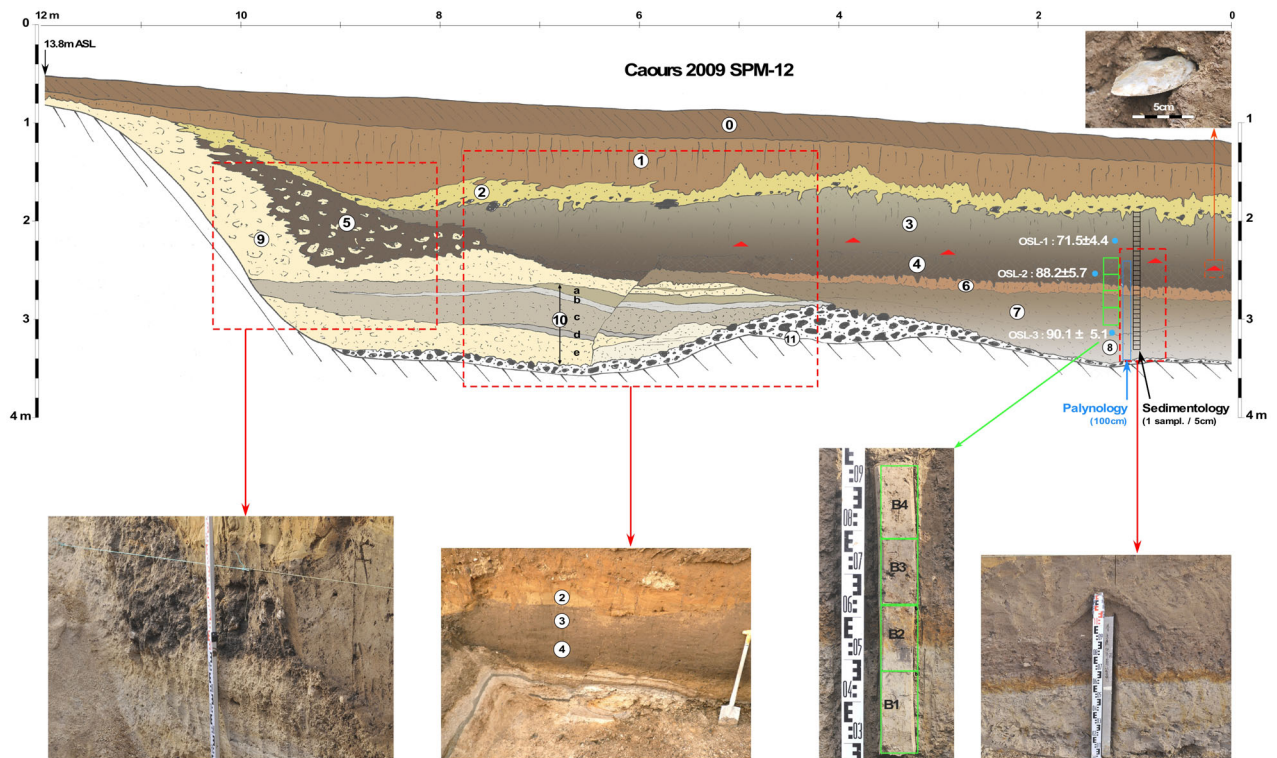


Fig. 11. Caours 2009: stratigraphy of the slope sequence overlying the tufa formation in SPM-12 trench (location: see Figs 2B, 3; description: see Table 4).

Table 4. Description of the units of the pedosedimentary sequence from SPM-12.

Units	Description
U0	Humic brown sandy-clayey loam with scattered small flints and granular structure (Ap horizon of the topsoil).
U1	Brown to orange-brown compact sandy-clay loam with root tracks and numerous bioturbations (bioturbated Bt horizon of the topsoil).
U2	Homogeneous yellow-brown silty to silty-clayey sand with numerous bioturbations (root tracks, burrows). Basal erosive contact marked by hillwashed yellow sandy beds and scattered flint flakes and small pebbles.
U3	Homogeneous grey-brown clayey humic sandy silts with fine granular structure and numerous bioturbations (roots, burrows) infilled by sands from U2, diffuse lower boundary (steppe soil facies).
U4	Brown-black humic sandy-clayey silt with diffuse polyhedral to lamellar structure, numerous small FeMn concretions (2–3 mm), strongly bioturbated lower boundary (deep Bth horizon of grey forest soil). Some reworked Palaeolithic flint artefacts exhibiting a deep white patina were found scattered up to the top in this unit. One outstanding large black flint scraper (Quina type without patina) was recovered in the upper part of this soil unit close to the boundary with U3 (Fig. 11).
U5	Orange-brown silty-clayey horizon with numerous oxidation spots, concretions and iron oxide coatings.
U6	Dark grey sandy-clayey silt with numerous oxidized spots and small root tracks and earthworm tubules, millimetre-sized debris of flint with white patina.
U7	Homogeneous light grey sandy-clayey silt with scattered oxidized root tracks, scattered small flint fragments.
U8	Lenticular heterogeneous slope deposit consisting of a mixture of black-brown sandy-humus silt with granular structure and reworked calcareous tufa blocks. Units U3 to 8 combined as Lbh unit in Figs 3, 10, 23B.
U9	Heterogeneous and massive calcareous deposit made up of the accumulation of reworked tufa blocks embedded within a sandy calcareous matrix.
U10	Set of stratified <i>in situ</i> whitish fine calcareous tufa layers including interbedded greyish silty lenses. a – Brownish to greyish silty tufa, b – fine grey calcareous silt, c – homogeneous beige to grey beige granular tufa, d – homogeneous fine dark grey calcareous silt, e – light grey to pinkish calcareous silt with numerous aquatic mollusc shells and <i>Bithynia</i> sp. opercula.

U-series on tufa calcite thermoluminescence (TL) on heated flints, Optically Stimulated Luminescence (OSL) on quartz grains and combined Electron Spin Resonance and U-series (ESR/U-series) on herbivorous teeth (Antoine *et al.* 2006; Bahain *et al.* 2010, 2022). The obtained results are displayed in Tables S1.1–S1.8.

- U-series: Carbonate samples were analysed by U-series in three different laboratories: Laboratoire des Sciences du Climat et de l'Environnement (LSCE), Gif-sur-Yvette, France; Histoire naturelle de l'Homme Préhistorique (HNHP), Paris, France; GEOTOP, Montreal, Canada. Two analytical techniques were used, α -spectrometry at LSCE and HNHP and thermal ionization mass spectrometry (TIMS) at GEOTOP (Tables S1.1–S1.3; see details of the used analytical protocols in Antoine *et al.* 2006). We note that the U-content never exceeds 0.2 ppm in the Caours carbonate samples and the $^{234}\text{U}/^{238}\text{U}$ ratios are similar in the analysed samples, centred around 1.25, indicating a relative stability of the water geochemical U-composition. The quite high ^{232}Th content measured in the LSCE samples necessitated an age correction (Table S1.1). Despite this contamination, the U-series α -spectrometry values range between 101+12/–11 and 142+12/–11 ka while the TIMS ones are more homogeneous, comprised between 115+8/–7 and 128±4 ka.
- Thermoluminescence: Four heated flints were dated by thermoluminescence at Nottingham Quaternary TL Surveys, United Kingdom (Table S1.4) and one additional piece at Bordeaux Re.S.Artes, France (Table S1.5). The TL ages range from 113.3±6.7 to 133.4±14.6 ka, i.e. from the late MIS 6 to the first part of the MIS 5e.
- OSL: The OSL dating method was applied at LSCE on quartz grains extracted on two samples respectively taken from Caours tufa and carbonated silts using the analytical protocol described in Antoine *et al.* (2006). The obtained data (Table S1.6) and ages, 99±16 ka for OSL-1 and 114±19 ka for OSL-2, are younger than the U-series and TL ages and indicate a MIS5 age for the Caours Formation. More recently three OSL-quartz dating results were obtained from the colluvial clayey sandy silts and humic soil horizons from (Lbh complex) exposed in the profile SPM-122009 (Fig. 11) by the Re.S.Artes Dating Laboratory (Table S1.7). The result (90.1±5.1 ka) allows the dating of the first colluvial sediments that were deposited after the end of the Eemian interglacial on the new slope resulting from the erosion of the calcareous tufa and the incision of the present-day valley (see Synthesis and discussion). The two other dates (85.8±5.7 and 71.3±4.4 ka) confirm the allocation of the humic soils to the Early Weichselian.
- ESR/U-series: The ESR/U-series method was applied at the HNHP laboratory on Caours teeth, five from archaeological level N1 and one from N3 (Table S1.8). A weighted mean age of 125±9 ka was calculated from the ESR/U-series individual dates, confirming the Eemian age of the sequence.
- Caours geochronological framework: An overview of the geochronological data currently available on the Caours site is displayed in Fig. 13. The mean ages obtained both on the different dated stratigraphical units (U1: 123.0±3.1 ka; U2 and 4: 123.4±6.1 ka; U5: 123.4±8.2 ka; U5 to U11: 124.0±11.0 ka) and on the whole sequence (123.1±2.8 ka) are highly reproducible and allow undoubtedly the attribution of the

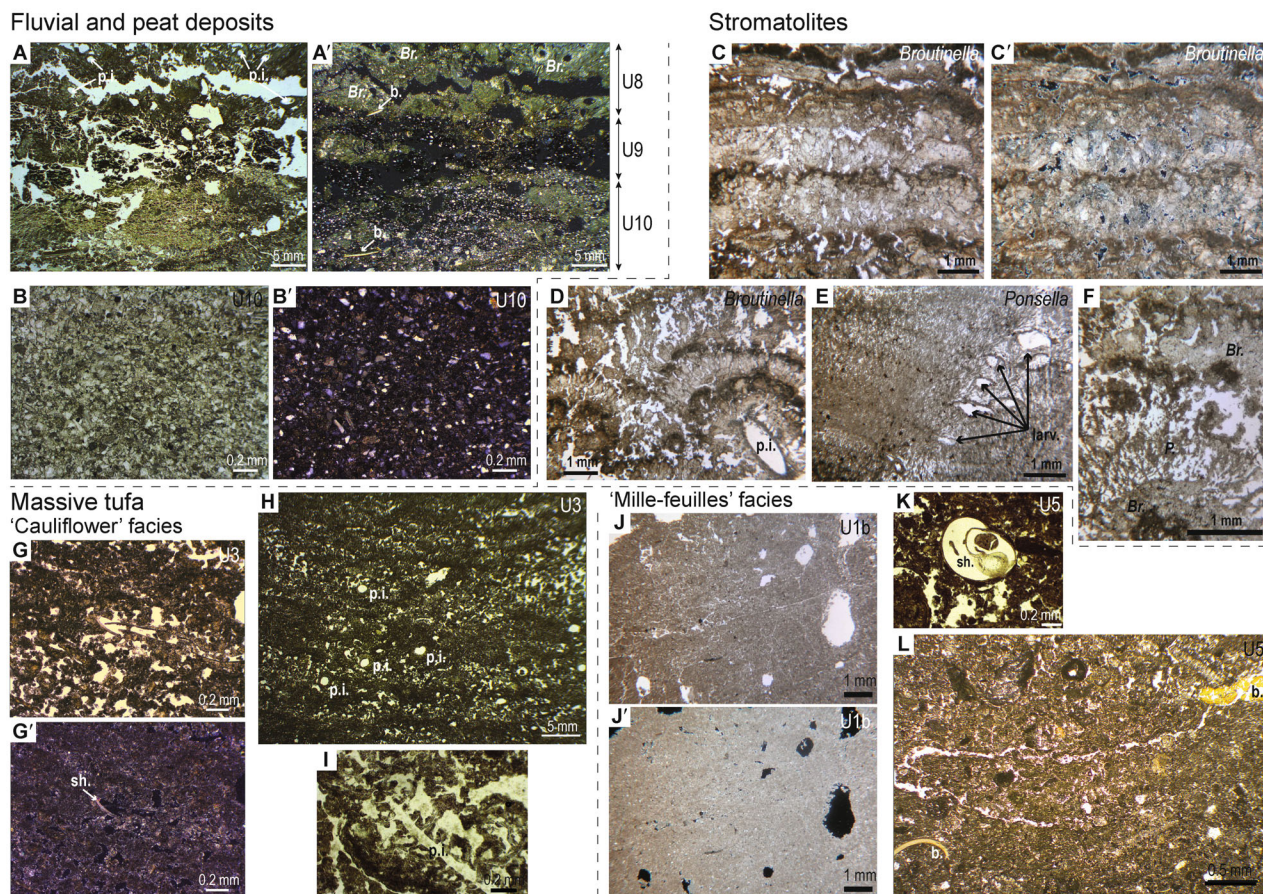


Fig. 12. Photographs of thin sections of typical fluvial, peat and carbonated facies observed at Caours. Scales are given for each of them. Fluvial and peat deposits: A–A': transition from unit 10 to 8 in plane-polarized (PP; A) and cross-polarized (XP; A') light (*Br.* = *Broutinella*; *b* = bone fragments; *p.i.* = plant imprints – only some are shown in unit 8). B–B'. Detail of the fluvial facies of unit 10 in PP (B) and XP light (B'). Stromatolites: C–C' and D. *Broutinella* laminated constructions in PP (C, D) and XP (C') light (*p.i.* = plant imprints). E. *Ponsella* construction (PP light; *larv.* = holes are the traces of insect larvae). F. Stromatolite construction showing the alternation of *Broutinella* (*Br.*) and *Ponsella* (*P.*) layer (PP light). Massive tufa: G–G' to I. 'Cauliflower' facies in PP (G, H, I) and XP (G') light. This facies is built of *Broutinella* fascicules encrusting gastropod shell (*sh.*) and plant remains (most porosity corresponds to plant imprints (only some are shown, *p.i.*)). I. Typical plant imprint (leaf?) featuring one main axis and secondary branches (*p.i.*), within small *Broutinella* fascicules. J–J' to L. 'Mille-feuilles' facies in PP (J, K, L) and XP light (J'). This facies exhibits lower porosity and diffuse lamination (J–J') and frequently feature well-preserved shells (*sh.*) and bones (*b.*) corresponding to archaeological levels N-1 or N-2 (unit 5, K and L).

formation to the Eemian interglacial stage. Besides, a palaeomagnetic survey, undertaken in the base of the sequence in 2009, confirmed the occurrence of the Blake Event at Caours (Sier *et al.* 2014). However, taking into account the current uncertainties concerning the duration of the Blake Event and its position within the Eemian interglacial, this result cannot be included in the discussion of the geochronological assessment of the site.

Palaeontological data

Malacology

Shells are abundant and well preserved throughout the Caours silty and tufaceous deposits, providing a valuable proxy for reconstructing the contemporary palaeoenvironmental evolution of the sequence. Continental snails

are small organisms whose distribution can be affected by local parameters and tufas can show high lateral variability; thus, several profiles have been sampled during the multiple excavations undertaken in the last 20 years. This strategy has allowed the reconstruction of point variations in the valley floor habitats and the identification of major landscape changes due to global climate forcing.

The first results, presented and discussed in previous publications (Antoine *et al.* 2006; Limondin-Lozouet 2011; Limondin-Lozouet & Preece 2014), highlighted three main environmental episodes recorded by malacofauna. The succession starts with marshy conditions at the end of the Saalian glacial and evolves towards the development of a closed vegetation cover followed by a third phase of forest decline during the Eemian interglacial. Since then, the palaeoenvironmental dynamics inferred from molluscs have been considerably

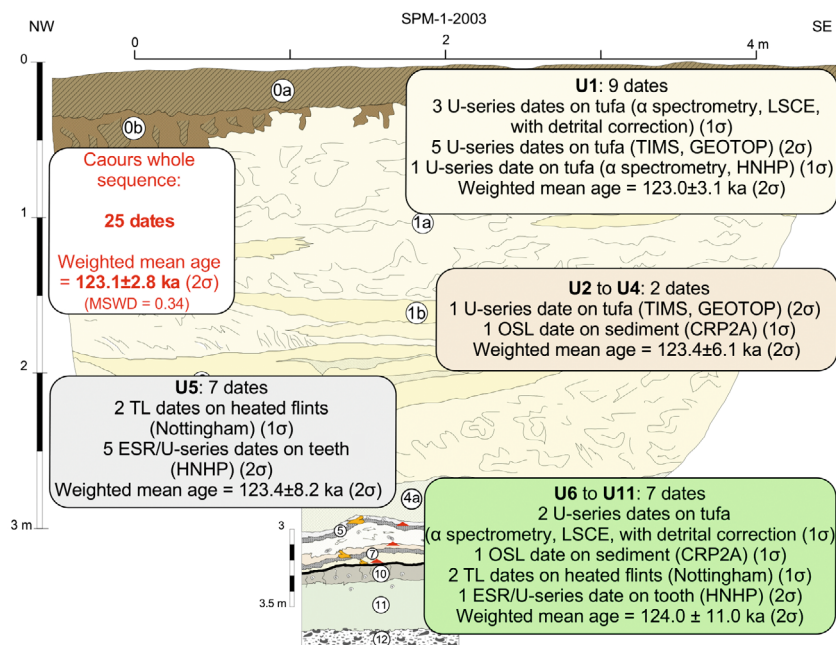


Fig. 13. Summary of the whole geochronological data set available for the Caours site. The weighted mean ages were calculated using Isoplot software (Ludwig 2003).

improved by adopting a higher resolution sampling protocol on selected profiles representative of the most complete stratigraphical record. In this paper, we present a combination of the best succession obtained from two profiles of the East section excavated in 2007 in the southern sector S-2 (Figs 2B, 8).

The two profiles studied, A3-East and East-2007, are 14 m apart and cover the silty alluvial deposits and the overlying tufa formation, respectively (location: Fig. 8). They were sampled continuously at a 5-cm resolution (Figs 8, 14, 15). Samples of 5-kg weight were analysed for molluscs according to standard procedures: wet sieving on a 0.5-mm mesh and minimum totals based on both complete shells and fragments (Puisségur 1976). The palaeoenvironmental data presented here are based on the study of 66 samples that yielded 32 108 individuals belonging to 80 taxa of which 71 could be assigned to species (Table 5). The evolution of the malacological assemblages is presented in percentage frequency histograms (Figs 14, 15). Most of the samples yielded a high number of individuals allowing a good statistical representation; however, some of them were below the critical threshold of 50 individuals and for these, species occurrences are just noted with an open dot on the diagrams. The molluscan succession can be divided into five biozones based on the occurrence and/or maximum development of particular species and/or on their disappearance throughout the sequence.

