



HAL
open science

Late Middle Pleistocene (MIS 10–6) glacial–interglacial records from loess–palaeosol and fluvial sequences from northern France: a cyclostratigraphic approach

Pierre Antoine, Nicole Limondin-Lozouet

► **To cite this version:**

Pierre Antoine, Nicole Limondin-Lozouet. Late Middle Pleistocene (MIS 10–6) glacial–interglacial records from loess–palaeosol and fluvial sequences from northern France: a cyclostratigraphic approach. *Boreas*, 2024, 53 (4), pp.476-503. 10.1111/bor.12662 . hal-04763635

HAL Id: hal-04763635

<https://hal.science/hal-04763635v1>

Submitted on 2 Nov 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.


L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



Late Middle Pleistocene (MIS 10–6) glacial–interglacial records from loess–palaeosol and fluvial sequences from northern France: a cyclostratigraphic approach

PIERRE ANTOINE  AND NICOLE LIMONDIN-LOZOUET

BOREAS



Antoine, P. & Limondin-Lozouet, N.: Late Middle Pleistocene (MIS 10–6) glacial–interglacial records from loess–palaeosol and fluvial sequences from northern France: a cyclostratigraphic approach. *Boreas*. <https://doi.org/10.1111/bor.12662>. ISSN 0300-9483.

This contribution summarizes the most informative loess–palaeosol sequences (LPS) and fluvial terrace records from the late Middle Pleistocene (LMP) of northern France demonstrating the reliability of the cyclostratigraphic approach for the interpretation of pedosedimentary sequences controlled by major glacial–interglacial climatic cycles. In this area, continental mollusc assemblages from interglacial fluvial silts and calcareous tufas are particularly rich and diverse and marker species define the malacological signatures of each interglacial optimum for Marine Isotope Stages (MIS) 11, 9 and 5e. This approach shows that the forest was less developed during MIS 7, suggesting that climatic conditions were either drier and/or cooler than during other Pleistocene interglacials. In the Somme basin, the terrace system shows that two alluvial formations were deposited between early MIS 8 and late MIS 7. In some LPS, the occurrence of two pedosedimentary sub-cycles (IIa and IIb), separated by a relatively long (~12 ka) and cold period, corresponding to an ‘aborted glacial’ (MIS 7d), underlines the complex pattern of this unusual ‘interglacial’. Overall, during the LMP, each soil complex corresponding to interglacial and early-glacial periods from MIS 11 to MIS 5 is broadly made up of the same soil facies but exhibits a specific succession pattern or signature. Throughout the area, LPS show a huge change in both the deposition rates and the geographical extent of typical calcareous loess at the beginning of MIS 6. This so-called ‘Loess Revolution’ probably reflects a change in the palaeogeography of the southern North Sea and eastern Channel source areas at times marked by the coalescence of the British and Scandinavian ice sheets. MIS 6 is also characterized by the oldest evidence of permafrost development in the area. In addition, this work allows the age of the Lower/Middle Palaeolithic boundary to be confirmed, with the oldest occurrence of Levallois technology being around 300 ka.

Pierre Antoine (pierre.antoine@lgp.cnrs.fr) and Nicole Limondin-Lozouet, Laboratoire de Géographie Physique (LGP), UMR8591 CNRS-Université Paris 1 Panthéon-Sorbonne & Paris Est Créteil, 2 rue Henri Dunant, 94320 Thiais, France; received 28th December 2023, accepted 2nd May 2024.

The late Middle Pleistocene (LMP) corresponds to the period bracketed between the end of the Holsteinian and the beginning of the Eemian interglacials that is known as the Saalian or Saalian Complex (Cohen & Gibbard 2011). In global deep-sea records (SPECMAP) it encompasses the time interval between the end of Marine Isotopic Stage (MIS) 11 (~374 ka) and the beginning of MIS 5e (~130 ka). The two interglacial periods that occur during this long time-span (244 ka) show very different patterns: MIS 9 and MIS 7 (or intraSaalian interglacials). Indeed, while the peak of MIS 9 (9.3 or 9e~320 ka) is relatively simple and short (~10 ka as MIS 5e), MIS 7 is markedly longer (52 to 60 ka) and more complex (including a 12-ka-long ‘aborted glacial’ labelled 7d). MIS 7 thus stands distinctively apart from the last several interglacial cycles (Wendt *et al.* 2021). Following the low-amplitude glacial Termination III (TIIIb), MIS 7e was a relatively weak and particularly short interglacial, followed by a return to glacial conditions during MIS 7d (PAGES 2016). Glacial conditions terminated with TIIIa, which gave way to a second interglacial with three distinct substages (MIS 7c, b, a), the intensity of which was close to that of the MIS 5a and 5c interstadials of the early Last Glacial period (Weichselian early-glacial).

In western Europe, the glacial–interglacial climatic pattern is particularly well recorded in the fluvial terrace systems and associated loess–palaeosol sequences (LPS) of the Seine and Somme River basins in northern France (Lautridou *et al.* 1999; Antoine *et al.* 2000, 2007, 2019; Chaussé *et al.* 2000, 2004; Limondin-Lozouet & Antoine 2006; Fig. 1). A similar pattern is found on the other side of the Channel in the Thames basin but without significant LPS cover (Bridgland 1994; Gibbard 1994; Bridgland & Schreve 2004).

In fluvial systems, interglacial deposits are particularly well described in the chalky areas of the Paris basin and southeast England where calcareous tufa deposits have allowed the preservation of a rich set of bio-indicators on which the reconstruction of palaeoenvironments is based (Antoine *et al.* 2006, 2024; Limondin-Lozouet & Antoine 2006; Preece *et al.* 2007; Dabkowski 2014). However, although MIS 11 and 5e are well represented, MIS 9 and MIS 7 tufa sequences have not yet been clearly proven and dated. The records of these last two interglacial periods have been recovered from alluvial sequences that have often been truncated by erosional processes.

In terms of marine deposits, it is likely that in stable areas MIS 7 beach deposits associated with relatively low

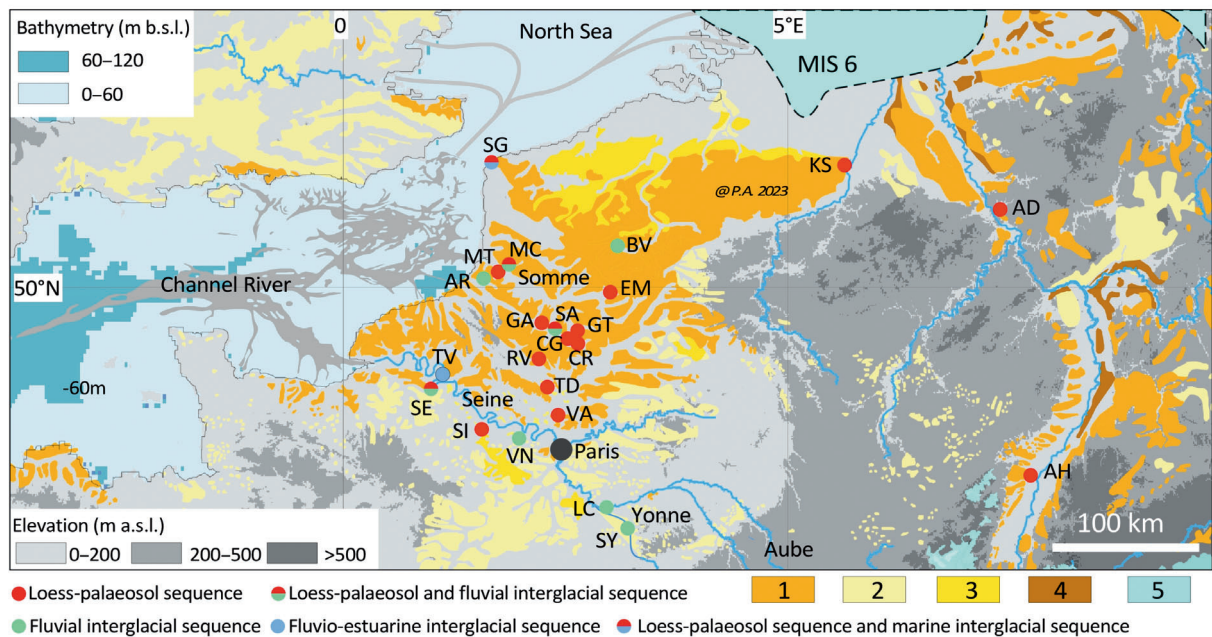


Fig. 1. Location of late Middle Pleistocene loess–palaeosol sequences and fluvial interglacial sites cited in this study (loess map according to Antoine *et al.* 2013, modified). Sites: SG = Sangatte; MC = Menchecourt; MT = Mautort; AR = Arrest; GA = Grâce-Autoroute; EM = Etrécourt-Manancourt; SA = Saint-Acheul; CG = Cagny-la-Garenne; CR = Cagny-Rocade; GT = Gentelles; RV = Revelles; VA = Villiers-Adam; TD = Therdonne; SE = Saint-Pierre-Lès-Elbeuf; TV = Tourville; LC = La Celle; SY = Soucy; SI = Saint-Illiers-la-Ville; VN = Vernon; BV = Biache-Saint-Vaast; AD = Ariendorf; KS = Kesselt; AH = Achenheim. (1) Loess; (2) sandy loess; (3) thin loess (<2 m, marginal areas); (4) aeolian sands; (5) MIS 6 maximum ice extension.

sea levels (Siddal *et al.* 2003; Dutton *et al.* 2009; Choudhury *et al.* 2020) were later eroded during younger highstands such as MIS 5e.

The sedimentary archives of the successive glacial periods of the LMP are derived from both the loess and various slope deposits of the LPS and from the fluvial record where they correspond to thick sets of gravels and sands that form the main body of the alluvial terraces (Antoine *et al.* 2019). Loess, fluvial gravels and sands associated with periglacial environments and with high-energy braided river systems are very poor in terms of fossil content.

Finally, it should be emphasized that the LMP was the time of a major change in the Palaeolithic record of western Europe (west of the Rhine River) at the transition between MIS 9 and 8 at about 300 ka ago when the last Acheulean industries (with handaxes) were replaced by the oldest Middle Palaeolithic, characterized by the massive use of Levallois technology (Hérisson *et al.* 2023).

The aim of this paper is to provide an overview of the response of western European landscapes to interglacial climatic forcing between MIS 11 and MIS 5e, based on the terrace systems of northern France and their associated LPS, which constitute a particularly complete record for the period under consideration. It begins with a brief summary of the main western European terrace sequences combining loess and fluvial terraces followed

by a quick presentation of the Somme and Seine terrace systems.