Biozone 1: cold-tolerant open-ground assemblage. – This zone is identified in the basal green silt unit (Fig. 14, U11, samples M10–M4). Mollusc populations are

well-developed with a large number of shells but low diversity. Four species represent almost the entire terrestrial community. All are tolerant eurythermic species regularly observed in the glacial deposits of Europe (e.g. Ložek 1990; Rousseau *et al.* 1990; Moine 2008). The most notable taxon is *Columella columella*, a present-day boreo-alpine palustrine species whose range extends further south into periglacial territories in humid environments during cold periods (Rousseau & Keen 1989). The presence of the hygrophilous species *Oxyloma elegans* and *Trochulus hispidus* reinforces the wet character of this biotope. Very similar faunas have been recorded in the flood-plain silts that invaded the Somme valley during the Younger Dryas stadial (Limondin 1995; Limondin-Lozouet & Antoine 2001). Aquatic taxa are well represented during this episode, suggesting the regular occurrence of flooding phases in the plain.

The mollusc fauna of Zone 1 indicates open wetland habitats that thrive in cold climatic conditions.

Biozone 2: expansion of forest assemblage. – Zone 2 corresponds to the emergence and development of forest biotopes in the Scardon Plain under interglacial climatic conditions. It extends from the upper part of the fluvial silts (U10) until the base of fine granular tufa (U4) overlying the uppermost grey layer (U5); all the archaeological levels (N-1 to N-4) are included within this environmental division. Zone 2 is subdivided into three subzones (a, b, c) corresponding to the stages of forest expansion.

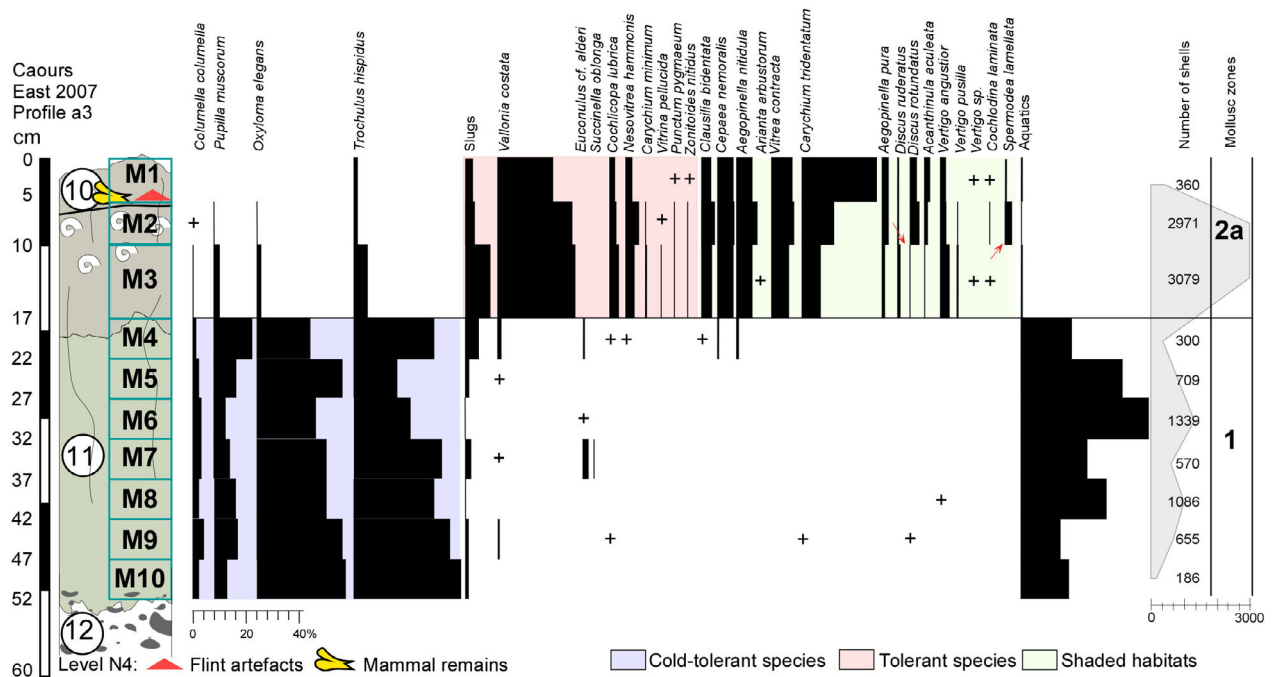


Fig. 14. Molluscan diagram through Profile 2007 East a3 (location: Fig. 9: +13.5 m) showing the succession from the end of the Saalian until the earliest Eemian forest phase. Red arrows point to the *Discus* shift and the appearance of *S. lamellata* marking the transition from coniferous to deciduous woods. Crosses represent single shells.

Zone 2a applies to the grey facies of the silty unit, which contains the oldest archaeological level N-4 (Fig. 14, U10, samples M3–M1). The malacofauna changes radically, with a sharp increase in richness and diversity. The aquatic taxa have disappeared while the previously present open soil species are in strong decline and are replaced by a mesophilic snail community indicating the development of the ground cover. Most notable is the presence of an already well-established group of shade-loving species, typical of forest environments, which can only develop under fully temperate conditions. However, models of interglacial malacological succession show that only a few thermophiles appear in small numbers at the beginning of the temperature improvement (Mania 1995a, b; Ložek 2000; Limondin-Lozouet 2011). The abruptness of the transition observed at Caours suggests a hiatus in the sedimentary record corresponding to the very early phase of the interglacial. The forest group is composed of the most tolerant species of this category, which have a current distribution centred on northern and western Europe (e.g. *Cepaea nemoralis*, *Clausilia bidentata*, *Aegopinella nitidula*, *A. pura*, *Discus rotundatus* being the most abundant). One of these, *Discus ruderatus* is no longer present in the Somme and is now a northeastern species, widespread in Scandinavia but restricted southward to mountain habitats (Welter-Schultes 2012). Today, *D. ruderatus* is particularly common in coniferous forests. Its presence at the beginning of interglacial

succession is a classical feature of European Quaternary sequences (Mania 1995a; Ložek 2000). In lowland deposits, it is rapidly replaced by its congener *Discus rotundatus*, a more thermophilic taxon whose current distribution does not reach Scandinavia. The ‘*Discus* switch’ is interpreted as the transition from coniferous forest to hardwood habitats in the western European sequences (e.g. Preece & Day 1994; Meyrick & Preece 2001; Limondin-Lozouet *et al.* 2005, 2020). In the Caours succession, this switch is observed in the upper part of U10 between samples M3 and M2 (Fig. 14). The appearance of *Spermodaea lamellata*, another allochthonous species in the Somme valley and a typical species of old deciduous woodlands (Kerney & Cameron 1979), after the decline of *D. ruderatus* reinforces this interpretation (Fig. 14).

The malacofauna of Zone 2a indicates a semi-open environment with pioneer woodland habitats developing in the early Eemian. In this subzone, the succession of forest molluscs records the transition from coniferous to deciduous woodland biotopes. The earliest archaeological occupation N-4 is contemporary with this second forest stage, when the landscape can be described as open hardwoods.

Zone 2b is mainly related to the fine dark grey silty tufas of U7 and U7', which contain the archaeological level N-2 (Fig. 15, East 2007, samples U7', M1–M2). Malacofaunas are extremely rich and diversity increases. The shaded habitat group exceeds both tolerant snails



Fig. 15. Molluscan diagram through Profile 2007 East (location Fig. 9; +0.5 m). In poor samples, species occurrences are noted with an open dot, crosses represent single shells.

Table 5. List of malacological taxa identified in the profiles of the East section 2007 at Caours. Species are presented according to the ecological groups defined by Puisségur (1976). Species that are now out of range in the Somme basin are identified by a code representing their current geographical range in Europe: A = Alpine; B = Boreal; C = Central; N = North; W = West; S = South.

Caours Profiles a3 East and East 2007					
	Genus	Species	Author	Out of range	
1. Forest	<i>Acanthinula</i>	<i>aculeata</i>	(O.F. Müller, 1774)		
	<i>Aegopinella</i>	<i>nitidula</i>	(Draparnaud, 1805)		
	<i>Aegopinella</i>	<i>pura</i>	(Alder, 1830)		
	<i>Balea</i>	<i>heydeni</i>	Maltzan, 1881		
	<i>Clausilia</i>	<i>bidentata</i>	(Ström, 1765)		
	<i>Cochlodina</i>	<i>laminata</i>	(Montagu, 1803)		
	<i>Daudebardia</i>	<i>rufa</i>	(Draparnaud, 1805)	C & S	
	<i>Discus</i>	<i>ruderatus</i>	(Hartmann, 1821)	B & A	
	<i>Helicodonta</i>	<i>obvoluta</i>	(O.F. Müller, 1774)		
	<i>Hygromia</i>	<i>limbata</i>	(Draparnaud, 1805)		
	<i>Lauria</i>	<i>sempronii</i>	(Charpentier, 1837)	S & A	
	<i>Macrogastra</i>	<i>rolphii</i>	(Turton, 1826)		
	<i>Macrogastra</i>	sp.			
	<i>Oxychilus</i>	<i>navarricus</i>	(Bourguignat, 1870)		
	<i>Pagodulina</i>	<i>pagodula</i>	(Des Moulins, 1830)	C & S	
	<i>Platyla</i>	<i>polita</i>	(W. Hartmann, 1840)	C & A	
	<i>Ruthenica</i>	<i>filigrana</i>	(Rossmässler, 1836)	C	
	<i>Spermodea</i>	<i>lamellata</i>	(Jeffreys, 1830)	N & W	
	<i>Sphyradium</i>	<i>doliolum</i>	(Bruguère, 1792)	S & A	
	<i>Vertigo</i>	<i>pusilla</i>	(O.F. Müller, 1774)		
2. Semi-Forest	<i>Clausilia</i>	sp.			
	<i>Arianta</i>	<i>arbustorum</i>	(Linnaeus, 1758)		
	<i>Cepaea</i>	<i>nemoralis</i>	(Linnaeus, 1758)		
	<i>Cepaea</i>	sp.			
	<i>Discus</i>	<i>rotundatus</i>	(O.F. Müller, 1774)		
3. Humid Forest	<i>Fruticicola</i>	<i>fruticum</i>	(O.F. Müller, 1774)		
	<i>Macrogastra</i>	<i>ventricosa</i>	(Draparnaud, 1801)	C	
5. Open ground	<i>Columella</i>	<i>columella</i>	(G. von Martens, 1830)	B & A	
	<i>Pupilla</i>	<i>muscorum</i>	(Linnaeus, 1758)		
	<i>Truncatellina</i>	<i>cylindrica</i>	(A. Férussac, 1807)		
	<i>Vallonia</i>	<i>costata</i>	(O.F. Müller, 1774)		
	<i>Vallonia</i>	<i>pulchella</i>	(O.F. Müller, 1774)		
	<i>Vertigo</i>	<i>pygmaea</i>	(Draparnaud, 1801)		
	7. Mesophilous	<i>Balea</i>	<i>perversa</i>	(Linnaeus, 1758)	
		<i>Clausilia</i>	<i>dubia</i>	Draparnaud, 1805	
		<i>Cochlicopa</i>	<i>lubrica</i>	(O.F. Müller, 1774)	
		<i>Helicigona</i>	<i>lapicida</i>	(Linnaeus, 1758)	
<i>Nesovitrea</i>		<i>hammonis</i>	(Ström, 1765)		
<i>Oxychilus</i>		<i>cellarius</i>	(O.F. Müller, 1774)		
<i>Oxychilus</i>		sp.			
<i>Punctum</i>		<i>pygmaeum</i>	(Draparnaud, 1801)		
<i>Trochulus</i>		<i>hispidus</i>	(Linné, 1758)		
<i>Vitrea</i>		<i>contracta</i>	(Westerlund, 1871)		
<i>Vitrina</i>		<i>pellucida</i>	(O.F. Müller, 1774)		
8. Hygrophilous		Slugs			
	<i>Carychium</i>	<i>tridentatum</i>	(Risso, 1826)		
	<i>Columella</i>	<i>edentula</i>	(Draparnaud, 1805)		
	<i>Succinella</i>	<i>oblonga</i>	(Draparnaud, 1801)		
9. Paludal	<i>Vertigo</i>	<i>angustior</i>	Jeffreys, 1830		
	<i>Carychium</i>	<i>minimum</i>	(O.F. Müller, 1774)		
	<i>Euconulus</i>	<i>alderi</i>	(J.E. Gray, 1840)		
	<i>Euconulus</i>	sp.			
	<i>Oxyloma</i>	<i>elegans</i>	(Risso, 1826)		
	<i>Vallonia</i>	<i>enniensis</i>	(Gredler, 1856)		
	<i>Vertigo</i>	<i>antivertigo</i>	(Draparnaud, 1801)		
	<i>Vertigo</i>	<i>moulinsiana</i>	(Dupuy, 1849)		
10. Aquatic	<i>Vertigo</i>	sp.			
	<i>Zonitoides</i>	<i>nitidus</i>	(O.F. Müller, 1774)		

(continued)

Table 5. (continued)

Caours Profiles a3 East and East 2007				
	Genus	Species	Author	Out of range
Stagnant waters	<i>Anisus</i>	<i>septemgyratus</i>	(Rossmässler, 1835)	
	<i>Anisus</i>	<i>spirorbis</i>	(Linnaeus, 1758)	
	<i>Galba</i>	<i>truncatula</i>	(O.F. Müller, 1774)	
	<i>Stagnicola</i>	<i>palustris</i>	(O.F. Müller, 1774)	
	<i>Valvata</i>	<i>cristata</i>	(O.F. Müller, 1774)	
Slow waters	<i>Acroloxus</i>	<i>lacustris</i>	(Linnaeus, 1758)	
	<i>Ampullaceana</i>	<i>balthica</i>	(Linnaeus, 1758)	
	<i>Anisus</i>	<i>vortex</i>	(Linnaeus, 1758)	
	<i>Hippeutis</i>	<i>complanatus</i>	(Linnaeus, 1758)	
	<i>Lymnaea</i>	<i>stagnalis</i>	(Linnaeus, 1758)	
	<i>Planorbis</i>	<i>planorbis</i>	(Linnaeus, 1758)	
	<i>Planorbis</i>	sp.		
	<i>Radix</i>	<i>labiata</i>	(Rossmässler, 1835)	
	<i>Radix</i>	sp.		
	<i>Valvata</i>	<i>piscinalis</i>	(O.F. Müller, 1774)	
	<i>Pisidium</i>	<i>milium</i>	Held, 1836	
	<i>Pisidium</i>	sp.		
	Running waters	<i>Ancylus</i>	<i>fluviatilis</i>	(O.F. Müller, 1774)
<i>Physa</i>		<i>fontinalis</i>	(Linnaeus, 1758)	
<i>Pisidium</i>		<i>nitidum</i>	Jenyns, 1832	
Ubiquitous	<i>Bithynia</i>	<i>tentaculata</i>	(Linnaeus, 1758)	
	<i>Pisidium</i>	<i>casertanum</i>	(Poli, 1791)	
Spring	<i>Belgrandia</i>	<i>marginata</i>	(Michaud, 1831)	S

and aquatic species, accounting for 55 to 80% of the total assemblage per sample (Fig. 15). However, almost two-thirds of this percentage is due to the development of *Carychium tridentatum*, which is a hygrophilous taxon particularly abundant in the forest litter. Molluscs from open terrestrial habitats have almost disappeared. All newcomers are forest species with narrower ecological tolerance and current western, alpine and central European ranges such as *Cochlodina laminata*, *Sphyradium doliolum*, *Helicodonta obvoluta* and *Pagodulina pagodula* (Kerney & Cameron 1979; Welter-Schultes 2012), some of which are absent from the Somme region today (Table 5).

The molluscan fauna of Zone 2b shows a marked development of the forest biotope. The Neandertal populations of the N-2 level evolved therefore in more closed environment.

Zone 2c developed around the upper fine grey level (U5), which locally can reach 30 cm in thickness on the 2007 South section (Fig. 9) and contains the archaeological level N-1 (Fig. 5B). Four samples were taken from U5 in the 2007 South section (Table 6) and, in the 2007 East section subzone 2c, is represented by samples M12 to M15 (Fig. 15). The proportion of molluscs from shaded habitats is stable around the highest value (80%) but forest snails are now predominant and represent almost all of this percentage (Fig. 15, Table 6). In addition, the diversity of this group has greatly increased with eight new taxa (Fig. 15). The new species are all strictly forest snails with narrow ecological requirements.

Several of them, now extinct in the region, have a current range in central Europe (e.g. *Ruthenica filigrana*, *Macrogastra ventricosa*), some of them extending southwards to the Mediterranean area (*Platyla polita*, *Daudebardia rufa*). Among these species, *D. rufa* and *M. ventricosa* have occurrences strictly limited to this subzone.

The malacological populations of Zone 2c reflect the development of a closed canopy under fully temperate climatic conditions; it corresponds to the maximum extension of the forest within the Caours sequence.

The evolution of land snail communities in Zone 2 shows the progressive development of the forest biotope in three stages separated by episodes of aquatic input. These are illustrated by a significant increase in aquatic taxa in U8 and U6, mainly represented by the crenophilous species *Belgrandia marginata* (Fig. 16). This Hydrobiidae lives in springs (Germain 1930) and is typical of Pleistocene interglacial deposits in Europe (Kerney 1977; Keen 1990; Sanko *et al.* 2011; Limondin-Lozouet 2022). The stages of forest expansion are related to fine-grained organic units illustrating stable environmental episodes (U10, U7, U5) and hosting the archaeological settlements, while the aquatic inputs revealing occasional flooding of the plain correspond to granular tufa deposits. The maximum development of forest molluscs at the top of Zone 2 (U5) can be interpreted as the interglacial optimum. The allochthonous species present during the forest expansion (Fig. 16) are of primary importance in defining the

Table 6. Mollusca from U5 sampled on the South 2007 profile in Caours. EG column refers to ecological groups described in Table 5. Proportions of each group per sample are given in percentages.