Loess and fluvial terraces in western Europe: a combined record of global glacial–interglacial climatic cycles

In the great European plains, loess deposits represent the largest and thickest correlative formations of the successive glacial stages of the Quaternary (Pecsi 1990; Haase *et al.* 2007; Lehmkuhl *et al.* 2016, 2021). In this large area, LPS can reach a thickness of 20 to 60 m downwind of the major rivers of central Europe such as the Rhine, the Danube in Serbia and Bulgaria (Evlogiev 2007; Jipa 2014; Marković *et al.* 2015), or the Dnieper in Ukraine (Lindner *et al.* 2002; Dodonov *et al.* 2006; Fedorowicz *et al.* 2013). Indeed, during glacial periods large alluvial plains, characterized by braided river systems that developed in cold and open environments, were major sources of dust for deflation and then for loess deposition (Antoine *et al.* 2003c). Alluvial plains were sites of bare soils in which the channelling of wind energy during storm events was able to drift coarse sands on exposed slopes (Antoine *et al.* 2001, 2019).

There is thus not only a very important genetic link between loess and fluvial dynamics during the Quaternary (Smalley *et al.* 2009), but also a morphological

link, as loess deposits have provided ‘cover deposits’ for the successive alluvial sequences in the European stepped terrace systems. LPS have long been recognized as reference records of Pleistocene glacial–interglacial cycles (Kukla 1977; Lautridou 1985; Marković *et al.* 2015; Antoine *et al.* 2020). Since the pioneering works of Kukla (1977), the cyclic glacial–interglacial climate signal, revealed by pedostratigraphic analysis of the LPS, then quantified by magnetic susceptibility and calibrated by palaeomagnetism, has been parallelized with deep-sea records (Lisiecki & Raymo 2005).

This cyclostratigraphic approach (Hinnov 2013) has been reinforced in the last 30 years by $^{40}\text{Ar}/^{39}\text{Ar}$ dating of tephra layers embedded into these LPS (Van den Bogaard & Schmincke 1990; Horvath 2001; Fitzsimmons *et al.* 2013; Jensen *et al.* 2016), or more generally by luminescence dating of silt particles from loess (Frechen & Dodonov 1998; Marković *et al.* 2015; Lomax *et al.* 2019).

In the major European river basins LPS preserved as cover deposits of alluvial terraces have long been considered as a reliable tool for relative dating of the underlying fluvial deposits such as in the terrace systems of the Danube (Kukla 1977), the Rhine (Brunnacker *et al.* 1982; Demir *et al.* 2018), the Somme and the Seine rivers (Bourdier 1974; Lautridou 1985; Lautridou *et al.* 1999; Antoine *et al.* 2000, 2003c; Cliquet *et al.* 2009; Antoine 2019) (Fig. 2).

In these last two river valleys, reference long LPS such as Saint-Pierre-lès-Elbeuf (Lautridou 1985; Cliquet *et al.* 2009) and Cagny-la-Garenne (Haesaerts & Dupuis 1986; Antoine 1994) show a pedosedimentary record starting in the Middle Pleistocene around 400 ka. In the Seine River, older LPS probably dating back to the

Early Cromerian have been locally identified in deep sinkholes in the Cretaceous chalk substratum (Iville V & VI and Bosc-Hue VII: Lautridou 1985). In northern France, a few sequences showing up to three interglacial soils have been described but are no longer accessible. Finally, in the Somme valley (Fig. 2), well known since the end of the 19th century for its important role in the emergence of Quaternary geology and prehistory (e.g. Bahain & Antoine 2019), ‘old loess’ was mentioned at the beginning of the 20th century on the Very High Terrace (Commont 1909). During the last 30 years, an unprecedented increase in the number of rescue archaeological excavations has led to the discovery of new reference LPS in the Somme basin (Fig. 1): Mautort (Antoine 1994; Antoine *et al.* 2000); Grâce-Autoroute (Antoine *et al.* 2003c, 2020); Cagny-Rocade (Tuffreau *et al.* 1997; Antoine *et al.* 2021); Gentelles (Tuffreau *et al.* 2017); Revelles (Lamotte *et al.* 2019), Villiers-Adam (Antoine *et al.* 2003a) and finally Etricourt-Manancourt (Hérisson *et al.* 2016; Coutard *et al.* 2019).

Main features of the stepped terrace systems of the Somme and Seine river valleys

During glacial periods, the palaeo-Seine and palaeo-Somme river valleys were tributaries of the south bank of the Channel River, which flowed into the Atlantic (Fig. 1). To the north the Somme River shows a stepped Quaternary fluvial terrace system incised into the Upper Cretaceous chalk. Generally protected by a well-developed loess–palaeosol cover (up to 8 m thick), this system consists of 10 stepped alluvial formations extending between +5/6 and +55 m above the maximum

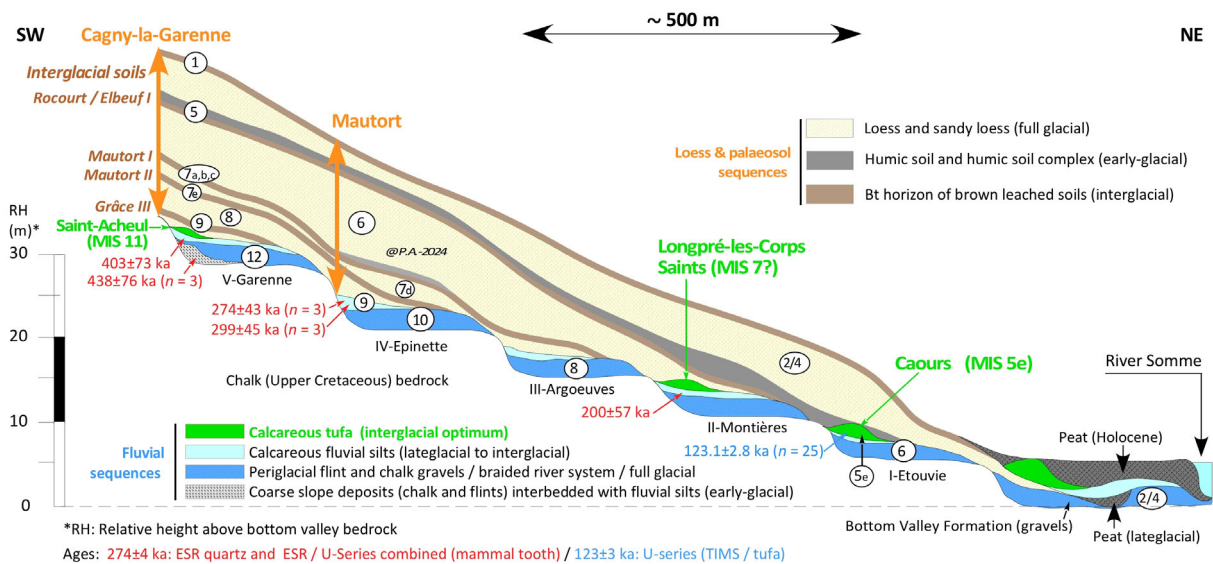


Fig. 2. Fluvial and the LPS cover sequences from the last 500 ka in the stepped terrace system of the Somme basin (modified according to Antoine *et al.* 2007, 2019).

incision of the present-day valley into the bedrock. The different bedrock steps and associated alluvial formations can be traced along at least one 50-km-long valley segment (Middle Somme) where they are separated by sharp incision steps of 5 to 6 m in height (Fig. 2). The relative height of the contact between the successive alluvial sequences and their respective bedrock steps can thus be used to securely place the stratigraphic sequences of regional reference sites and associated archaeological layers within the Somme River system. Furthermore, in the Somme valley, a multidisciplinary approach to studying the fluvial sequences (stratigraphy, sedimentology and palaeontology) has shown that each alluvial formation corresponds to the morpho-sedimentary budget of a glacial–interglacial cycle (Fig. 2). This approach to investigating the system is strengthened by the combination of several types of geochronological data: electron spin resonance (ESR) dating of fluvial quartz grains, ESR/U-series dating of large mammal tooth enamel, thermal ionization mass spectrometry (TIMS) dating on interglacial calcareous tufa and palaeomagnetic data for alluvial Formation IX (Grâce Formation; Fig. 2).

The Somme River terrace system represents a model of response to glacial–interglacial climate cycles in the context of a slow uplift of the margins of the Paris Basin (55 m for 1 Ma). Both the geochronological and palaeoenvironmental contexts of this system are currently among the best established in Europe for the last 1 Ma, providing an accurate control of the chronology of the archaeological data and a good basis for the overlying loess–palaeosol sequences (Antoine *et al.* 2007, 2019).

The same stepped terrace pattern is found in the Middle and Lower Seine Valley where the incision rate is also close to 50–60 m for the last 1 Ma (Lautridou *et al.* 1999; Jamet 2014). In the Seine system the main difference is the occurrence of two distinct bedrock steps for the Last Glacial (Rouen I and Rouen II alluvial formations; Fig. 3; Jamet 2014) whereas the Somme shows only one: the ‘Bottom Valley Gravels’ (Fig. 2). Another point is the occurrence of two stacked interglacial fluvio-estuarine sequences, dated to MIS 9 and 7, respectively, within the Tourville sand and gravel formation (Lautridou 1985; Balescu *et al.* 1997; Jamet 2014).

Despite 150 years of research this situation has never been found in the Lower Somme valley, where estuarine deposits have been suspected at Menchecourt, near Abbeville (Bourdier 1969, 1974) but still never demonstrated and dated. This situation could be due to a slightly different large-scale tectonic background between the two valleys. Indeed, the Lower Somme is connected to the eastern Channel, which is characterized by a relative subsidence indicated by the preservation of thick Tertiary deposits and stacked Quaternary fluvial formations, whereas the submarine Lower Seine Valley shows stepped terraces fully incised into the secondary limestone bedrock, in continuity with the different alluvial

formations distinguished upstream of the present estuary (Benabdellouahed *et al.* 2013).

Middle Pleistocene MIS 11, 9 and 7 interglacial records from river systems

In slope deposits, interglacials are represented by well-developed decalcified palaeosols that lack bioproxies, thus palaeoenvironmental reconstructions of temperate periods should therefore be sought in fluvial sequences where calcareous and/or organic deposits may be present and favour the preservation of palaeontological remains. However, research carried out in both the Somme and Seine valley basins has demonstrated that peat layers from the Middle Pleistocene, if any, are rarely preserved (Antoine *et al.* 2007). Temperate episodes are mostly represented by fine sandy and silty deposits, which sometimes are overlain by calcareous tufa formations. In these sedimentary contexts, palynological contents are poorly preserved, and mammalian faunas associated with archaeological levels can provide palaeoenvironmental snapshots, but the most suitable and continuously preserved bioproxy allowing the reconstruction of Middle Pleistocene interglacial dynamics are malacofauna (Limondin-Lozouet & Preece 2014). Malacological studies have shown that thermophilous species can reappear in sandy and silty levels that form the upper part of fluvial aggradations but full interglacial conditions represented by the development of closed canopy environments are only recorded within calcareous tufa sequences (Rousseau *et al.* 1992; Antoine & Limondin-Lozouet 2004; Limondin-Lozouet & Preece 2014).