Caours	South 2007			Samples			
	Genus	Species	Author	56	57	58	59
1	<i>Acanthinula</i>	<i>aculeata</i>	(O.F. Müller, 1774)	1	2	8	31
1	<i>Aegopinella</i>	<i>nitidula</i>	(Draparnaud, 1805)	7	1	4	13
1	<i>Aegopinella</i>	<i>pura</i>	(Alder, 1830)	8	14	52	156
1	<i>Balea</i>	<i>heydeni</i>	Maltzan, 1881				1
1	<i>Clausilia</i>	<i>bidentata</i>	(Ström, 1765)	18	5	15	27
1	<i>Cochlodina</i>	<i>laminata</i>	(Montagu, 1803)	3	6	5	17
1	<i>Daudebardia</i>	<i>rufa</i>	(Draparnaud, 1805)	4	2	20	33
1	<i>Helicodonta</i>	<i>obvoluta</i>	(O.F. Müller, 1774)	10	14	8	10
1	<i>Hygromia</i>	<i>limbata</i>	(Draparnaud, 1805)	1		1	2
1	<i>Oxychilus</i>	<i>navarricus</i>	(Bourguignat, 1870)				2
1	<i>Pagodulina</i>	<i>pagodula</i>	(Des Moulins, 1830)	8	11	27	84
1	<i>Platyla</i>	<i>polita</i>	(W. Hartmann, 1840)	2	12	41	98
1	<i>Ruthenica</i>	<i>filograna</i>	(Rossmässler, 1836)	75	97	142	130
1	<i>Sphyradium</i>	<i>doliohum</i>	(Bruguère, 1792)	1	4	12	19
		%G1		60.26	72.1	57.17	42.47
2	<i>Cepaea</i>	<i>nemoralis</i>	(Linnaeus, 1758)	16	11	17	33
2	<i>Discus</i>	<i>rotundatus</i>	(O.F. Müller, 1774)	14	11	48	126
2	<i>Fruticicola</i>	<i>fruticum</i>	(O.F. Müller, 1774)	1	1	1	4
		%G2		13.54	9.87	11.26	11.11
3	<i>Macrogastra</i>	<i>ventricosa</i>	(Draparnaud, 1801)		3	2	
		%G3		0	1.29	0.34	0
5	<i>Pupilla</i>	<i>muscorum</i>	(Linnaeus, 1758)			1	2
5	<i>Truncatellina</i>	<i>cylindrica</i>	(A. Férussac, 1807)				1
5	<i>Vallonia</i>	<i>costata</i>	(O.F. Müller, 1774)			1	
		%G5		0	0	0.34	0.2
7	<i>Clausilia</i>	<i>dubia</i>	Draparnaud, 1805	3	3	7	2
7	<i>Cochlicopa</i>	<i>lubrica</i>	(O.F. Müller, 1774)		1	2	15
7	<i>Helicigona</i>	<i>lapicida</i>	(Linnaeus, 1758)	2	1	1	7
7	<i>Nesovitrea</i>	<i>hammonis</i>	(Ström, 1765)				2
7	<i>Oxychilus</i>	<i>cellarius</i>	(O.F. Müller, 1774)	20	3	20	42
7	<i>Punctum</i>	<i>pygmaeum</i>	(Draparnaud, 1801)		1	2	26
7	<i>Trochulus</i>	<i>hispidus</i>	(Linné, 1758)	3	2	23	75
7	<i>Vitrea</i>	<i>contracta</i>	(Westerlund, 1871)	5	4	24	110
		%G7		14.41	6.44	13.48	19.02
7'	Slugs			18	9	12	26
		%G7'		7.86	3.86	2.05	1.77
8	<i>Carychium</i>	<i>tridentatum</i>	(Risso, 1826)	3	13	82	326
8	<i>Succinella</i>	<i>oblonga</i>	(Draparnaud, 1801)				2
		%G8		1.31	5.58	13.99	22.36
9	<i>Carychium</i>	<i>minimum</i>	(O.F. Müller, 1774)				1
9	<i>Euconulus</i>	<i>alderi</i>	(J.E. Gray, 1840)				1
9	<i>Oxyloma</i>	<i>elegans</i>	(Risso, 1826)	2	1	1	12
9	<i>Vertigo</i>	<i>antivertigo</i>	(Draparnaud, 1801)				1
		%G9		0.87	0.43	0.17	1.02
10	<i>Ampullaceana</i>	<i>balthica</i>	(Linnaeus, 1758)			1	2
10	<i>Belgrandia</i>	<i>marginata</i>	(Michaud, 1831)	1		4	26
10	<i>Bithynia</i>	<i>tentaculata</i>	(Linnaeus, 1758)	2	1		
10	<i>Pisidium</i>	<i>nitidum</i>	Jenyns, 1832				1
10	<i>Planorbis</i>	<i>planorbis</i>	(Linnaeus, 1758)	1		2	1
		%G10		1.75	0.43	1.19	2.04
	Number of shells			229	233	586	1467
	Number of species			26	26	31	38

malacological signature of the Eemian interglacial in the region.

Biozone 3: decline of forest assemblages. – Zone 3 covers layers of granular calcareous tufa from the base of U4 to the first half of U2 that includes samples M16 to M35

(Fig. 15). The number of shells is very irregular and in several samples is below the threshold of statistical representativeness, especially in the middle part of U3 (M25 to M28). The forest snail community is still present but shows a strong decrease in richness and diversity, which becomes more pronounced in the second half of

the zone. The most permanent population of terrestrial molluscs is represented by tolerant species adapted to wet and marshy habitats (*Cochlicopa lubrica*, *Oxychilus cellarius*, *Trochulus hispidus*, *Oxyloma elegans*, *Carychium minimum*, *Zonitoides nitidus*). In addition, some open soil taxa reappear sporadically (e.g. *Vallonia costata*). Aquatic molluscs constitute an important part of the assemblages during this episode. In the first half of Zone 3 the aquatic taxa are represented by a diverse community of fluvial species. In the second half, they are accompanied by large populations of the spring species *B. marginata* (Fig. 15).

The fluctuating richness and gaps in the malacological record suggest a phase of relative environmental instability. The assemblages in Zone 3 reflect a mosaic landscape. The forest cover has been greatly reduced and wetlands develop in the vicinity of tree patches in a plain regularly impacted by flooding events.

Biozone 4: open ground habitats. – Zone 4 is identified in the massive tufa deposits of U2 and U1a (Fig. 15, East 2007, samples M36–M43). Shell numbers are increasing and remain at a consistent level. Wetland tolerant species and the impoverished forest group are continuously maintained throughout this biozone (Fig. 15). Riverine aquatic species are present in moderate proportions. The identification of Zone 4 is based on the development of an open field community composed of species of drier habitats (*V. costata*, *V. pulchella*, *P. muscorum*, *Truncatellina cylindrica*, *Vertigo pygmaea*).

The landscape is similar to that of the previous area with reduced open woodland surrounded by marshy areas, but now coexisting with well-drained habitats that develop in a stabilized environment.

Biozone 5: impoverished damp assemblages. – Zone 5 is identified in the upper porous calcareous tufa of U1 with abundant encrusted plants (Fig. 15, East 2007, samples M44–M55). Malacological assemblages are characterized by low numbers of shells and decreasing diversity. The former drier open-ground snail populations have almost disappeared. Shaded habitats are only represented by a few of the most tolerant semi-forest taxa (*D. rotundatus*, *Cepaea*, *V. contracta*). The group of tolerant molluscs inhabiting humid biotopes is the best developed (Fig. 15).

The mollusc communities of Zone 5 describe an open lowland environment with wetlands, where forest biotopes are no longer present. Although the permanence of some thermophilic snails implies interglacial conditions, the strong impoverishment of the fauna suggests a significant drop in temperature.

Main conclusions. – The Caours mollusc succession allows us to reconstruct the palaeoenvironmental dynamics of the Scardon Plain from the late Saalian to the Eemian. The extremely abrupt transition from

non-diverse cold climate assemblages to rich thermophilic communities indicates a hiatus corresponding to the very beginning of the interglacial. However, this hiatus is of limited duration, as the evolution of the forest snail group records the transition from coniferous pioneer woods to deciduous forests. The increase in diversity is constant throughout the period of forest development described in Zone 2. The maximum development of forest biotopes is interpreted as the interglacial optimum. Thereafter, no new species arrivals are observed and the subsequent loss of taxa affects primarily the most thermophilic group of forest habitats. During this period of climatic degradation, lowland vegetation becomes less dense, flooding results in peaks in aquatic communities, and swampy biotopes become dominant. Compared to the regional present-day and earlier Holocene malacofaunas, many of the species present in the early part of the deposit are allochthonous (Fig. 16). Most of them are specialized species of closed habitats. Their order of appearance is directly dependent on their ecological tolerance and their distance from the refuge areas distributed along the Atlantic coast and in central Europe, the most southerly species only reaching the Somme basin at the climatic optimum (Limondin-Lozouet & Preece 2014). To date, the malacological succession of Caours is the longest and richest known in the region for this period. It appears to be an essential reference for identifying the specific malacological content of the Eemian interglacial, providing a reliable biochronological marker for northwestern European sequences.

Mammal remains

Large and meso-mammals. – The Caours annual excavations, carried out between 2005 and 2010 and then from 2015 onwards, allowed the discoveries of 19 557 well-preserved remains of large and meso-mammals distributed over all the archaeological layers from sectors S-1 and S-2 (Tables 7, 8). Most faunal remains come from archaeological level N-1 ($n = 8861$) allocated to the Eemian optimum according to malacological and geochemical data, but levels N-2 and N-4 also contained a large amount of mammal remains ($n = 707$, and 1677, respectively). In the northern excavation (S-1) the faunal remains are less abundant ($n = 5947$). At Caours, the surface condition of the large mammal bones from the four archaeological levels in the southern sector (S-2) is very good and does not show any traces of reworking or fluvial transport. In a few rare cases, marks due to the activity of carnivores (gnawing), rodents (trimming) or roots (dissolution) that subsequently penetrated the archaeological levels have been observed. The rarity of these taphonomic stigmata indicates that the accumulation of the different bone assemblages was exclusively the result of human activity. In addition, the refitting of the various flint knapping products shows that they were not

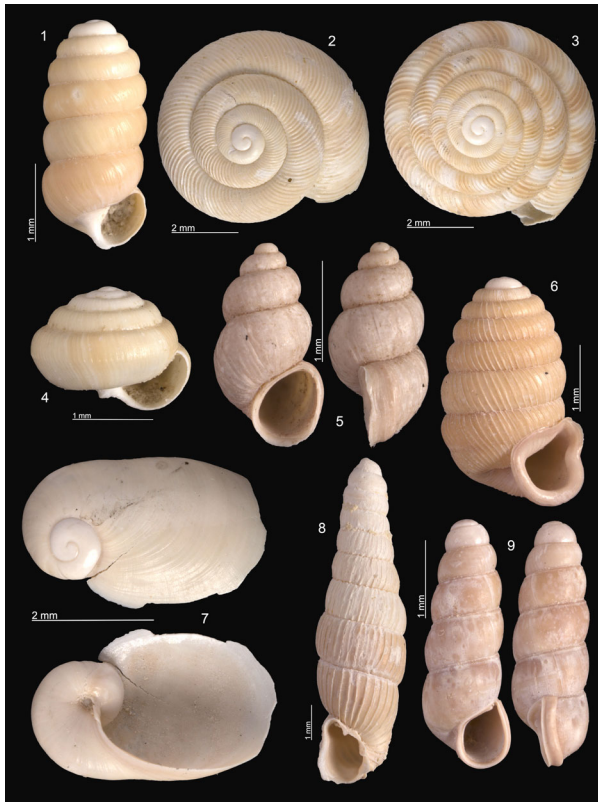


Fig. 16. Some species of particular importance in the palaeoenvironmental succession recorded at Caours. 1. *Columella columella* (U11) is a cold-tolerant taxa of the late Saalian; 2. *Discus ruderatus*; 3. *Discus rotundatus*; 4. *Spermodia lamellata* are three diagnostic species of the Eemian pioneer forest in unit 10; 5. *Belgrandia marginata* (U5) is an aquatic gastropod living in the water table and typical of Pleistocene interglacial deposits; 6. *Pagodulina pagodula*; 7. *Daudebardia rufa*; 8. *Ruthenica filigrana*; 9. *Platyla polita* are all strict forest mollusks now extinct in the Somme basin, they develop in U5 during the maximum extension of the forest (photographs: P. Lozouet, MNHN Paris).

displaced after their production. What is more, several fragments of flakes found just a few centimetres apart were joined together, showing that these artefacts had not been moved since their abandonment. These observations indicate that the four levels of human occupation at Caours S-2 have remained virtually intact since their deposition (see below). On the other hand, in the northern sector S-1 (level Nc), the faunal and flint assemblages were partially reworked by the flooding of the river (rounding of the angles of the long bone fragments, wear on the edges of the flint flakes). Hence, the study of the fauna (taphonomy, age classes and skeletal profiles of the taxa) confirmed the initial hypothesis (Auguste in Antoine et al. 2006; Auguste 2009) that Neandertals were the only accumulators of the Caours bone assemblages (Sévêque 2017).

Overall at least 250 mammal individuals have been identified distributed into 12 taxa described hereafter (Auguste 2009; Figs 17, 18):

- Straight-tusk elephant, *Palaeoloxodon antiquus* (Falconer & Cautley, 1847). The fragments of dental elements of the proboscidean present at Caours are clearly those of this elephant, and not of a representative of the mammoth lineage.
- Grassland rhinoceros, *Stephanorhinus hemitoechus* (Falconer, 1868). The animal is similar to that found in many Pleistocene sites in northern France (Guérin 1980). It can be easily distinguished by its dental and bony elements from the forest rhinoceros, *Stephanorhinus kirchbergensis*, and especially from the woolly rhinoceros, *Coelodonta antiquitatis* (Fig. 17E). However, the dimensions recorded show a fairly large form, taller than that of the late Middle Pleistocene. A similar massive grassland rhinoceros was found in Unit 5 of the Waziers site, also assigned to the Eemian interglacial (Auguste et al. 2022).
- Horse, *Equus taubachensis* Von Reichenau, 1915. Comparison with horses from the Late Saalian (MIS 7 and 6) and Eemian (MIS 5e) periods allows the Caours horse to be compared with one of the forms already identified during these periods (Fig. 17G). It appears that this horse has clearly elevated protocone indices on its premolars and molars, which is observed in *Equus taubachensis* from the Eemian interglacial travertines of the eponymous Taubach site (Bratlund 1999). Horses from the end of the Saalian show weaker protocone indices, such as *E. achenheimensis*, identified regionally at Biache-Saint-Vaast (Pas-de-Calais, MIS 7) or in Waziers Unit 4 (Auguste et al. 2022).
- Aurochs, *Bos primigenius* Bojanus, 1827. The animal shows species-specific characteristics that easily differentiate it from the bison, in terms of both its teeth and bones (Fig. 17D). It shows an animal of large stature comparable to that common during the Pleistocene.
- Red deer, *Cervus elaphus* (Linnaeus, 1758). It is comparable to the present form and to known forms from the Middle and Upper Pleistocene (Fig. 17A). It is the best-represented species in terms of number of remains and individuals in almost all levels of Caours, except in level 1 of S-2 where the fallow deer dominates the assemblage (Fig. 18).
- Fallow deer, *Dama dama* (Linnaeus, 1758). At Caours, the presence of fallow deer is an important part of the faunal assemblage. This species, typical of interglacial conditions and forest environments, is generally rare in the Pleistocene sequences of north-western Europe. (Fig. 17B). The species present at Caours is closely related to the modern European fallow deer, and differs from the red deer and roe deer not only in size but also in several anatomical features. It is the dominant species in level 1 (S-2).
- Roe deer, *Capreolus capreolus* (Linnaeus, 1758). The roe deer identified at Caours is identical to the present form (Fig. 17C).

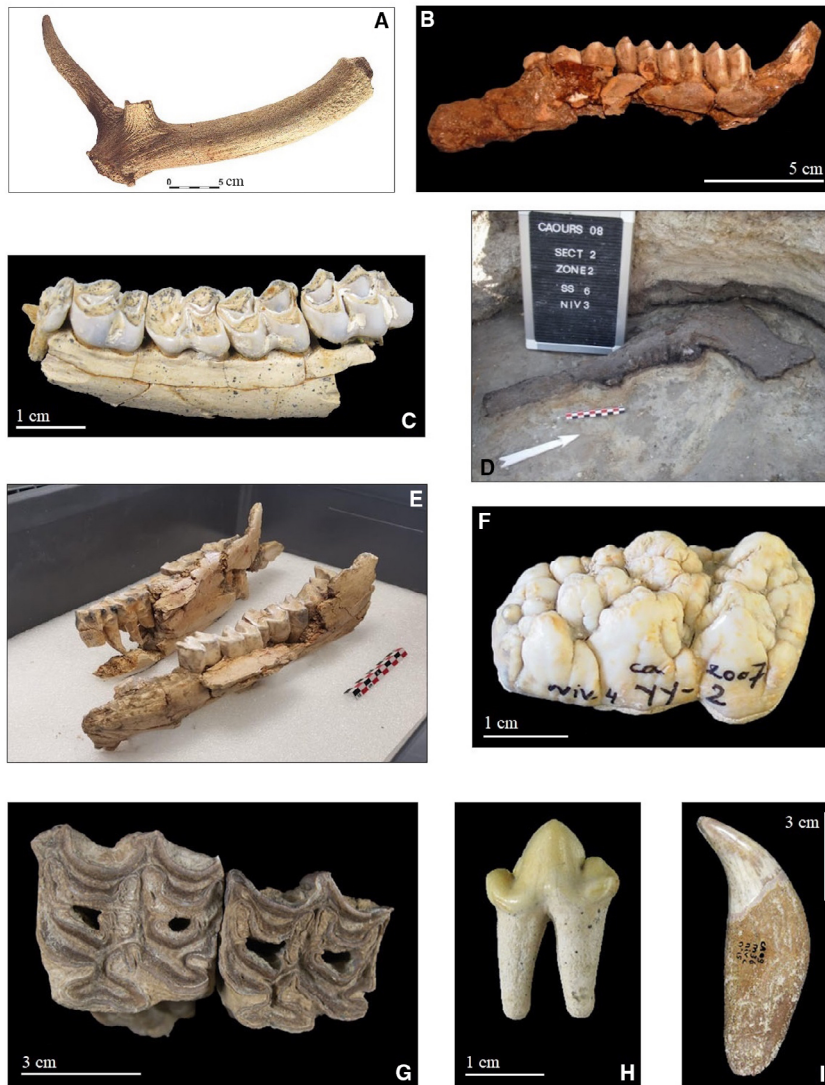


Fig. 17. Main large mammal species identified at Caours. A. *Cervus elaphus*, antler. B. *Dama dama*, hemimandible. C. *Capreolus capreolus*, hemimandible. D. *Bos primigenius*, hemimandible. E. *Stephanorhinus hemitoechus*, mandible. F. *Sus scrofa*, upper molar. G. *Equus taubachensis*, upper premolar and molar. H. *Canis lupus*, lower premolar. I. *Ursus arctos*, upper canine (photographs: P. Auguste, P. Antoine, N. Sévêque; CAD: N. Sévêque).