The sandy and silty phases are located on the alluvial plain and, if their limestone content is good, they provide well-preserved malacofauna, which can be quite abundant. These riparian environments are often made up of a mosaic of biotopes, ranging from aquatic habitats to wooded areas and various more or less humid open areas. The Quaternary malacocenoses, fossilized by sand and silt deposits, reflect the juxtaposition of these different micro-environments. They form heterogeneous assemblages in which aquatic, marshy, wooded and even xerophilous species can be found side by side. Certain thermophilic elements in these faunas clearly indicate a temperate climate, but the variety of environmental contexts sometimes makes it difficult to identify a precise phase in the interglacial dynamics. Furthermore, lowland sand and silt sequences are often subject to reworking and/or erosion, thus disrupting the malacological record of environmental change.

Calcareous tufa deposits, on the other hand, have several major advantages. They fossilize a wide variety of biological communities *in situ*, allowing a range of biological indicators to be compared on records with few disturbances due to sedimentary hiatus or reworking. The successive malacocenoses of the tufas are much more

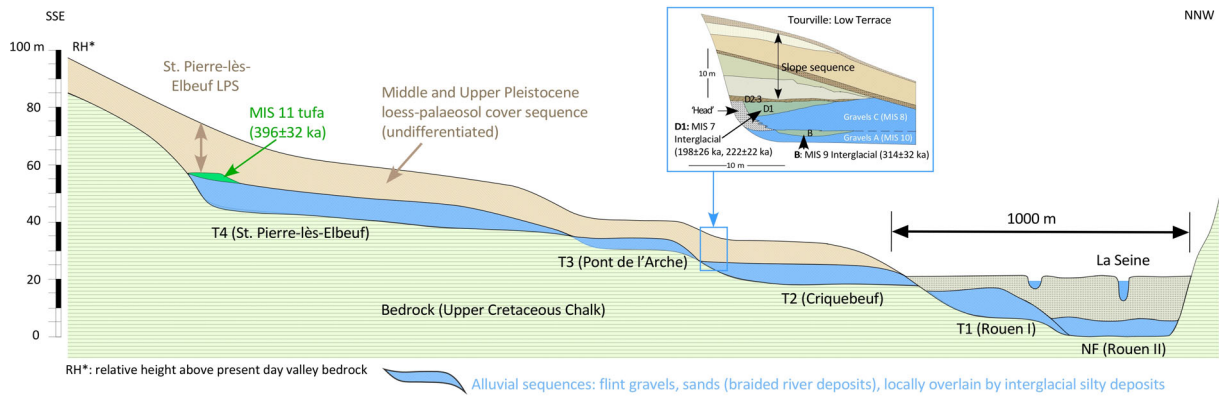


Fig. 3. Transect of the Seine River terrace system in the lower area around Saint-Pierre-lès-Elbeuf, including position and simplified stratigraphy of the Tourville Low Terrace formation (redrawn according to Jamet 2014 and Lautridou 1985).

homogeneous. It is often possible to identify the part of the interglacial to which they correspond. Due to their lithological characteristics, calcareous tufas are extremely suitable for the establishment and development of malacological populations. They are therefore the best and most regularly preserved group of fossils in such deposits. This observation makes the malacological approach particularly important in the study of temperate phases, because the climatic optima of interglacial periods in fluvial environments are only before represented in these contexts. Finally, tufas can be dated directly from calcite by several methods (radiometric, luminescence), allowing the establishment of an accurate chronology for these formations (Dabkowski 2014).

However, tufas are not equally preserved for each interglacial. In the study area, the best records are from MIS 11, MIS 5e and MIS 1. They have provided the framework for malacological successions that allow the reconstruction of interglacial dynamics as well as the identification of malacological signatures specific to each interglacial. These are based on the presence of species that are either extinct or no longer living in the region studied, and whose occurrence in the successions depends on the distance from the refuge areas, following a similar pattern during the interglacial periods from the Iberian Atlantic to the central and finally the southern European refugia (Limondin-Lozouet 2011; Limondin-Lozouet & Preece 2014). The following review of interglacial malacological records from the Somme and Seine basins obtained in tufaceous and fluvial deposits (Fig. 4), is supplemented where available by data from other bioproxies.

MIS 11 record: a framework for Middle Pleistocene interglacial dynamics

MIS 11 malacological record should be briefly mentioned as a comparative basis for assessing the evolution of malacocenoses during Middle Pleistocene interglacials.

In the Somme, two MIS 11 series are known at Arrest (Rousseau *et al.* 1992) and near Amiens combining data from Saint-Acheul and Cagny-la-Garenne (Antoine & Limondin-Lozouet 2004; Limondin-Lozouet & Antoine 2006) (Fig. 2). In the Seine valley, three tufas have been studied at Vernon, Saint-Pierre-lès-Elbeuf (Fig. 3) and La Celle (Rousseau *et al.* 1992; Cliquet *et al.* 2009; Limondin-Lozouet *et al.* 2020). The latter is by far the most important reaching 9 m in thickness and providing an almost complete sequence of the environmental evolution during MIS 11c (Limondin-Lozouet *et al.* 2020). The malacofauna is extremely rich with more than 90 species. The malacological succession is divided into four zones showing an early marshy environment with thermophilous pioneer species (zone 1), then the emergence of the coniferous forest environment (zone 2a), the shift to deciduous tree cover and its progressive expansion (zones 2b and c) until a maximum development during the optimum (zone 3: forest snails accounting for 60–70% of the mollusc population) and its retreat at the end of the Interglacial (zone 4). The La Celle sequence is the only one that allows an in-depth observation of the establishment of the ‘*Lyrodiscus* fauna’, which is present in all MIS 11 malacological successions from northern France and southwestern England tufas (Limondin-Lozouet & Preece 2014). This particular forest assemblage includes several extinct snails and a number of species outside their modern range of Atlantic, central and southern European origin, making it a recognized biostratigraphic marker for the MIS 11c series in northwestern Europe (Limondin-Lozouet 2017). In fact, the malacological sequence at La Celle serves as a model for the placement of the other, shorter sequences within the dynamics of the interglacial period (Limondin-Lozouet *et al.* 2020). In addition to reconstructing environments, it provides a means of relative dating that is inaccessible to radiometric methods for such an ancient period (Limondin-Lozouet *et al.* 2015). The dense, humid

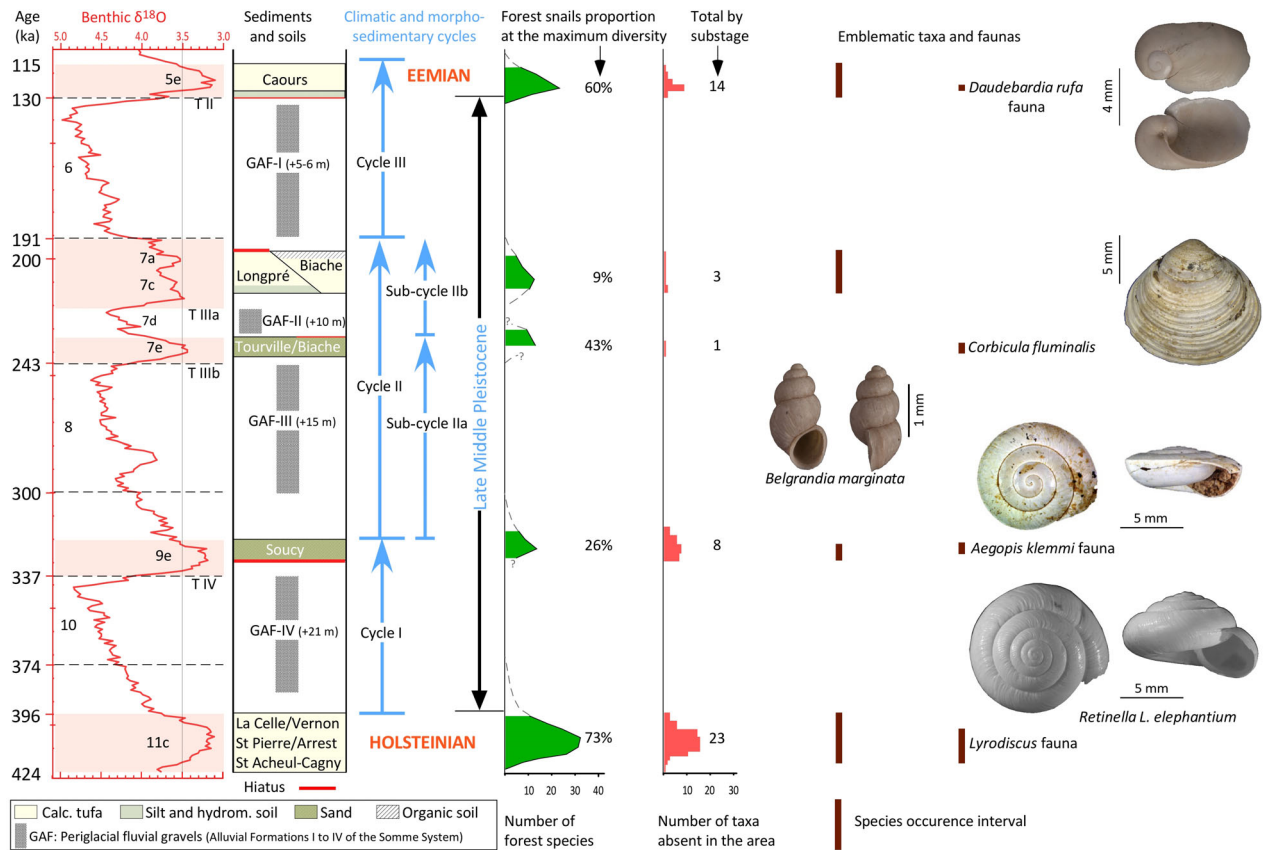


Fig. 4. Summary of malacological contents of interglacial sequences from MIS 11 to 5e in northern France.

forest biotope revealed by the *Lyrodiscus* assemblage is complemented by botanical data. Leaf imprints collected at La Celle indicate the presence of several southern trees (*Buxus*, *Ficus*, *Celtis*) at the time of the forest optimum. Furthermore, the remains of *Cervus elaphus*, *Equus* sp. type Hoxne, *Macaca sylvanus*, and *Hippopotamus incognitus* confirm the particularly temperate nature of this period (Auguste 2009). Finally, geochemical data measured on tufa calcite demonstrate that MIS 11c in the Paris Basin was warmer and wetter than both the Holocene and the Eemian (Dabkowski & Limondin-Lozouet 2022).