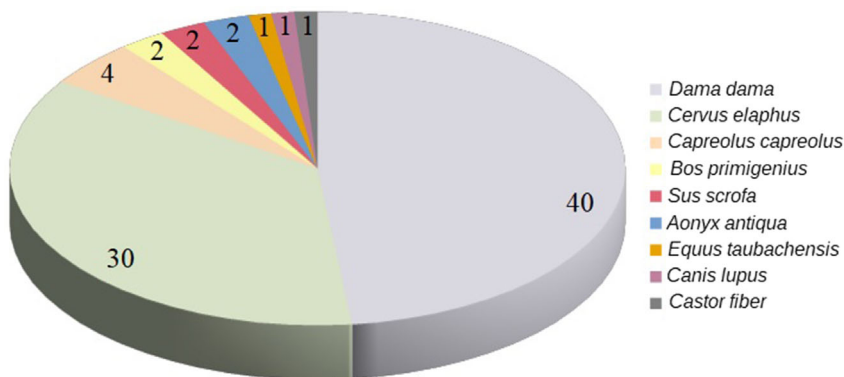


Fig. 18. Unit 5: large mammal species distribution with a minimum number of individuals (MNI).

Table 7. Evolution of the mammalian associations from the four archaeological layers of the southern sector (S-2).

Species occurrences per archaeological level	N-1	N-2	N-3	N-4
<i>Palaeoloxodon antiquus</i>				X
<i>Stephanorhinus hemitoechus</i>		X	X	X
<i>Bos primigenius</i>	X	X	X	X
<i>Equus taubachensis</i>	X			X
<i>Ursus arctos</i>			X	
<i>Cervus elaphus</i>	X	X	X	X
<i>Dama dama</i>	X	X	X	
<i>Capreolus capreolus</i>	X	X	X	X
<i>Sus scrofa</i>	X		X	X
<i>Canis lupus</i>	X			X
<i>Castor fiber</i>	X		X	X
<i>Aonyx antiqua</i>	X		X	

- Wild boar, *Sus scrofa* Linnaeus, 1758. The animal found in Caours is large, matching the known massiveness of Pleistocene boars (Fig. 17F).
- Beaver, *Castor fiber* Linnaeus, 1758. The beaver present in Caours is comparable to the modern European beaver.
- Claw-less otter, *Aonyx antiqua* (De Blainville, 1841). Two species of otters are known from the late Middle and Late Pleistocene. The common otter (*Lutra* sp.) is apparently less common than the claw-less otter (*Aonyx antiqua*) in northern France, the latter being present, for example, at Biache-Saint-Vaast at the beginning of MIS 7 and at Waziers during MIS 5e (Auguste 2009; Auguste et al. 2022). The otter identified at Caours clearly shows the strong development of the jugal teeth compared to the common otter, with several diagnostic features, particularly on the upper premolars, highlighting a more omnivorous diet than the common otter, which is piscivorous (Auguste 1995a, b).
- Wolf, *Canis lupus* Linnaeus, 1758. The wolf observed in Caours seems to be quite close to the present form (Fig. 17H).
- Brown bear, *Ursus arctos* Linnaeus, 1758. The remains of an ursid have been identified very sporadically at Caours (Fig. 17I). The morphology of certain elements allows us to relate it to the brown bear. The Caours bear is comparable to the present-day brown bear, but is more massive, as known in northwestern Europe during the Pleistocene (Auguste 1995a, b).

Overall, the mammal assemblage described above is typical of forest environments that developed during the Pleistocene interglacials. The red deer clearly dominates the fauna of Caours, followed by the fallow deer. The latter is the dominant species in level N-1, which underlines the high density of the forest cover during the climatic optimum (Fig. 18). Aurochs and roe deer, which live in open landscapes, are present in almost all levels, but never in very large numbers. The archaeological levels N-4 to N-1 show peculiarities in their faunal

assemblages highlighting the environmental evolution from the beginning of the interglacial up to the Eemian optimum.

The occurrences of the megaherbivores straight-tusk elephant and grassland rhinoceros are significant. The former is restricted to the earliest occupation N-4 while the latter is recorded from N-4 to N-2 but does not survive in the closed canopy described for the last settlement N-1 (Table 7). Furthermore, the fallow deer, which appears in N-3, becomes dominant in N-1.

Therefore, the environment for N-4 seems to be still partly open, then it closes, with the remarkable development of the forest cover for level N-3 and former ones. The faunal assemblage from level N-1 then suggests a very densely forested environment. These interpretations are strongly consistent with the progressive establishment of forest cover under interglacial conditions as recorded by malacological data (cf. supra). Taxa associated with aquatic environments, i.e. the beaver and the otter, are absent from N-2 but present in the other three levels (Table 7).

From a chronological point of view, the position of this fauna in a sedimentary sequence encompassing the Eemian interglacial until the climatic optimum is therefore in perfect agreement with the degree of evolution of certain species (e.g. Taubach's horse and the grassland rhinoceros) and the mammalian association. It characterizes the typical fauna of the last interglacial in northern France and northern Europe (Auguste 2009). A comparable large mammal archaeological assemblage is present at Neumark-Nord 1 and 2 (Germany, Fig. 1), also dated to the Eemian and including straight-tusk elephant, grassland rhinoceros, forest rhinoceros, fallow deer, red deer, aurochs, steppe bison (*Bison priscus*), horse (*Equus* sp.), wolf, cave lion (*Panthera spelaea*) and cave bear (*Ursus spelaeus*) (Gaudzinski-Windheuser et al. 2014, 2018, 2023).

Micro-vertebrates. – Several stratigraphical layers were tested to study the microfaunal assemblages, but only unit 5 (archaeological level N-1) provides abundant and well-preserved remains. They have a brown patina

similar to that of large mammal bones. In addition, some rodent teeth show signs of digestion (enamel alteration). This suggests that at least some of the accumulation may be due to the action of a predator (Fig. 19).

The first study of the microfauna of Caours was carried out on samples extracted from the SPM-12003 test pit and in particular from the humic tufa horizon of U5 (Figs 4, 5B). It allowed the following list of fauna to be established (according to Escudé, in Antoine *et al.* 2006): *Arvicola* cf. *terrestris* ($n = 6$), *Apodemus sylvaticus* ($n = 4$), *Microtus agrestis* ($n = 1$), *Clethrionomys glareolus* ($n = 1$), *Cricetus major* ($n = 1$), *Talpa europaea* ($n = 1$), *Rana* cf. *temporaria* ($n = 2$), *Bufo bufo* ($n = 2$), *Anguis fragilis* ($n = 1$), and unidentified snake, fish and bird remains (Table 8). This work allowed the conclusion of an interglacial forest environment and the immediate proximity of a watercourse corresponding to a riparian type environment.

Most of the remains found at Caours during the recent excavations (2021–2022) also come from the archaeological level N-1 with 773 remains of small mammals, 78 remains of herpetofauna, 15 remains of birds and 4 of fishes. Rodents are the most represented with *Arvicola amphibius* (MNI = 10), followed by *Myodes glareolus* (MNI = 6), *Microtus arvalislagrestis* (MNI = 4) and

Microtus subterraneus (MNI = 1). Insectivores are also present with *Sorex* sp. (MNI = 4) and *Talpa* sp. (MNI = 1) (Table 8). Compared to earlier data (Escudé, in Antoine *et al.* 2006), *Apodemus sylvaticus/flavicolis* and *Cricetus major* are not present, perhaps due to the size of the sample.

The determined species are either affiliated with temperate environments (*Microtus subterraneus*; *Myodes glareolus*; *Talpa* sp.) or ubiquitous (*Arvicola amphibius*; *Microtus arvalislagrestis*). This palaeocommunity is similar to that found at other Eemian sites in northern Europe: in the UK, Mitnor Cave (Currant & Jacobi 2001) and Swanton Morley (Coxon *et al.* 1980); in Germany, Lehringen, Gröbern, Schönfeld, Stuttgart-Untertürkheim, Taubach and Burgtonna (van Kolfschoten 2000). It reflects a temperate climate with a well-developed forest cover, especially indicated by the presence of *Myodes glareolus*. The presence of more open areas is possible, but given the location of the site, these could be humid open areas.

Cenogram. – The palaeoenvironmental reconstruction of the mammalian assemblage of the richest N-1 level is based on a cenogram that takes into account the large, meso and small mammals (Table 9). The cenogram shape corresponds to a mixed profile of wooded and open areas in a distinctly humid climate (Fig. 20). The regression line shows an excellent correlation between species size and the profile of the line. The absence of taxa between the otter and the ground vole, causing a break in the correlation line, can be explained by the fact that the meso-mammal species often identified in other deposits such as the common fox, the wild cat or even an undetermined mustelid, are not present at Caours. This bias is due to the strong anthropization of the faunal assemblage, but has no palaeoecological value. In view of this observation, the Caours N-1 cenogram is perfectly consistent with a heavily wooded landscape and a clearly

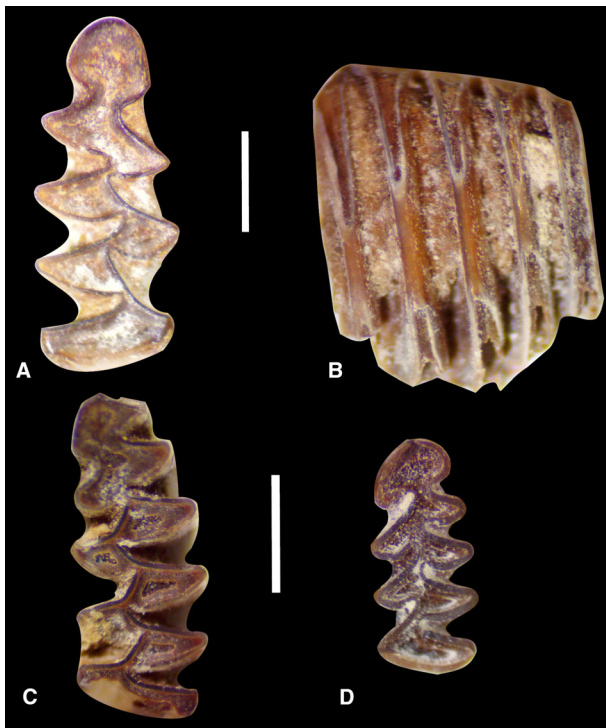


Fig. 19. Rodent remains from U5 archaeological level N-1 (U5) of the Caours site. A. Lower first molar (right) of *Arvicola amphibius*. B. Lower first molar (left) of vole showing medium intensity digestion marks. C. Lower first molar (left) of *Microtus arvalislagrestis*. D. Lower first molar (left) of *Myodes glareolus*. Scale = 1 mm. (photographs: L. Lebreton).

Table 8. Faunal list and minimum number of individuals (MNI) of micro-vertebrates from U5 (archaeological level N-1) of Caours.

This study		Escudé in Antoine <i>et al.</i> (2006)	
<i>Arvicola amphibius</i> (water vole)	10	<i>Arvicola</i> cf. <i>terrestris</i>	6
<i>Microtus arvalislagrestis</i> (common/field vole)	4	<i>Apodemus sylvaticus</i>	4
<i>Microtus subterraneus</i> (common pine vole)	1	<i>Microtus agrestis</i>	1
<i>Myodes glareolus</i> (bank vole)	6	<i>Clethrionomys glareolus</i>	1
<i>Talpa</i> sp. (mole)	1	<i>Cricetus major</i>	1
<i>Sorex</i> sp. (shrew)	4	<i>Talpa europaea</i>	1
		<i>Rana</i> cf. <i>temporaria</i>	2
		<i>Bufo bufo</i>	2
		<i>Anguis fragilis</i>	1
		Snake (indet.)	
		Fish (indet.)	
		Bird (indet.)	

temperate climate. This interpretation correlates well with the malacological and geochemical data, which place the maximum extent of the forest and the climatic optimum at unit 5.

Palaeobotany

Despite several attempts at palynological analysis carried out at the LGP Meudon, then at the IMEP-CNRS, Marseille (V. Andrieu-Ponel, pers. comm. 2007), it has not been possible to identify a sufficient number of pollen grains to allow a reliable interpretation of the contemporary vegetation of the peat and, more generally, of the Caours Eemian sequence. However, in one sample from the peaty layer U9, 48% of grains were identified ($n = 119$) and they are widely dominated by trees (especially *Corylus*, *Pinus*, *Quercus* and *Ulmus*; Table S2).

In addition, abundant plant imprints were discovered during preparation works before the archaeological

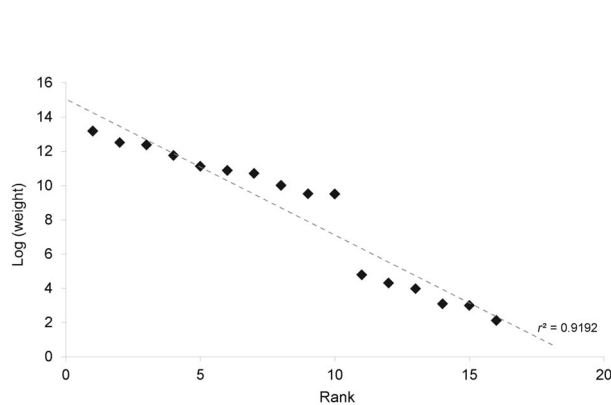


Fig. 20. Cenogram for Caours archaeological level N-1.

Table 9. Faunal list ordered by decreasing body size (as log of the estimated weight) for Caours archaeological level N-1.

Taxon	Log (weight)
<i>Bos primigenius</i>	13.182
<i>Equus taubachensis</i>	12.512
<i>Cervus elaphus</i>	12.367
<i>Sus scrofa</i>	11.754
<i>Homo neanderthalensis</i>	11.127
<i>Dama dama</i>	10.878
<i>Canis lupus</i>	10.711
<i>Capreolus capreolus</i>	9.999
<i>Castor fiber</i>	9.51
<i>Aonyx antiqua</i>	9.499
<i>Arvicola amphibius</i>	4.787
<i>Talpa</i> sp.	4.305
<i>Microtus arvalislagrestis</i>	3.974
<i>Microtus subterraneus</i>	3.091
<i>Myodes glareolus</i>	2.993
<i>Sorex</i> sp.	2.116

excavations, including a bunch of *Asplenium scolopendrium* leaves in living position (Antoine et al. 2006; Figs S3D, S4, no. 13). Then, two sets of specimens were recovered *in situ* within indurated facies of the southern excavation, mainly above unit 5 (Fig. 8: Tmf): one from lenses in the massive tufa and one from a small channel exposed during the excavation (Fig. 8: 'Channel 1' + 14 m). Among them, 98 leaf imprints exhibit well-preserved morphological features allowing their identification at the genus or even specific level (Leaf Architecture Working Group 1999).

Within the massive tufa, a total of 39 imprints belonging to 10 identified taxa were collected (Fig. S4, no. 1 to 5): *Salix* sp., *Salix* cf. *S. caprea-cinerea* and *Salix caprea* L., cf. *Euonymus* sp. L., *Corylus avellana* L., *Rhamnus* sp., *Hedera helix* L., *Clematis vitalba* L., *Cornus* sp. (*C. mas* and *C. sanguinea* cannot be distinguished by the foliar morphology), *Sambucus* sp., *Quercus* sp. and a possible *Acer* sp. leaf.

These mesophilous to mesoxerophilous and semi-heliophilous species correspond to an arboreal vegetation growing under temperate and oceanic climatic conditions. In the small channel (Fig. S4, no. 6, 7; $n = 49$ imprints), *Salix* is the most frequent taxon, represented by several species: *Salix* sp. 1, *Salix* sp., *Salix caprea*, *Salix* cf. *S. caprea-cinerea*. *Cornus* sp. and numerous undetermined Poaceae are also present. This assemblage is characteristic of a riparian vegetation where open vegetation grows in the vicinity of the channel. Overall, two biotopes seem to have co-existed at Caours: a riparian vegetation (small channel) and a nearby mesophilous forest. All the species are still present in the current vegetation. In the Paris basin another set of encrusted leaf imprints from an Eemian tufa sequence at Resson (Fig. 1) has been recently reassessed (Jolly-Saad & Dabkowski 2021). All the species identified at Caours are also present at Resson, where a more diverse flora was however described. Eemian vegetation dynamics are well known with pollen data available in France in sequences such as La Grande Pile, Les Echets, Ribains, Le Bouchet and Saint Frons. It has long been noted that Eemian pollen diagrams from northwestern and central Europe display a characteristic association of trees suggesting a very uniform vegetation development in the area during this period with a high percentage of arboreal pollens (Wijmstra 1969; Müller 1974; Woillard 1978; de Beaulieu & Reille 1989, 1992; Tzedakis 1993; Börner et al. 2018). Based on this result, six zones were defined (E1 to E6) describing the rise, optimum and decline of the forest cover (Cheddadi et al. 1998). The results obtained in the present study are fully compatible with the allocation and the dating of the Caours tufa formation to the Eemian and more particularly to the interval corresponding to the palynological zone Eemian E4 as defined by Cheddadi et al. (1998).

Geochemical analyses on tufa calcite

As continental carbonates precipitating at ambient temperature, tufas have been identified since the 1980s as suitable archives for palaeoclimatic information through geochemical analyses, especially oxygen and carbon stable isotopes (calcite $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$; see Andrews 2006 and references therein). However, Caours was one of the very first Pleistocene tufas (with La Celle, MIS 11, Seine-et-Marne) where such proxies were investigated. Comparisons with the robust, strictly parallel and independent, palaeoenvironmental record provided by malacological data demonstrated that $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in tufas are important proxies of palaeoclimatic variations during former interglacials, as already known for the Holocene (Dabkowski *et al.* 2011). Variations in tufa $\delta^{18}\text{O}$ are mainly induced by changes in the mean annual atmospheric temperature while the $\delta^{13}\text{C}$ is a proxy of moisture conditions, especially related to the vegetation and soil type/abundance. At Caours, the Mg/Ca ratio also provided information on the rainfall amount, showing a strong correlation with the $\delta^{13}\text{C}$ record (Dabkowski *et al.* 2016).

The main climatic feature recorded at Caours is the strong, warm and wet climatic optimum, characterized by high $\delta^{18}\text{O}$ and low $\delta^{13}\text{C}$ values and contemporaneous with U5 (archaeological level N-1). Temperature then shows fluctuations, the coolest conditions being recorded in the upper part of the tufa deposit (minimum $\delta^{18}\text{O}$ values in U2 and U1; Fig. 21). In terms of humidity, the most important change occurs at the transition between U3 and U2, after which drier conditions are recorded by higher values of $\delta^{13}\text{C}$ (Dabkowski *et al.* 2016). Compared to geochemical data from the Holocene tufa of Saint-Germain-le-Vasson (Normandy, France), carbon and oxygen stable isotopes from Caours suggest that, in northern France, the Eemian was not significantly warmer than the current interglacial but experienced wetter conditions (Dabkowski & Limondin-Lozouet 2022).

At Caours, high-resolution analyses were also performed on a well-crystallized laminated tubular stromatolite. They combined detailed micromorphological observations with C and O stable isotopes on infralaminae samples. This study demonstrates that reliable information on seasonality is available from Pleistocene tufa stromatolites and suggests that seasonal changes in water temperature during the Eemian were essentially similar to the modern ones. For details, readers should refer to Dabkowski *et al.* (2015).

Summary of the Palaeolithic record

Five archaeological levels have been identified in Caours. Four of them (N-1 to N-4) are located in the southern area (S-2), the fifth (Nc) is in the northern area (Fig. 22).

The study of the abundant faunal remains shows many stigmata linked to the exploitation of the carcasses to recover the meat (cut marks), the marrow (long bones showing helicoidal fractures, sometimes associated with other elements resulting from the impact during the fracturing), the tongue (cut marks on mandibles and hyoid bones) as well as the fur (cut marks on wolf metapodials), thus demonstrating the butchery function of the site. Presence of burnt bones and heated artefacts indicate the presence of fireplaces in some levels (especially N-4) during the butchering operations (Locht 2021; Moreau 2023). Additionally, the behaviour of humans settled in Caours has been studied not only in terms of both animal management and exploitation, but also through the question of group mobility. Combining the sex ratios, mortality profiles, seasonality and the quantity of meat consumed at each level, several types of behaviour have been identified that are specific to each archaeological level and to species within these levels: totally opportunistic predation regarding both species and individuals; opportunistic predation of species, but selection of individuals; specialized hunting of deer or, even more specifically, of adult male deer. Within the Caours site, multiple subsistence behaviours are thus revealed in the management of animal populations. While some of these behaviours were totally opportunistic, others reflect an organized approach, which can be explained by the search for a balance between hunting effort and supply of raw material. Neandertal knowledge of the eco-ethology of prey is demonstrated by the example of the selective hunting of adult male deer at the beginning of the coldest season.

Regarding the lithic industries, the raw material is of local origin in each archaeological level. Observations of the cortex of the flint artefacts show that the blocks of flint come from the top of the fluvial gravel formation (U12). The blocks are of small dimensions, rarely reaching 15 cm. The quality of the raw material is relatively poor and some blocks are affected by frost. The knapping objective is directed towards the exclusive production of flakes, according to direct Levallois and discoidal methods, but also unipolar and bipolar ones, in proportions that seem to vary from one level to another. The presence of all the elements of the 'chaîne opératoire' and the numerous refittings show that the knapping activities took place on the site. Neandertals produced cutting edge flakes for immediate use in butchering activities.

The five archaeological levels of Caours provide a detailed technological view of the technical systems implemented by the Neandertals during the last interglacial. These are characterized by the likely combination, at least at certain levels, of discoid and Levallois debitage. Discoid cores are most often unifacial. The association of these two production systems seems to be one of the characteristics of Eemian industries (Locht *et al.* 2016).

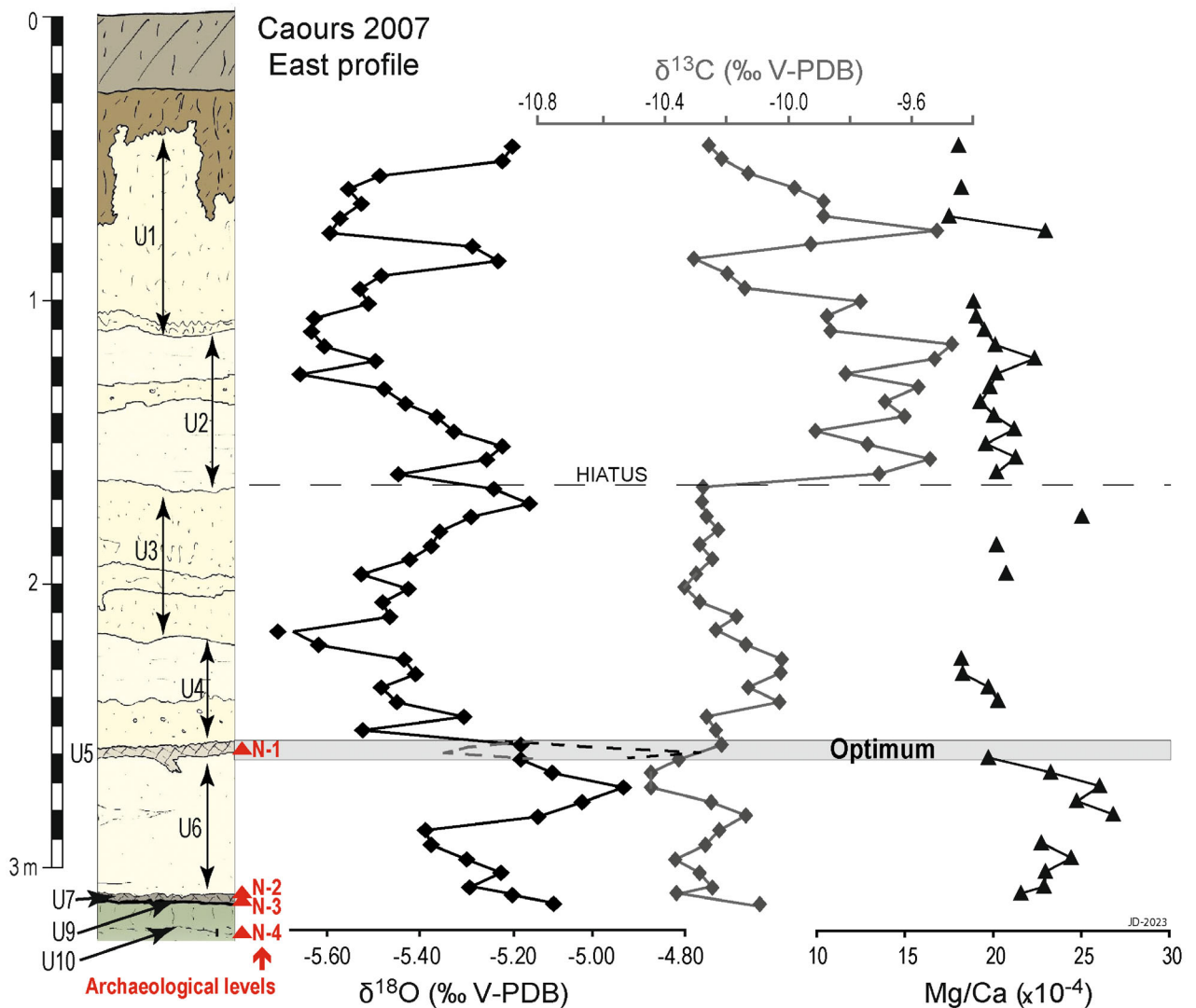


Fig. 21. Summarized geochemical data from 'Caours 2007 – East Profile' (samples M1 to M55, Fig. 8: +0.5 m; modified after Dabkowski *et al.* 2016). The stratigraphical sequence is shown on the left. Diamonds are calcite stable isotope data ($\delta^{18}\text{O}$ in black and $\delta^{13}\text{C}$ in grey). Black triangles are Mg/Ca ratios. Additional isotopic data from unit 5 are shown as dashed lines (samples M56 to M59 from profile Caours 2007 South, Fig. 9: +1.8 m; stratigraphical correlation, depth scale not respected), highlighting the strong $\delta^{18}\text{O}$ maximum and $\delta^{13}\text{C}$ minimum during the optimum.

Based on the data from Caours, a general consideration about the Eemian lithic industries can be made after an overview of other European Eemian industries (Wenzel 2007; Loch & Depaep 2015; Loch 2018; Hérissou *et al.* 2023). The Levallois and discoidal debitage are well represented there, but these series seem to be characterized by low technical investments and appear to be of fairly average quality. The difficulty of sourcing good quality raw material in a wooded and closed environment may be a partial explanation for this phenomenon (Loch *et al.* 2014). Hypotheses can be formulated, according to which stone tools had a secondary role compared to other materials such as wood, easily available in an interglacial context (Otte 2015). The Eemian spear from Lehringen (Germany), like the Holsteinian pieces from Schöningen

(Germany), is a remarkable example (Thieme & Veil 1985; Thieme 1997). Rarely preserved, wooden artefacts would thus lift part of the veil on the plant component of the panoply of Neandertals' hunting weapons. The abundance of denticulates, often used for woodworking, in the Eemian lithic industries of Germany, can also support such an assumption (Richter 2005; Thiébaud 2005).

Synthesis and discussion: lithostratigraphy and palaeoenvironmental evolution

Lithostratigraphy of the alluvial Caours Formation

Following a formal stratigraphical approach, it is proposed to define the *Caours Formation* as a sedimentary

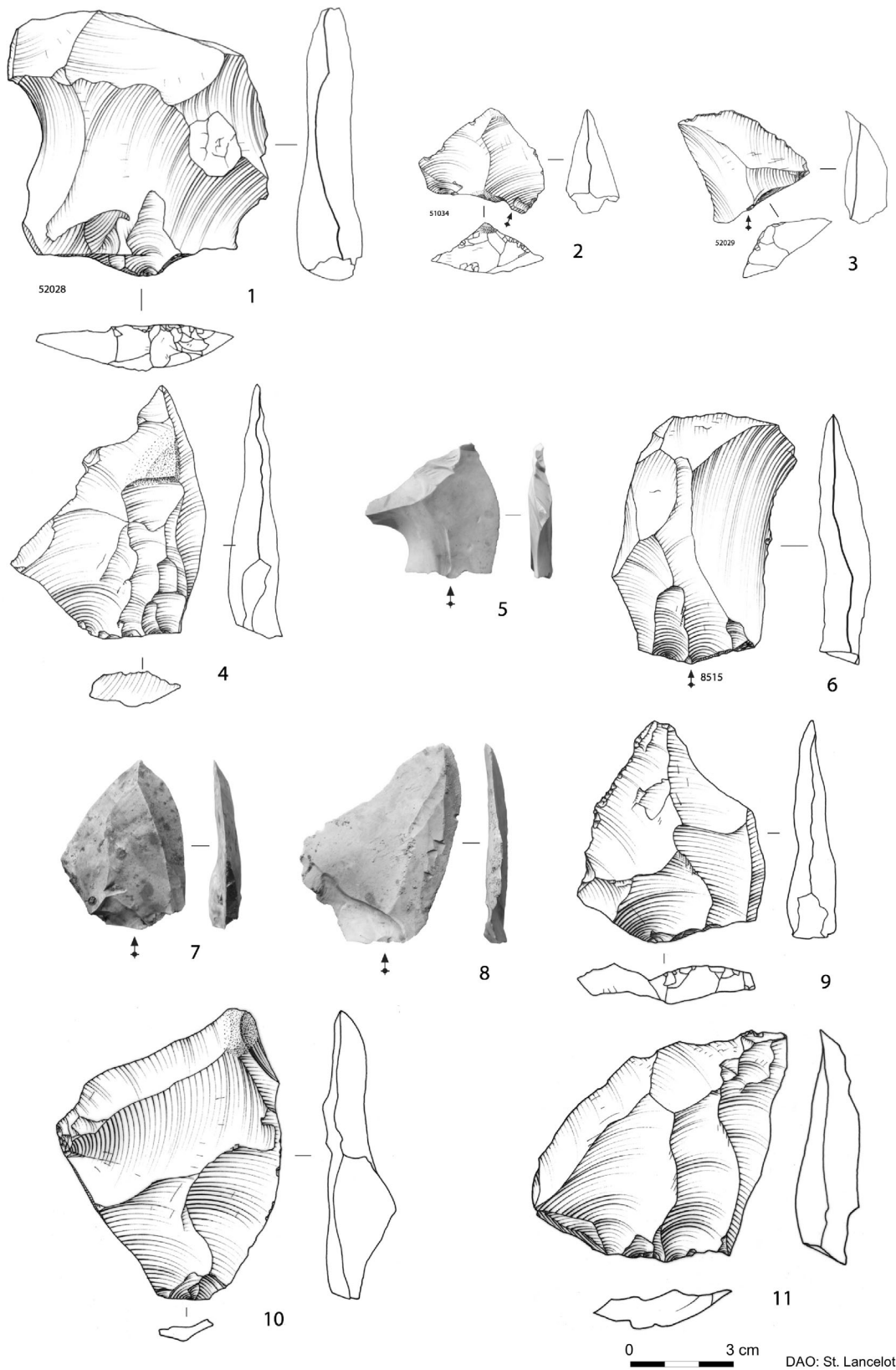


Fig. 22. Typical lithic artefacts from Caours: levels N-1 (1 to 3), N-2 (4 to 6), N-3 (7 to 9) and N-4 (10, 11). N-1. 1. Typologically Levallois flake; 2 and 3. Pseudo-Levallois points. N-2; 4. Pseudo-Levallois point; 5. Regular flake; 6. Typologically Levallois flake. N-3; 7 and 8. Pseudo-Levallois points; 9. Typologically Levallois flake. N-4; 10 and 11. Pseudo-Levallois points.

formation bringing together the various stratigraphical units corresponding to alluvial deposition environments and fluvial sedimentary processes described at Caours. The *Caours Formation* is thus delimited at its base by a main erosion boundary with the underlying Cretaceous chalk bedrock (Upper Turonian/Lower Coniacian), and at its surface by the unconformable erosion boundary with overlying slope deposits (colluvial deposits humic soils, loess, topsoil and colluvial deposits).

The formation is composed of two Members separated by significant sedimentary changes and/or stratigraphical unconformities.

Lower Member (1): detrital fluvial deposits (Figs 3, 4: Gf, Lf and Tn, U12 to U9). – The basal fluvial deposits at Caours are mainly represented by poorly stratified heterometric flint and chalk gravels overlying the chalk bedrock that was reached in three drillings and in a pit dug with an excavator in the western part of the 2009 excavation (Fig. 2B). This makes it possible to accurately set the base of the Caours alluvial layer at +5 m relative height above the maximum incision of the present-day valley. This 2 to 3 m thick gravel deposit disappears rapidly towards the valley between ST-9 and ST-10. Its undulating surface also drops by about 2.5 m between the two ends of the transect and shows, in the central part, a ~40-m-wide channel-like depression between ST-6 and ST-8 (Fig. 3). These gravels are generally covered, in sedimentary unconformity, by fine light grey-green calcareous silts moulding the topography of the gravels (Lf). This unit ends with a more compact facies, about 10 cm thick exhibiting orange oxidation tracks (Lgb marshy soil), itself covered by a thin black peaty layer (Tn/U9). The presence of this compacted peat is one of the original features of the Caours site and the only example of Pleistocene peat ever described in the Somme basin after more than 150 years of research. Despite its thickness, the peat layer is present in all the areas where the fluvial silts are preserved, indicating the development of a peat bog throughout the whole southern area and making a reliable stratigraphical level mark.

Since the 2005 excavations, an additional unit represented by a discontinuous thin tufa lens occurring at the contact between silts 11 and 10 (U10 and 11/Ltg) has been detected in the profiles of the southern area. This deposit, associated with a large number of floated mollusc shells (*Cepaea*), is trapped in small depressions affecting the surface of U11 or between U10a and U10b where this subdivision is possible (excavation 2007). This shows that tufa started developing in the Scardon palaeochannel before the deposition of the youngest silts of U10. The Lgv/Lgb/Tn stratigraphical set is separated from the main calcareous tufa layers by an erosive contact locally reaching the top of the gravels. It could be responsible for the reworking of the upper part

of the gravels and their encrustation (laminated crusts) such as in the channel of area 2–2005 (Fig. 6).

Upper Member (Member II): calcareous tufa deposits (Fig. 3: Tg, Ltg, Tm and Tfl, Fig. 4: U1 to U8). – This 2 to 3.5 m thick sedimentary set mostly comprises massive, beige to light grey-white, calcareous tufas observed throughout the A–B transect and in most of the test pits (Figs S1, S2). They are generally outcropping close to the surface (~0.3 m) and only covered by a thin ploughing horizon (Ap/Hbs) including reworked tufa blocks.

The whole member is a complex juxtaposition of various facies corresponding to four main families: (i) Purely fluvial tufa facies with oncoliths and oncolitic sands, organized from metric to decametric lenses with low angle stratification, are present exclusively in the northern part of the area (Fig. 2B). They indicate deposition in a fairly high-energy fluvial context and are often marked at the base by erosive contact (channel). In the 2009 excavation, a finely laminated beige-grey organic facies was observed, testifying to an episode of channel filling with decreasing dynamics ending with a very calm episode (millimetre-scale laminations with organic debris and traces of driftwood). (ii) Very fine fluvial facies with a sandy-silty texture, weakly stratified or homogeneous with medium or low energy. They have a geometry of small lenses (10–30 cm thick for 3–5 m wide) showing subhorizontal stratification (Figs 4, 6, 8, 9; U1b and U2). (iii) Massive tufa facies, with traces of encrusted vegetation, which represent most of the tufa mound and indicate a marshy type environment with very weak fluvial dynamics (Figs 4, 6, 8, 9; U1a). (iv) Millimetre to centimetre thick stromatolitic facies represented by tabular stromatolites (slabs), more or less undulating or in the shape of half-sheets 20 to 40 cm in diameter (Str), and tubular stromatolites often grouped in large blocks (Stt) (Figs 5D, E, 7D).