MIS 9: Soucy (Yonne valley, Seine Basin)

No tufa deposit has yet been discovered for the MIS 9 interglacial in the Paris Basin. This temperate episode is only recorded in the fluvial sequence at Soucy in the Yonne valley (Fig. 1). The alluvial deposits, with a maximum thickness of 6 m, are composed of coarse gravel with flint pebbles at the base (4 m thick), cut by several palaeochannels filled by 0.5 to 2 m thick fine fluvial sandy-silt layers. In the Yonne stepped terrace system, the Soucy alluvial formation overlies the fifth step above the maximum incision of the present valley

and can therefore be allocated to the Middle Pleistocene (Chaussé *et al.* 2000, 2004). Several ESR dates obtained on the coarse gravel together with amino acid measurements on shells from the sandy beds, converge in attributing this sequence to MIS 10 and 9 (Chaussé *et al.* 2000, 2004). Malacofaunas were sampled on six profiles within the fine sandy-silt deposits. The 37 samples yielded a rich fauna comprising 63 species, divided into 40 terrestrial snails and 23 aquatic species (Limondin-Lozouet 2001). This high level of diversity, together with the occurrence of several strictly thermophilous snails, allowed an interglacial context to be established. A few species out of their modern range occur at Soucy, most of them being forest snails of central European origin. There is also a notable extinct forest taxon *Aegopsis klemmi*, recorded for the first time in western Europe, which was previously known only from Middle Pleistocene sites in central Europe, always under interglacial climatic conditions (Limondin-Lozouet 2001).

The four biozones of the malacological succession describe a composite landscape of wooded and open areas evolving towards a more open environment. Zones Scy1 and Scy2 correspond to the maximum diversity of biotopes and the occurrence of *A. klemmi* is restricted to

zone Scy2, which provides the best development of the forest group (up to 26% of the mollusc population). In the next two biozones (Scy3 and 4), the sharp decrease in the number of species and their distribution in a smaller number of ecological groups indicate more open and uniform environments. Several studies have shown that malacological associations in valley bottoms are never extremely rich in forest molluscs, even during the warmest phases of interglacials (Kerney 1971; Gilbertson 1980; Green *et al.* 1996; Sommé *et al.* 1996). According to this observation, the fauna of Soucy biozone 2 could correspond to the interglacial optimum. Furthermore, although the fine fluvial sequence at Soucy does not show any major stratigraphic discontinuity, the abrupt transition from the coarse basal gravel to the overlying sandy-silt deposits (without any grain size gradient) implies the existence of a major hiatus between these two formations (Chaussé *et al.* 2000). It is likely that a large part of the sediments contemporary with the temperate phase was evacuated during periods of fluvial activity. In this context, the evolution of the landscape towards greater openness, as revealed by the malacofauna of Soucy, suggests correspondence with the end of the forested period of the MIS 9 interglacial (Limondin-Lozouet 2001).

Six Early Palaeolithic settlements were included in the Soucy deposits. The best-preserved and most abundant mammalian faunas are contemporaneous with the Scy2 mollusc zone, the main taxa being *Cervus elaphus*, *Equus*, *Bos primigenius*, *Megaloceros*, *Dicerorhinus mercki*, *Palaeoloxodon antiquus* and suggest a mixed environment of clear forest and open spaces under temperate and continental conditions (Chaussé *et al.* 2004; Lhomme *et al.* 2004).

In the Somme basin, the MIS 9 interglacial is locally represented in a lens of fluvial calcareous silt overlying the gravels of the Alluvial Formation IV of the Somme system (Epinette Formation: Fig. 2). This layer, dated at about 280–300 ka by ESR on fluvial quartz grains and ESR-U/Th combined on large mammal teeth (Bahain *et al.* 2007), has yielded a large mammal assemblage including in particular *Cervus elaphus* and *Dama* sp. (Auguste 2009). Malacological data are not available for this site.

MIS 7: Biache Saint-Vaast, Tourville-la-Rivière and Longpré-les-Corps-Saints

Biache-Saint-Vaast. – At Biache in the Scarpe valley (Fig. 1), the succession consists of a fluvial sequence (gravels, coarse sands and tufa) overlain by slope deposits (solifluction silts, loess) (Sommé 1978; Tuffreau & Sommé 1988). Two episodes of Neanderthal occupation associated with mammalian faunas occur in the upper part of the fluvial units and in the solifluction deposits, which also contain pollen data (Munaut 1988; Auguste 2009). The main archaeological level at the

top of the fluvial formation has been well dated to MIS 7 (Bahain *et al.* 2015; Coutard *et al.* 2019) but given the distribution of dates and their margins of error, a more precise attribution within this chronological interval is not possible.

Molluscs were present throughout the sequence (Rousseau & Puisségur 1988). In the basal coarse sand although shells are in poor condition, an abundant population of the thermophilous bivalve *Corbicula fluminalis*, diagnostic of Pleistocene interglacial deposits in northwestern Europe (Meijer & Preece 2000), was recovered. The pollen spectrum was too disturbed for environmental interpretation, but temperate trees are particularly well represented (Munaut 1988). The 2-m-thick silty tufa that forms on top of the sand contains highly aquatic faunas, revealing a marshy environment and cool conditions. At its very top and in the overlying clay soil, the mollusc fauna becomes terrestrial. It is diversified (36 species), dominated by open-ground species, but also contains a fraction of thermophilous snails (up to 10.5% of the mollusc population in the top of the tufa) indicative of wooded habitats, suggesting a climatic improvement. In the first part of the tufa, tree pollen is rare and grasses predominate. In its upper part a mosaic landscape of open forest, in which *Quercus* is well represented, and steppe-like patches is reconstructed from pollen. Both indicators record an episode of climatic improvement with its optimum at the top of the tufa and characterize it as an interstadial of temperate continental climate (Munaut 1988; Rousseau & Puisségur 1988). The mammalian fauna associated with the contemporaneous archaeological layers indicates a wooded parkland prairie under a temperate and humid climate and is dated to MIS 7 (Biozone 24; Auguste 2009; Fig. 4). The subsequent solifluction deposits yield malacological assemblages that have lost their most thermophilous elements indicating a cooling while the palynological contents show a landscape evolution towards steppic conditions, with some tree patches remaining (*Pinus*, *Betula*). The second episode of archaeological occupation is characterized by a less diverse mammalian fauna, pointing to the coldest and driest climatic conditions assigned to the end of MIS 7 (Auguste 2009).