Towards the valley, from boreholes ST-10 and S.06-11, the surface of the tufa formation rapidly tilts and the deposits disappear between borehole SPM-2 and trench SPM-12 (Fig. 11). This morphology results from a major erosion phase that marks the upper limit of the Caours Formation, and the transition to slope deposits including colluvial sandy deposits and humic soils.

Slope deposits and humic soils. – Various slope deposits then cover the Caours Formation (Units Lbh to Srb; Fig. 3). The first unit created by the erosion of the tufa is represented by the Lbh unit (U4 to U6; Fig. 11), which is clearly distinguished by a facies of humus-brown detrital sandy silts (colluvium) and a fairly marked pedological structure (root porosity and traces of worms). This unit is separated from the sandy loessic silt Lsb by a new, very marked erosive contact, followed by the deposition of hill washed laminated sands associated with reworked flint pebbles (Sbr), probably originating from older fluvial

gravels occurring along the slope forming the southern bank of the Scardon river.

The Lsb unit, which appears in ST-10, then thickens very rapidly at the level of borehole ST-9 (>3 m) exhibiting a hydromorphic facies due to its position under the water level of the current valley. The connection with the valley floor formations was recently established thanks to the last drilling campaign towards the valley floor showing that this silty unit forms a large lens (over 100 m) preserved against the chalk slope with a maximum thickness of 3.5 m in ST-09-1 and ending in a bevel between ST-09-5 and ST-09-6. Given the geometry and facies (presence of sandy granular beds and small scattered flint flakes), this loess deposit does not correspond to a typical loess but more likely to reworked loess (runoff) preserved in the sedimentary trap represented by the junction between the valley bottom gravels and the chalk slope. These loesses are developed on the whole edge of the tufa massif after the erosion of the Lbh ensemble, as shown by the test pits (Fig. 2B).

Finally, the cross-sections revealed the presence of calcareous sandy loess trapped in the filling of a frost crack of about 3 m depth with 5 to 8 cm maximum opening (Fig. 6; Ls). This structure was observed over more than 8 m of lateral extension across the excavated area.

The top part of the cover is then formed by a typical reddish brown leached soil horizon (Lba), developed at the top of the loessic silt Lsb; towards the valley it shows a greyish hydromorphic facies with oxidation stains (Lbg). Nevertheless, this horizon is strongly eroded towards the slope where it rapidly disappears. In most of the massif, the tufa therefore outcrops at the sub-surface, either directly under the Hbs plough horizon, or under a layer of colluvium with reworked tufa blocks and scattered flints (Fig. 3).

Palaeoenvironmental evolution

Based on the litho-morpho-stratigraphical approach and the synthesis of sedimentological, palaeoenvironmental and chronological data obtained since 2002, the reconstruction of the environment evolution at Caours, summarized in Figs 23A, B, S5, Data S1, is subdivided into three parts: (i) final Saalian and early Eemian interglacial (MIS 6/MIS 5e): fluvial sequence of the Very Low Terrace of the Scardon river (Member I of the Caours Formation); (ii) Eemian interglacial (MIS 5e): calcareous tufa sequence (Member II of the Caours Formation); and (iii) Early Weichselian (MIS 5d–5a): slope sequence and associated humic soils; incision of the present-day valley.

As part of this summary, comparisons with other Eemian sites and sequences recently studied in northern France will be discussed: Erquinghem-sur-la-Lys (Nord: Sommé *et al.* 1996); Waziers (Nord: Deschodt

et al. 2022, 2023; Gauthier 2022) and Resson-La Saulsotte (Seine-et-Marne: Dabkowski *et al.* 2020, Jolly-Saad & Dabkowski 2021). However, given the uniqueness on a European scale of the association highlighted at Caours between a stratified and well-dated sequence of calcareous Eemian deposits including four distinct Palaeolithic levels, such comparisons are relatively limited.

They are even more limited with the numerous Eemian lacustrine sequences in northern Germany (sometimes including Palaeolithic levels), such as Neumark-Nord 2 (Pop 2014; Pop & Bakels 2015; Laurat & Brühl 2021), Lichtenberg (Nielsen *et al.* 2017) and Lehringhen (Hein *et al.* 2021) (Fig. 1). Indeed, at these sites, the proxy used to describe the evolution of the environment is pollen while, unfortunately, pollen grains are poorly preserved in the Caours calcareous tufas, where the palaeovegetation and forest dynamics are reconstructed from the particularly rich and well-preserved mollusc assemblages.

Final Saalian and early Eemian interglacial (MIS 6/MIS 5e): fluvial sequence of the Very Low Terrace of the Scardon (Member I of the Caours Formation). – The Caours Pleistocene sequence began with the deposition of a layer of poorly sorted flint and chalk gravels within an abundant sandy-calcareous matrix, exhibiting the facies typical of the periglacial fluvial units of the Somme terraces (Antoine 1994; Antoine *et al.* 2000). This coarse deposit, 2 to 3 m thick (U12), rests on an erosion surface (step) incised into the Upper Cretaceous chalk bedrock and located between +5 and +6 m relative altitude above the last stage of incision of the valley related to the last glacial (Weichselian: +5 m in the transect of Fig. 10). Given its position in the stepped terrace system and the overlying stratigraphical record, this periglacial alluvial formation is correlated with the alluvial Étouvie Formation, which is the last Saalian fluvial gravel layer attributed to MIS 6 (Antoine 1994; Antoine *et al.* 2000). The U-series dating results obtained on the tufa (Table S1.4) confirm this interpretation and the correlation of the lowest Member of the Caours Formation with MIS 6 (Fig. 23A).

This gravel unit is then systematically covered by a layer of fluvial calcareous silts (U11) themselves capped by a 10 to 15 cm thick grey-brown clayey silt horizon (U10), and then by a thin peat layer (U9). The U11 silty unit is a fine, homogeneous calcareous fluvial deposit (40 to 50% CaCO₃), the facies of which is identical to that of the calcareous silts usually observed in the Somme basin at the top of the alluvial sequences of the terraces (Antoine *et al.* 2007) and in the bottom valley formation (Antoine *et al.* 2003b). The boundary between gravels (U12) and silts (U11) reflects the transition from a periglacial braided fluvial system fed by strong lateral inputs of chalk and flint to a meandering system at the origin of the deposition of calcareous silty flood deposits (Fig. 23A). This evolution, already highlighted in the

Somme for various Pleistocene sequences, and especially at the transition between the end of the last glacial period and the Holocene (Antoine 1997; Antoine et al. 2000, 2012), reflects a sharp reduction in sedimentary transfers into the valley linked to the definitive cessation of coarse slope deposits (chalk and flint deposits with a chalk matrix). This results from the stabilization of the environment due to the disappearance of permafrost and the development of both plant cover and brown leached soils upon loess in temperate oceanic conditions (biostasis), as noticed in other European rivers (Gibbard & Lewin 2002). The resulting increase in the river capacity led to channel concentration and incision and a general lowering of flood levels, which now rarely reach the site.

At Caours, analysis of the malacofauna shows a rapid increase in the richness of assemblages from the base to the top of U11. The malacofauna assemblage in this deposit, which is very homogeneous and includes *Columella columella*, is characteristic of open and humid environments under cold climate conditions (Fig. 14). It can be compared to the faunas of the Younger Dryas from the bottom valley deposits of the Somme basin (Limondin 1995; Limondin-Lozouet & Antoine 2001). At Waziers, in northern France, the Eemian peat deposits cover silt deposits with cold-phase malacofauna that are attributed to the Late Saalian (Limondin-Lozouet 2022). Comparison of the malacological successions of the two sites shows a strong similarity between the faunas of Zone 1 at Caours and those of the median subzone at Waziers (1b), which is characterized by the development of *C. columella*. At Waziers, in the next subzone (1c), this boreo-alpine species is in sharp decline, while the first individuals of *Belgrandia marginata*, a thermophilous species typical of regional Pleistocene interglacials, appear in the aquatic fauna. This terminal stage of the Saalian/Eemian transition is missing at Caours and confirms the existence of a sedimentary hiatus between units 11 and 10.

The transition to U10 is highlighted in the sections of the southern sector by a localized concentration of *Cepaea* shells, which locally formed a centimetre-thick bed that was clearly visible during excavation (Antoine et al. 2006). Following this event and the associated hiatus, the malacological assemblages suddenly became typical of a forested terrestrial interglacial environment (Fig. 14). The rare aquatic taxa are only sporadic, while the thermophilous species from closed environments represent 20 to 30% of the assemblage. The terrestrial character of the environment is also indicated by the remarkable abundance of earthworm calcite granules observed both in thin sections and in the residues of malacological sieving (mesh size: 500 µm). Given the malacological and sedimentological observations, the fundamental shift, accompanied by a very clear hiatus in the malacological diagram, is therefore located at the contact between units 10 and 11. This hiatus and the

sudden disappearance of aquatic taxa (cessation of flood dynamics) clearly indicate a significant lowering of the water level in the river valley. This was the result of an incision phase occurring in the Scardon channel at the beginning of the Eemian, as has been demonstrated for the beginning of the Holocene (Preboreal), particularly in the valleys of the Paris Basin (Pastre et al. 2000; Antoine et al. 2003b).

Extension of the transect towards the present-day Scardon valley in 2009 (Fig. 10) revealed, beneath the Holocene silts and peats, the occurrence of a calcareous silty unit (Lcgv) showing a facies very similar to that of the calcareous silt of unit 11 (Lf) and to that of the Younger Dryas of the Somme basin (Limondin 1995; Antoine et al. 2003b). At Caours, the deposition of this unit follows an incision of the underlying loessic silty unit related to the beginning of the concentration of fluvial channels, likely during the early stages of the Weichselian Lateglacial (Antoine et al. 2003b, 2012). These observations reinforce the very clear analogy, in terms of stratigraphy, facies and malacological content, that appears between the base of the Caours sequence and that of the valley-bottom sequences corresponding to terminations II (MIS 6/5e) and I (MIS 2/1), respectively.

A much more gradual and detailed transition has recently been described at the base of the Waziers fluvial sequence in the Scarpe valley (North France). There the end of the Saalian is marked by the gradual concentration of the fluvial dynamics in a meandering system. It is associated with the deposition of fine fluvial calcareous sands and silts that pre-dates the development of peat marking the beginning of the Eemian, in a 'Lateglacial' type environment (Deschodt et al. 2023). At Waziers, the palynological study of the silty-peaty sequence provided a relatively continuous record of a vegetation succession typical of the Eemian in northern Europe (succession of phases with *Pinus-Betula*, *Ulmus*, *Quercus*, *Corylus*, and *Carpinus betulus*; Gauthier 2022). At this site, the boundary between the Saalian 'Lateglacial' and the Eemian interglacial, represented by the transition from pollen zones Waz-4 to Waz-5, corresponds to the establishment of temperate-cool climatic conditions associated with *Pinus* and *Betula* woodlands and the disappearance of steppe markers, as observed in other European sequences (Kenzer et al. 2018). By comparison with the Waziers pollen diagram, the hiatus revealed at Caours by the abrupt development of forest assemblages from the base of U10 and the transition from a coniferous to a deciduous forest, seen in the malacological record, would therefore correspond to the Waz-5 and Waz-6 palynozones. Therefore, contrary to what the first observations made in 2003 during the SPM-1 excavation suggested, the succession of units 10 and 11 at Caours does not correspond to a continuous record with the formation of a marshy soil at the top of an earlier silty-calcareous deposit, but rather to at least two very distinct silty depositional phases, the last of

which ended with the development of the marshy soil that characterizes U10. In fact, in several Caours profiles from the southern sector, a thin lens of tufaceous sand (U10/11) overlapping an erosive contact with localized carving features was observed at the contact between units 10 and 11 (Fig. 8, +13.5 m; Ltg). The tufaceous dynamics, which will later greatly increase at this site, therefore start at the beginning of the interglacial. However, at that time, these dynamics remain essentially localized within the Scardon channel, slightly below the site.

This configuration can be compared to that already described for the Holocene calcareous tufas of the Somme valley, whose sedimentation began during the Preboreal period at the bottom of the channel in the Somme valley, for example at Etouvie or Chaussée-Tirancourt (Antoine 1997). At these sites, stratified calcareous tufas form at the bottom of fluvial channels deeply incised into the Weichselian gravels at the Younger Dryas to Early Preboreal transition. The bottom of the channel is in contact with the chalk aquifer, allowing cold water rich in dissolved carbonates to be injected into the fluvial environment. This situation allows rapid heating of the water table, potentially leading to precipitation of CaCO_3 , producing tufa deposits.

In this context, the deposition of the fine tufa deposits observed between U11 and U10 may have occurred during flood episodes capable of reworking tufa elements from the main channel (oncoliths, encrusted twigs etc.) and depositing them at the immediate margin of the channel in S-2, located near the palaeo-riverbank (Fig. 23A, Stage 2). However, it cannot be ruled out that these first contributions of fine fluvial tufas were also fed by small channels occurring at the foot of the slope, such as 'Channel 3', whose activity began very early in parallel with level N-4 (Fig. S5, ST1). Lastly, this dynamic could also have been responsible for the transport by flotation of a large part of the accumulation of *Cepaea* shells observed at the base of unit 10. From a sedimentological point of view, the transition between units 11 and 10 is associated with a marked increase in the percentage of organic carbon and a decrease in the percentage of carbonates, which are clearly visible in U10 (Antoine *et al.* 2006). Observations made in the field and on thin sections (Fig. 12) confirm the interpretation of this horizon as a small valley floor soil developed in a wooded area at a short distance from the water table at the time (Fig. 23A, Stage 3).

In the excavation of the southern part of the deposit (S-2), the first Palaeolithic level (N-4) represented by lithic artefacts with a concentration of flint knapping places, numerous bone remains, heated flint artefacts and burnt bones, was revealed at the boundary between U11 and U10 in the sectors where the latter was not very thick (± 10 cm). However, in areas where U10 is thicker (up to 20 cm) and has been subdivided into two subunits (10a–10b, 2007 sections, Fig. 8), the artefacts

appear systematically at the boundary between the two subunits.

The malacological assemblages in unit 10 correspond to the beginning of the development of the interglacial deciduous forest, comparable, by analogy with regional Holocene data, to the Boreal chronozone (Limondin-Lozouet 2011), which indicates forest mollusc numbers in excess of 25% for this period (Limondin 1995). They would therefore be contemporary with the Waz-7 pollen zone at the Waziers site, which is characterized by the expansion of the deciduous forest (Gauthier 2022). The bone remains of large herbivores found at Caours in association with the flint artefacts from level N-4 (Fig. 17) also indicate a typical interglacial environment, essentially forested, but the presence of straight-tusk elephant and abundant rhinoceros remains indicate the occurrence of local open areas.

Regarding the Palaeolithic settlements, the first occupation of the site by Neandertals (N-4) thus took place during an initial phase of the Eemian, as soon as the valley had been incised sufficiently for the site no longer to be systematically flooded by high water. Human occupations were then located on the outer edge of an alluvial plain in a vegetated and relatively well-drained terrestrial environment (abundance of earthworms, terrestrial molluscs). Evidence of human occupation was then rapidly fossilized by silty-calcareous flood deposits associated with an overall rise in the water level (Fig. 23A, Stage 3), which allowed very good preservation of both flint artefacts and faunal remains.

Subsequently, the tendency for the water level to rise in the valley is clearly illustrated by the development of a peat bog, of which unit 9 represents a highly compacted relict (Fig. 23A, Stage 4). It should be noted that the preservation of a peat bog within a Pleistocene terrace sequence is currently unique in the Somme basin. This exceptional preservation can probably be attributed to the rapid emplacement of the overlying tufa formation, which 'sealed' these deposits preserving them from later erosion processes. However, this peat has undergone considerable compaction, as shown by thin-section observations (Fig. 12A, A') and the intense deformation of the pollen grains. The rate of undetermined grains is consequently very high in this level (more than 35%) (Table S2).

A Palaeolithic level, extremely rich in bone remains, especially deer teeth, associated with cut flints, was excavated at the top of the peat border (U9) in the southern sector. This corresponds to an occupation that took place after an initial phase of desiccation and compaction of the peat, in an environment that should have been accessible again to the Palaeolithic groups (Fig. 23A, Stage 6). The numerous large mammal bone remains (especially rhinos) that make up a large proportion of the artefacts from level N-3 are deformed by compaction processes resulting from the subsequent accumulation of the 3 to 4 m thick calcareous tufa.

However, it did not affect the spatial distribution of this assemblage, as attested by the numerous faunal remains found in anatomical connection and the refittings of broken flint artefacts (Moreau 2023). Finally, the abrupt lithological change, which is marked by a clear contact in all the profiles between the end of the peaty episode and the start of the tufas (Units 9/8), is not associated with any notable erosive processes.

Eemian Stage (MIS 5e interglacial): calcareous tufa sequence (Member II of the Caours Formation). – In view of the very significant differences in facies and stratigraphical balance revealed by the transect between the southern and northern sectors of the Caours site, the interpretation of the palaeoenvironmental evolution contemporaneous with the edification of the calcareous tufa sequence during the Eemian is presented hereafter in two independent parts, followed by a correlation between the two sectors and the integration of all the facies into a general palaeoenvironmental model (Fig. 23).

Southern sector dominated by massive tufa facies (Fig. 2B). In the southeastern half of the transect the tufa sequence rests generally directly on the peat layer U9 or the marshy soil horizon U10 as in ST-5 (Fig. 3). Generally speaking, the tufa accumulation begins with facies that are fairly rich in oncoliths, and small encrusted twigs and mollusc shells (U8), indicating a strong fluvial dynamic linked to the outflow of springs located at the base of the chalk slope, in a configuration that can be observed today, such as in the Noye River, a small tributary of the Somme river (Fig. 23A).

The study of the ostracods, previously published in detail (Carbonel in Antoine et al. 2006; Table S3), shows a sudden increase in the number of individuals and especially the benthic fauna in the granular tufa of U8, indicating the flooding of the sector (Fig. 23B, Stage 7). In addition, both ostracods and molluscs indicate that, from the outset, the tufa layers were laid down in relation to springs, in a raised topographical position compared to the water level of the alluvial plain, beyond the reach of floods (Fig. 23B, Stage 7). Within the first tufaceous deposits (U8), the significant development of *Belgrandia marginata* reflects a peak in spring activity directly fed by the resurgence of the chalk aquifer at the foot of the slope. At Waziers, this species is thriving in the Eemian peat levels (U5, Limondin-Lozouet 2022).

At Caours, this dynamic is interrupted by several stabilization episodes indicated by the development of small grey organic tufa horizons with a fine matrix that are very rich in terrestrial malacofauna, microfaunal remains (rodents), earthworm calcite granules and locally containing charcoals (U7 and U5; Figs 4, 5B, S3A). The Palaeolithic artefacts and associated large mammal faunal remains are all found in these stabilization horizons, particularly in U5 (Fig. 5B). Within these small grey horizons, the malacological content indicates

distinctly temperate and forested conditions, in line with the data derived from the large fauna (occurrence of *Cervus elaphus* and *Bos primigenius*). In U5, the malacological assemblages are particularly rich and diverse, with over 70% of the populations made up of forest taxa (Fig. 14). The assemblages are enriched by species that are highly specialized in closed habitats, the occurrence of which is limited to this episode. The malacofauna of U5 reveals a closed environment corresponding to the maximum development of forest cover and to the temperate and humid climatic optimum demonstrated by the isotopic record from the tufa CaCO₃ (Fig. 21; MIS 5e optimum, around 123 ka). Among the various palynological tests, one sample from U5 yielded 35% of hazel pollen (72% of AP, Table S2); a proportion compatible with a correlation with the Waz-9 palynozone of Waziers (Gauthier 2022) and an attribution to the E4 zone of the northwest European Eemian Stage, both corresponding to the thermal optimum (Cheddadi et al. 1998). On a regional scale, the E4a zone has also been described by Sommé et al. (1996) using pollen contents over a thickness of more than 4 m in the Erquinghem-sur-la-Lys borehole (northern France).

At Caours, the geochemical data, which indicate the presence of the thermal optimum in U5, support its attribution to the E4 zone of the Eemian Stage dated at around 123 000 years ago in northwestern Europe (Turner 2000; Cohen et al. 2021); a conclusion in perfect agreement with the averaged U-series TIMS ages obtained on the stromatolites associated with this part of the sequence (Table S1). Moreover, *Corylus* is already present in the peat of U9 (Table S2), as in zone E3b of the Eemian Stage palynological zonation, where it appears for the first time. Based on the estimates of the duration of the interval corresponding to the E3b–E4 succession (Zagwijn 1996; Cohen et al. 2021), units 9 to 5 at Caours could therefore cover a time interval of about 2000 years.

Generally speaking, the sedimentological data from the sequence encompassing U11 to U5 show a fairly clear increase in the percentage of organic carbon (0.5 to 0.6%) in both U7 and U5, indicating the development of vegetation (bioturbations). At the same time, the relative drop in carbonate content indicates a significant leaching of the sediment (weak pedological weathering) and an increase in biological activity (–5 and –10%, respectively, Antoine et al. 2006). These horizons are therefore similar to ‘microsoils’, indicating periods of reduced spring activity and a slightly drier environment (seasonally?), favourable to the occupation of the site by terrestrial mollusc fauna, earthworms, rodents, large mammals and, finally, Palaeolithic people. The rare charcoal remains collected in U5 (*Fraxinus* sp., S. Thiébault, pers. comm. 2003), whether of natural or anthropogenic origin, also indicate a much drier environment than during the deposition of the underlying and overlying tufa layers.

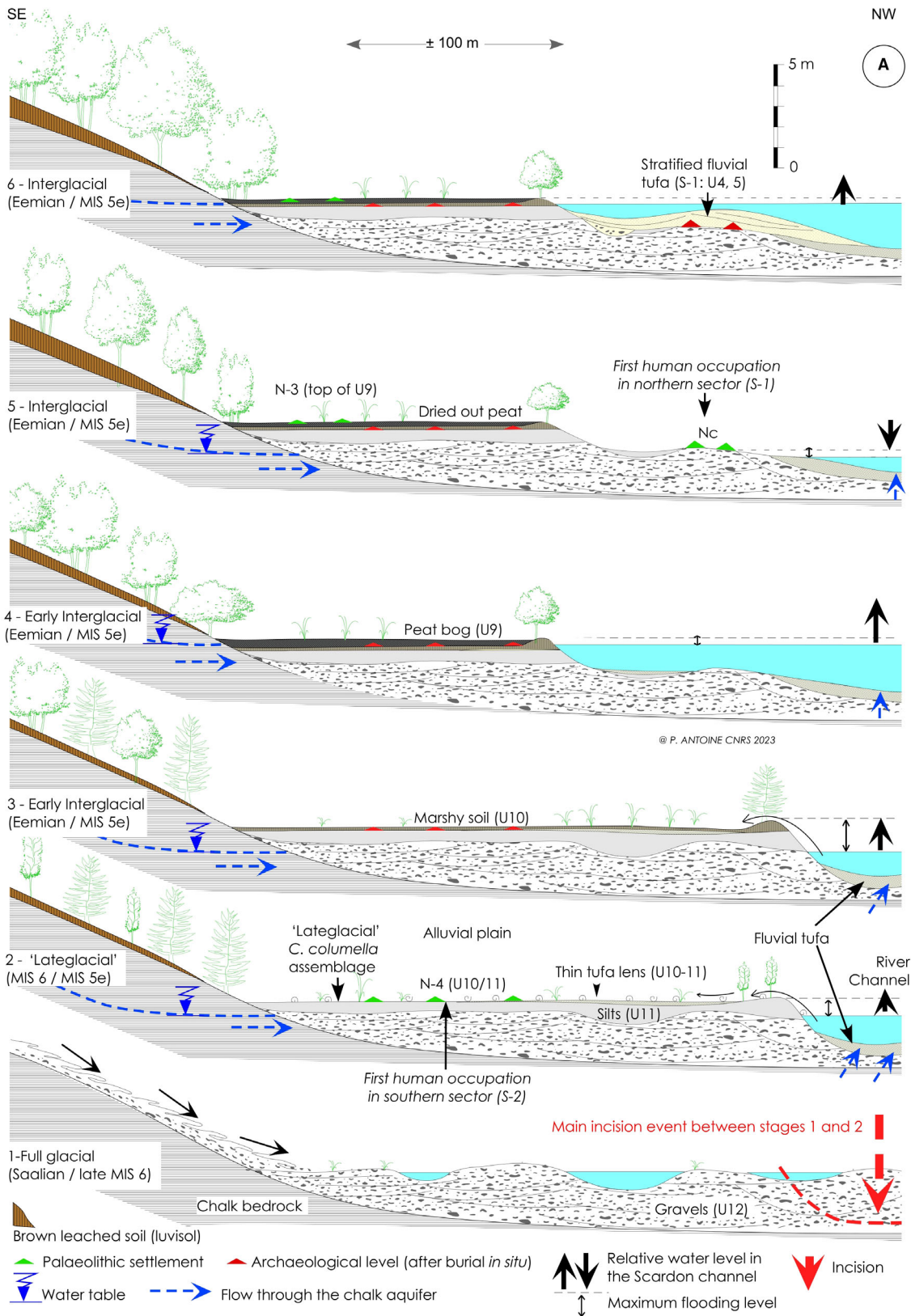


Fig. 23. Palaeoenvironmental reconstruction of the Caours Formation. A. From the Late Saalian to the Eemian interglacial optimum: edification of the tufa sequence and location of the associated Neanderthal occupations (N-4 to N-1). B. From the Eemian optimum to the Weichselian Early-glacial (MIS 5d–a): erosion of the tufa surface then incision of the new valley.

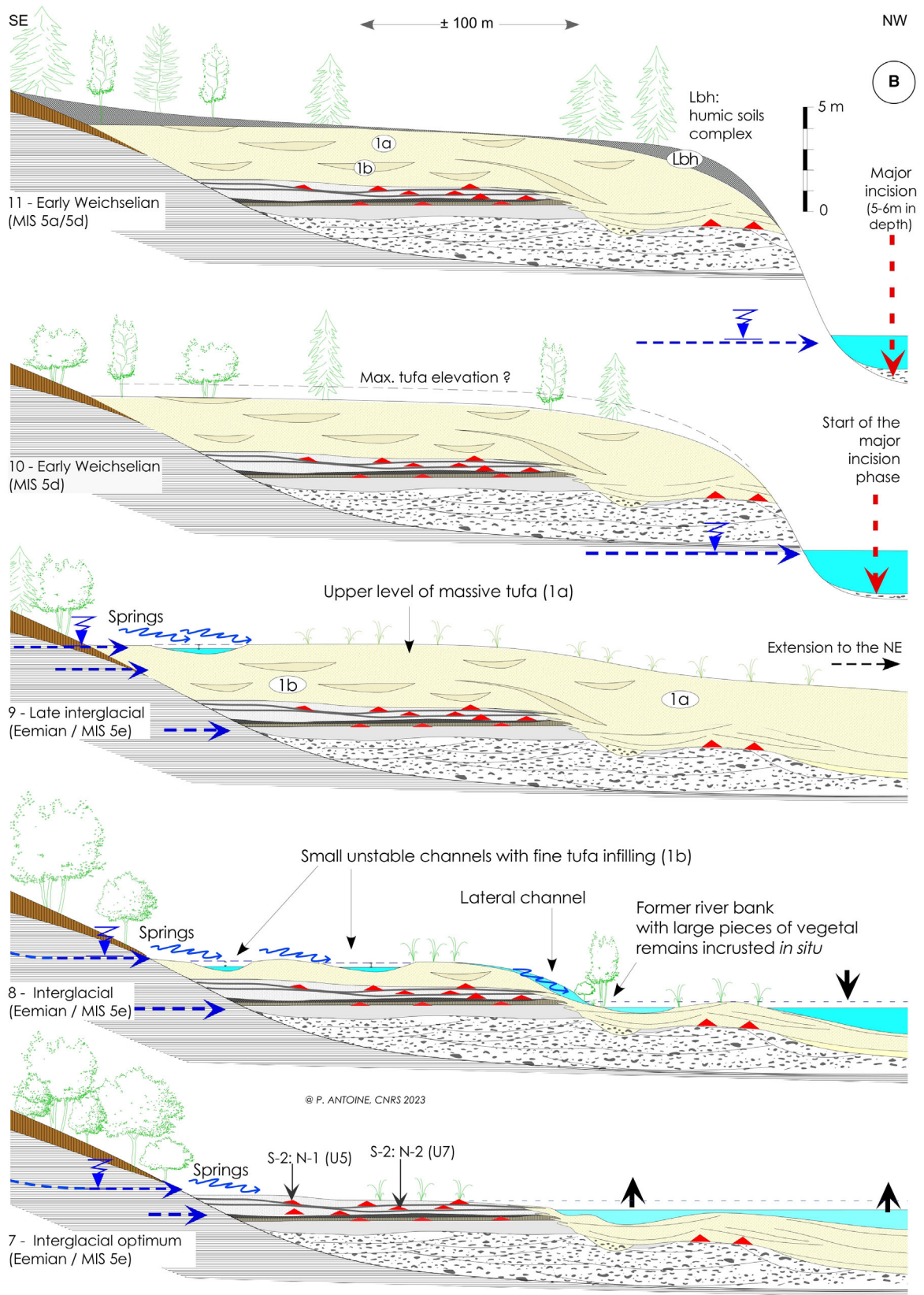


Fig. 23. (continued)

Thin-section observations showed that these levels were characterized by a ‘mille-feuille’-type facies built by *Ponsinella*, edged with organic matter, which nevertheless required a minimum amount of moisture to grow, probably resulting from seasonal water runoff fed by springs punctuating the foot slope. Furthermore, the ostracod assemblages from U7 and U5 are always characterized by the importance of benthic and spring species (Carbonel in Antoine *et al.* 2006). They probably correspond to episodes of slightly more marked flow within an overall landscape dominated by well-drained environments, contemporary with the formation of the small humic horizons on which human occupation took place (levels N-2 and N-1).

In general, at the base of the tufa sequence (U8 to U5), there is a very good correlation between the calcite isotopic signal ($\delta^{18}\text{O}$) and the environmental changes described by malacology (Dabkowski *et al.* 2011, 2016). The temperature increases as the forest develops, its maximal extension being contemporaneous with the climatic optimum (the most temperate and humid period). The alternations observed between the phases of tufa formation, relatively poor in malacofauna and totally sterile in terms of mammal remains and Palaeolithic artefacts, and the two greyish ‘microsoils’ with rich terrestrial malacofauna, abundant earthworm granules and Palaeolithic levels (U7 and U5) are the results of decimetric fluctuations in the relative water level throughout the southern part of the site (S-2). It is proposed that these phases of relative lowering of the water table in S-2, contemporaneous with the ‘microsoils’ of U7 and U5, result from local incision processes within the small channels from the foot of the valley slope. This process likely occurred during short episodes characterized by a rapid increase in the power of springs located at the foot of the valley slope in a particularly wet environment. The upper greyish horizon (U5) is characterized by a much higher density of small mammals, molluscs and large fauna remains and a higher organic carbon content (TOC: 0.5 to 0.6%). It therefore seems to reflect a slightly longer period of environmental stabilization (several centuries?).

The transition between the top of U5 and the rest of the tufa sequence is marked by a sudden peak in water flow responsible for the generalized activation of the small slope channels, the erosive activity of which locally strongly eroded U5 and the associated archaeological level (reworked artefacts in the bottom of the channels; Fig. 9, Channel 2 ‘marmite’). The part of the Caours tufaceous complex that post-dates the climatic optimum (2.5 to 3 m thick on average) is represented by various tufa facies built up *in situ* (encrusted vegetation) forming large irregular blocks (locally >1 m) including laminated layers and irregular stromatolitic spherical bodies with millimetre-thick laminae.

Within the mass of calcareous tufas, shallow channels are filled with alternating fine powdery tufa and beds of

centimetre-sized oncoliths, highlighting slow to moderate fluvial dynamics (Fig. 23B, Stages 8 and 9). The course of these channels was observed during the excavations showing that they were fed by springs that gushed out from the hinge between the lower slope and the valley floor. They are disconnected from the water body of the Scardon valley by the rapid vertical growth of the tufa massif. Ostracods from this period indicate a water supply essentially linked to springs, with cold, clear and carbonated water. Mollusc assemblages contain numerous aquatic species, occasionally including the crenophilous taxon *Belgrandia marginata* while the terrestrial snails describe a mosaic landscape with open habitats and reduced wooded patches (Fig. 15, Zones 3 and 4).

In the Somme basin, the presence of a homogeneous chalk substratum with high fissure porosity generates a huge aquifer beneath the plateaus, which gradually sinks towards river valleys feeding their alluvial aquifers via the gravel layers below the river channels (Roux & Comon 1978). This water table, separated from the surface and active channel by silts and peats, is usually under pressure and causes resurgences within the valley at discontinuities in the sedimentary infilling (valley springs) and/or in the channel floor if this latter reaches the top of the gravels. However, during major episodes of water recharge, the piezometric level may rise above the surface of the valley and springs are then reactivated at the contact between the foot slope and valley floor, as recently observed during the last major floods in the Somme valley in 2001 (Cosandey *et al.* 2003). At Caours, variations in the intensity of spring-related flows are indicated within the tufas of the southeastern part of the transect by the presence of numerous small, shallow (depth: 0.2 to 0.5 m max.) channel structures and by the activity of the localized channels that cut into the base of the sequence (Channel 3: Figs 9C, D, S3E, S5). In this context, the sedimentation of tufas fed by water from springs disconnected from the water level of the alluvial plain would therefore indicate periods of particularly marked hydraulic recharge during the Eemian interglacial. According to malacological data, the small channels interbedded in the massive tufa (1a) are characterized by episodic functioning (Fig. 23B, Stages 8 and 9), which did not allow the development of perennial aquatic fauna. The characteristics of the facies observed in the field and in thin sections, and in particular the development of colonies of *Broutinella* cyanobacteria (cauliflower facies), show that the environment was always underwater. It was therefore hardly conducive to human occupation and no archaeological artefacts were found in this massive tufa. A few bone remains were found in lenses of channelled fine tufa that could correspond to rejections from an occupation located further up on the slope (Fig. 9, unit 1b).

The upper part of the complex, which is more massive and highly indurated, mainly results from the *in situ*

encrustation of marshy vegetation. These crusts, which form around living plant stems and leaves (Fig. 5D: Stt), can be more than 40 cm long and 5 to 10 cm in diameter. Unlike Holocene facies where small tubular oncoliths abound in medium-energy fluvial environments (channels), here large indurated crusts developed in a palustrine environment with stagnant water and a heavily vegetated environment. In thin sections, *Broutinella* and *Ponsella* cyanobacteria, which indicate water depths of less than 0.3 m, have also encrusted a large number of plant fragments. One example of a plant mass preserved by calcareous encrustation yielded a set of fern leaves (*Asplenium scolopendrium*) measuring 30 to 40 cm (Fig. S3D). The presence of this species, which is characteristic of temperate, very damp and shady calcareous environments, implies a heavily vegetated environment able to offer it protection. The other plant remains (leaf casts) from the upper part of the SPM-1 sequence (Fig. 4: U1) correspond in particular to *Salix* group *caprea*, *Salix* type *viminalis*, *Carpinus* sp., *Fraxinus* sp. and *Buxus* (Fig. S4) and indicate temperate conditions although geochemical proxies clearly register a cooling (Fig. 21). Mollusc fauna also indicates wetlands and a temperate climate but a marked decline of wooded habitats (Fig. 15, Zone 5).

Numerous examples of laminated concentric concretions (Stt) with tubular cores corresponding to the imprints of 1 to 20 mm in diameter plant stems were discovered during the excavations. Some of these can be up to 120 mm in diameter and contain more than 30 undulating millimetre-sized laminae. These laminae form domes visible to the naked eye, resulting from the irregular growth of successive algal colonies (Fig. 5E). These facies are found mainly in the northern sector (S-1) and in neighbouring test pits and excavations. This

distribution indicates the existence, at this location, of a slightly depressed zone, particularly wet and rich in palustrine vegetation at the level of the southern bank of the palaeo-Scardon likely to be submerged during flooding events (Fig. 23B, Stage 8).

Finally, the presence of numerous crusts of small-diameter plant stems (1–2 mm) preserved in living position indicates a stagnant environment when this part of the tufaceous massif was being formed. Current analogues can be found locally in the Somme basin, for example on the right bank of the Noye valley, 15 km to the southeast of Amiens (Fig. 1). Here, a system of springs emerges beneath the gravel of the alluvial plain at the junction between the valley and the lower slopes, feeding a heavily vegetated marshy valley floor that provides an image of what the landscape may have been like at Caours during the last interglacial period. Other present-day examples are known from southwestern France, such as in the Coly River, where tufa dams are locally deeply incised by concentrated streams at the origin of deep ‘marmite type’ features. The combination of present-day analogues with all of the palaeoenvironmental information obtained at Caours for the main Neandertal occupation (N-1) is at the base of the palaeolandscapes reconstructions illustrated by Fig. 24.

Northern sector dominated by fluvial facies (S-1, Fig. 2B). In the northern and northwestern half of the transect, the thickness of the tufas decreases rapidly and their succession is dominated by stratified fluvial facies resting directly on the gravels of the alluvial formation (Fig. 3, Tf1 and Cht facies). These deposits fossilized evidence of a human occupation associated with very abundant bone remains showing anthropogenic fracturing and cut marks (Level Nc: Fig. 7C).



Fig. 24. Landscape and site reconstruction: the Caours site during the Eemian interglacial (drawing B. Clarys).

Excavation revealed that the upper part of the gravel was impregnated with a matrix of light grey-green calcareous silt identical to that of unit 11 in the southern sector. Malacological analysis of a sample of this silt showed an assemblage entirely comparable to that described in the middle part of the calcareous silts in the southern sector (U10 and 11). These observations show that these greenish fluvial silts were deposited in the northwestern part of the site where they were then eroded during an episode of migration of the Scardon channel followed by a temporary lowering of the water level (Fig. 23A, Stage 5). This phase is responsible for the ‘plateau’ morphology on which are preserved the Palaeolithic remains. The whole area located between the northern end of S-2 and borehole ST.8 is then overlain by finely laminated fluvial tufa facies Flt (Fig. 3), deposited by the palaeo-Scardon river. Thanks to the numerous test pits dug in 2006 and 2009 (Figs S1, S2), the boundary between the area characterized by stratified fluvial tufas associated with the palaeo-Scardon river and the area dominated by massive facies fed by springs at the bottom of the slope can be clearly identified. It corresponds to a steep palaeo-riverbank that was especially exposed in the 2005 Section East (Fig. 6) and in the northern part of the current excavation (2020–2023). According to the 2006–2009 test pits, fluvial facies appear systematically in the lower part of the tufaceous sequence in a line running along the northern boundary of S-2-2005 (Fig. 2B).

These facies, which have a maximum thickness of about 1.5 m, consist of large subhorizontal lenses with oblique stratification that are often shallowly inclined and correspond to meander bars (Fig. 23A, Stage 6). Given the geometry of the valley in the area of the Scardon–Drucat confluence, this structure reflects the progressive infilling of the convexity of the meander by fluvial tufas resulting from a gradual migration of the confluence towards the northeast. The gradual decline in alluvial dynamics and the clogging of S-1 are logically linked to the movement of the channel in this direction.

The stratigraphical reconstruction and connections established between the southern area S-2, dominated by massive tufas, and the northern area S-1, show that the fluvial facies in S-1 pre-date the tufa sedimentation in S-2. Subsequently, the massive facies, which began to form in the upper part of the slope, expanded towards the axis of the Scardon valley as the meander moved, eventually covering the fluvial facies of the northern sector (Fig. 23B, Stage 9). This dynamic has been observed in all the boreholes and the change between the two types of facies is often quite abrupt and highlighted by tabular layers made up of encrusted stromatolitic tufa (Fig. S1).

Weichselian Early-glacial (MIS 5d-5a): slope sequence and associated humic soils; incision of the present-day valley. – The transect crossing the full Caours Formation (Fig. 10) shows that the thickness of the tufa mass

decreases rapidly towards the valley, where the deposit ends abruptly at the level of borehole ST-10 (Fig. 3). To the northwest of this transition zone of very limited extent (~5 m) appears a sequence of non-calcareous slope deposits beginning with a humic dark grey-brown silty-sandy complex (Lbh) followed by the emplacement of stratified hillwashed sands and then by sandy loess the thickness of which rapidly increases towards the present valley. The stratigraphy of this ‘stratigraphical hinge zone’ is fundamental in describing the end of the interglacial and the transition to the early Weichselian. The full stratigraphy was observed and described over a length of more than 10 m in the SPM-12-2009 trench (Fig. 11). First it shows that, following the erosion of the edge of the calcareous tufa massif, the sedimentation changes drastically with the deposition of sandy-silty deposits fed by colluvial processes and interrupted by the formation of humic soil horizons indicating more stable periods (Fig. 11). The base of the Lbh pedosedimentary sequence (U8 to U3) is characterized by a relatively homogeneous silty-clay texture showing, however, from bottom to top, a decrease in TOC values (0.25% to less than 0.1%) and a concomitant increase in clay values (18 to 27%). These sedimentological changes indicate a progressive increase in the intensity of the erosion of the interglacial soil on loess (Bt horizon) present higher up on the southern slope of the Scardon valley. The colluvial facies of the sediment of U8 and U6 is also demonstrated by the presence of reworked yellow-orange clay coating fragments (papules), mainly inherited from the erosion of a Bt horizon of interglacial brown leached soil, and numerous small scattered flint fragments. This deposit also underwent some phases of deep freeze (fragmentation of clay coatings subhorizontal lamellar structure), in keeping with its attribution to a post-Eemian cold stage. Based on their stratigraphical position and sedimentological characteristics, the deposition of units U8 to U6 is linked to slow colluvial processes fed by the erosion of clayey soil horizons (interglacial Bt and Bth from the base of the Weichselian Early-glacial, Antoine *et al.* 2016a) present on the near slope of the south bank of the Scardon. OSL quartz dating obtained at the very base of U7 (90.1 ± 5.1 ka) supports the attribution of this deposit to a phase of slope destabilization essentially contemporary with SIM 5b (Rederstall stage or GS 22).

The increase in TOC in the upper part of U7 and then in U6, associated with the appearance of clay-humus to silt-humus coatings in the bio-porosity, can be linked to the development of the overlying Bth horizon (U4). The clays, which have been severely degraded by freeze–thaw, and the abundance of small ferromanganese nodules indicate a periodic and localized saturation of the environment with a redistribution of iron (a process also observed in the overlying units 4 and 3). In the overlying humic horizon (U4), high TOC values (0.4%) associated with numerous thick, brown to brownish-black, mostly fragmented, stratified clay-humus to silt-humus coatings

are typical of Bth horizons of grey forest soils as defined in the early-glacial soil record of northwestern Europe (Antoine *et al.* 2016a; Haesaerts *et al.* 2016). Within stratified clay coatings, homogeneous clay laminae generally represent phases of stability, whereas accumulations of silt layers indicate seasonal phases of destabilization of the soil surface during episodes of melting snow cover (Antoine *et al.* 2003a, 2016a). These features are typical of the Bth horizon of the Saint-Saulieu-1 soil allocated to MIS 5a or GI 21 (Antoine *et al.* 2016a). The OSL age obtained in the middle part of U4 (88.2 ± 5.7 ka) is in perfect accordance with the allocation of this soil to MIS 5a. Here, this soil horizon is however truncated and affected by the impact of deep seasonal frost processes. We note the discovery near the upper limit of U4 of one isolated outstanding Middle Palaeolithic black flint artefact (large scraper with a Quina-type retouching; Fig. 11).

The upper part of the humic soil complex (U3) is then separated from the preceding soil by a strong erosion and a hiatus marked by the presence of scattered reworked Palaeolithic artefacts exhibiting a white patina, and a clear reduction in the clay content (22–20% max.). This last humic horizon (TOC: 0.35–0.4%) is characterized by an increase in coarse sand indicating an accentuation of erosion further up the slope (proximity of old residual Palaeogene sands?). Both cold climate and denudation of the environment are confirmed by the disappearance of *in situ* clay coatings (only reworked fragments from previous soils) and the predominance of coarser distal inputs. Given its stratigraphical position and characteristics and its OSL age (71.5 ± 4.4 ka), the U3 humic horizon can be correlated with the Saint-Saulieu 2 steppe soil, which marks the MIS 5a–MIS 4 transition at about 75–70 ka in the regional sequences (Antoine *et al.* 2016a). Generally speaking, the Caours humic soil complex according to its stratigraphical position, OSL ages exposed above as well as U-series TIMS ages from the underlying calcareous tufa ($\sim 123.1 \pm 2.8$ ka) can be securely correlated with the Saint-Saulieu Early Weichselian type sequence that records the response of the environment to climate variations from MIS 5d to MIS 5a (Antoine *et al.* 2003a, 2016a). In the Noye valley, a small tributary of the Somme, another site in a fluvial context (Ailly-sur-Noye, Fig. 1) shows tuffaceous deposits allocated to the Eemian interglacial incrusting the uppermost gravels from the alluvial formation of the Very Low Terrace and associated Palaeolithic artefacts (Locht *et al.* 2013). Overlying the gravels, the transition between the end of the Eemian Stage and the very early phases of the Weichselian glacial onset appear within organic fluvial calcareous grey silts in which the malacological community already bears witness to an open environment (Limondin-Lozouet in Loch *et al.* 2013).

At Caours, the deposition of hillwashed sands including scattered fragments of gelifRACTED flint then

highlights a major erosion phase affecting the entire slope (Figs 3, 10, Sbr) that corresponds to an erosive episode contemporary with the beginning of the Weichselian Pleniglacial. The sandy loess, which is trapped a little further north on the valley slope (Fig. 3, Sls), does not show the characteristics of the typical calcareous loess that developed during the Upper Weichselian Pleniglacial (~ 30 – 17 ka BP). It is more likely to belong to an early phase of the Lower Pleniglacial (~ 60 – 55 ka) during which local processes of reworking on slopes by runoff of local material (Tertiary sands) are common (Antoine *et al.* 2003a, 2016a, b). Boreholes drilled in the present alluvial plain have shown that these loesses extended significantly towards the present valley, where they rest directly on the valley-bottom gravels and form a thick lens along the chalky slope that bounded the present valley before the Holocene infilling (Fig. 10, Lsgv).

The study of the slope sequence that truncates and then overlaps the Eemian calcareous tufas of Caours towards the valley therefore provides fundamental data concerning the modifications in the environments in response to climatic forcing during the long and contrasting period of climatic transition ('step by step') that characterizes the transition between the end of the Eemian interglacial and the beginning of the Weichselian.

Furthermore, the attribution of the whole Caours humic soil complex to the Early Weichselian and the dating of the first colluvial deposits to about 90 ka imply that the incision processes responsible for the incision of the present-day valley in the chalk bedrock (down-cutting) appear very early in the climatic cycle, from the end of the interglacial and during stages 5d and 5c, as previously proposed for the terrace system of the Somme basin by Antoine *et al.* (2000, 2007).

Gibbard and Lewin (2002) stated that fluvial sequences representing the later parts of interglacials and their transition to the following cold periods are extremely rare. The Caours record is therefore particularly relevant to the debate about the timing of river incision and terrace formation in relation to interglacial–glacial climate cycles. This question has long been debated, for example in the Thames, for which Bridgland & Allen (1996) developed a model relating 'terrace formation to climatic fluctuations', in which bedrock incision is associated with 'cold climate conditions' (stage IV of the model). For Gibbard and Lewin (2002), using examples from the lowland rivers of southeast England, even if some 'renewed erosion' occurs during the Early Weichselian, the main incision phase 'erosion of substrate' would also occur later during a period of cold conditions and grassland vegetation. Thus the Caours data, which seem to contradict the conclusions presented above, will form the basis of a paper focusing on the dating of incision processes in terrace systems.

During the Weichselian Pleniglacial, the top of the Caours calcareous tufas was partly truncated by a

succession of erosion phases but no associated deposits have been preserved here except a remnant of calcareous loess trapped in a fine frost crack running through the tufa massif.

Recent (Holocene) erosion of the loess cover and soils then led to the formation of a thick layer of clayey silt (over 2 m thick) overlying the Holocene peat in the Scardon valley (Fig. 10, Cv1). The entire alluvial plain has become clogged with colluvial clayey silts in which the Scardon channel is now deeply entrenched (>2.5 m), as a result of a massive anthropogenic erosion. As part of new research focusing on the development and subsequent cessation of peat formations in the Somme basin investigations are planned on the Holocene section of the Caours transect.

Finally, as the Caours site is the only one in northern France and, more broadly, in western Europe to show the transition between the end of the Eemian and the beginning of the Weichselian on a continuous morphostratigraphical transect incorporating two successive stages of incision in the bedrock, it seems particularly important to continue research on the recording of this climatic and environmental hinge, which is fundamental for dating the incision processes of stepped terrace systems.

Conclusions

After more than 20 years of rich and intensive multi-disciplinary research at Caours the main conclusions can be summarized as follows:

- Caours is the first interglacial calcareous tufa sequence securely dated to the Eemian Stage (MIS 5e) in the Somme basin, and more broadly in northern France, by several methods (U-series, TL, OSL, ESR/U-series, mean age: 123 ± 3 ka) applied on various materials (carbonates, heated flints, sediments, and teeth, respectively). Caours yields hence a robust reference for Eemian interglacial palaeoenvironments of northwestern Europe, and especially for those corresponding to climatic optima that are rarely preserved in the stepped fluvial terraces systems.
- The Caours Formation now represents the most complete record of the evolution of the terrestrial mollusc fauna encompassing the end of the Saalian and the Eemian (including the climatic optimum), making it a new reference for northwestern Europe. The interglacial palaeoenvironmental dynamics inferred from the malacological succession can be compared with other Eemian records where the climatic optimum is recorded by pollen data.
- At Caours the climatic optimum is indicated in the same layers by $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ analysis on tufa calcite, following an approach explored for the first time on this site before its use on other French Pleistocene tufa sequences from MIS 5e and MIS 11.

- The complete data set (sedimentology, bio-proxies, geochemistry, dating) leads to a detailed and robust reconstruction of the modifications of the valley environments in northern France in relation to climatic changes from the end of the Late Saalian (MIS 6) to the Weichselian (MIS 5d–a).
- The 300-m-long continuous cross-section includes (i) the sequence of the Very Low Terrace covered by the Eemian tufa, (ii) then an Early Weichselian humic soil complex, and (iii) the bottom valley sequence (Weichselian and Holocene) is currently unique in northern France terrace systems. This outstanding stratigraphical record, combined with U-series TIMS (tufa) and OSL ages (colluvial deposits and humic soil complex), shows that the incision of the present-day river, leading to the formation of the Very Low Terrace, was achieved during the first stages of the Early Weichselian period (~MIS 5d and partly 5b), i.e. very early (and rapidly) compared to the whole interglacial–glacial climatic cycle.
- Caours yields an outstanding archaeological record consisting of four main *in situ* archaeological layers (flint artefacts and large mammal bone remains) perfectly preserved and separated by sterile tufa layers. This configuration is unique in western Europe and clearly demonstrates the adaptation of Neanderthals to a forested environment and to fully temperate conditions during the last interglacial.
- Today the archaeological site and the associated tufa sequence are preserved, providing both an archaeological reserve and a reference geological profile for future generations. Indeed, it is now intended that the site will remain open after the archaeological excavations have been completed, with long sections preserved and accessible to the whole research community working on the development of bio-proxies, geochemistry or dating methods.

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Author contributions. – PAN: stratigraphy, sedimentology, conceptualization, writing and editing, illustrations; NLL: malacology, writing and editing, illustrations; JD: micromorphology, geochemistry, writing and editing, illustrations; JJB: dating (ESR/U-series), summary of geochronological data, writing and editing; BG and JLR: U-series alpha spectrometry and TIMS dating; PAu and NS: large mammal study; GJ: pedomorphology; MCJS: leaf imprint study; AG: palynology; LL: micromammal study; JLL: archaeology.

Data availability statement. – All data associated with this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional Supporting Information to this article is available at <http://www.boreas.dk>.

Fig. S1. Logs of the 2006 test pits ($n = 12$).

Fig. S2. Logs of the 2009 test pits ($n = 20$).

Fig. S3. A. Close up of units 6 to 10 showing an *in situ* long bone preserved in archaeological level N-2 (unit 7). B. Lower jaw of *Stephanorhinus hemitoechus* from layer N-4 (2008). C. Large mammal remains (Cervidae antler) from archaeological layer N-3 (top of peat U9). D. Encrusted leaf of ferns (*Asplenium scolopendrium*). E. Close up of the stratigraphy of the infilling of Channel 3 (Profile 2007 South, Fig. 10) showing the subvertical shape of its SW bank (erosion through units 9, 10, 11 down to gravel unit 12).

Fig. S4. Leaf imprints from various indurated facies of the Caours Eemian tufa. 1. Monocotyledon leaves; 2. *Salix* cf. *S. caprea* (Salicaceae) (A), *Hedera helix* L. (Araliaceae) (B); 3. *Quercus* sp. (Fagaceae); 4. *Salix* cf. *S. caprea* (Salicaceae) (A), *Sambucus* cf. *S. nigra* (Caprifoliaceae) (B), cf. *Alnus* sp. (Betulaceae) (C–D); 5. cf. *Euonymus* sp. (Celastraceae); 6. *Clematis vitalba* L. (Ranunculaceae); 7. *Rhamnus* sp.; 8. cf. *Acer* sp. (Sapindaceae); 9. *Hedera helix* L. (Araliaceae); 10. *Salix caprea-cinerea* (Salicaceae); 11. *Salix* sp. (Salicaceae); 12. Unidentified taxa (A), *Salix caprea* L. (scale bar: 10 mm) (B); 13. *Asplenium scolopendrium*.

Fig. S5. Reconstruction of the sedimentary infilling of one of the largest lateral channels connected to springs located at the hinge between the lower slope and the valley floor (location: Figs 9, S3E, Channel 3). Description: see Data S1.

Table S1. Geochronological data.

Table S2. Summary of palynological analysis.

Table S3. Ostracod species from the Caours tufa according to Carbonel in Antoine *et al.* (2006).

Data S1. Formation of small channels at the foot of the slope and relationship to Palaeolithic occupation.