At Biache, both molluscs and pollen indicate the occurrence of the most thermophilous elements in the basal gravel unit. The presence of *Corbicula fluminalis* is an important element in the classification of this climatic episode as an interglacial. In the subsequent fluvial deposits molluscs and pollen indicate a temperate period of interstadial rank contemporaneous with the Neanderthal skulls level dated to MIS 7. A second milder period of less intensity is indicated by the molluscan fauna in the lower part of the slope deposits, while the palynological contents describe an open landscape with few trees. The structure and composition of the assemblages from this last episode are very similar to

those of the early Weichselian (MIS 5d to 5a) malacofauna observed in the region (Antoine *et al.* 1995; Loch *et al.* 2013).

Tourville-la-Rivière. – The thick Saalian alluvial sequence at Tourville-la-Rivière in the Seine valley (Figs 1, 3) is composed of two periglacial gravel sheets (layers A and C) including fluvio-estuarine deposits of MIS 9 age (layer B), overlain by sand and silt levels (D), laminated sands (E) and capped by periglacial deposits (layers F–K) dated to MIS 7 (Balescu *et al.* 1997; Lautridou *et al.* 1999; Coutard 2023). Silty sands of level D are divided into three subunits (D1, D2, D3), which yielded malacofauna (Puisségur 1983; Limondin-Lozouet & Moine 2023). Mammal remains associated with Neanderthal occupations have been recovered from subunits D1 and D2 (Auguste 2009, 2023).

All but one of the 32 mollusc species in the Tourville assemblages are terrestrial. In level D1 the diversity and richness of snail populations are balanced, indicating stable environmental conditions. These faunas contain species from open environments, but also up to 43% of thermophilic snails typical of forested areas in the upper part of the deposit. This significant development of demanding species is interpreted as reflecting an interglacial optimum (Puisségur 1983). The D1 top sample and the whole D2 level provide assemblages that mark a significant environmental change. The number and diversity of forest taxa are in sharp decline (10%), and only the populations of the most resilient species in this group, those that were present at the beginning of the interglacial recolonization (*Aegopinella nitidula*, *Cepaea*, *Arianta arbustorum*), are still present. At the same time, the number of molluscs living in open environments has exploded: *Pupilla muscorum*, the most abundant species in cold periods, *Trochulus hispidus*, *Vallonia*, characteristic of transitional climates, as shown in the malacological model of the Weichselian Lateglacial, and *Arianta arbustorum* (Limondin-Lozouet & Moine 2023). Together, these assemblages are very well adapted to late interglacial/early-glacial climates. In D3, the assemblage is similar to those of in D2, with an increase in *Pupilla muscorum* and *Succinella oblonga*, which are able to withstand the cold and wet phases. This fauna clearly reflects an early-glacial climate. The high level of development of forest snails in unit D1 (up to 43% of the mollusc population) suggests a possible correlation of D1 with the most pronounced temperate episode of MIS 7e.

Detailed list of mammal faunas shows the same transition from interglacial to glacial conditions (Auguste 2023). Level D1 contains a fauna of temperate climate indicating a mosaic landscape of sylvo-steppe and marshes, assigned as in Biache to Biozone 24 at the end of MIS 7 (Auguste 2009). In level D2 the fauna is representative of a more open environment in an early-glacial context (Auguste 2023).

Longpré-les-Corps-Saints. – In the Somme valley, the tufa of Longpré (Fig. 1) has been the subject of geomorphological, sedimentological malacological and palynological studies (Sommé *et al.* 1984). The tufa (1.3 m thick) rests on a greenish hydromorphic marshy soil with shells. This alluvial sequence is then partly eroded and covered by a non-calcareous clayey humic horizon of Grey-forest soil (Fig. 5).

Malacological results indicate a terrestrial assemblage in the basal palaeosol describing an open forest and then a marshy environment dominated by aquatic taxa in the tufa, but detailed malacological data are not given (Sommé *et al.* 1984). Pollen spectra were poorly preserved in the tufa. In the marshy and upper Grey-forest soils surrounding the tufa, palynology indicates cold climate plant formations.

A new unpublished malacological analysis was later carried out and is summarized in Fig. 5. Samples were taken at 10-cm intervals in the basal soil and within the tufa. The faunas are diverse (58 species, including 37 terrestrial taxa) and very abundant. In the tufa, the assemblages are dominated by aquatic molluscs, among which *Belgrandia marginata*, a spring species characteristic of Pleistocene interglacial deposits in western Europe (Limondin-Lozouet & Preece 2014), is well developed (Fig. 5). Land snails outnumber aquatic molluscs only in the basal sample but their high abundance throughout the tufa suggests the proximity of their native biotopes around the water body. Terrestrial assemblages were therefore studied separately to facilitate the reading of environmental changes (Fig. 5). The constant presence of forest snails indicates a temperate climate. Two environmental phases can be identified. The basal marshy soil assemblages contain taxa characteristic of pioneer temperate environments (*Discus ruderatus* and *Clausilia dubia*). In the tufa, *Discus rotundatus* becomes more abundant, indicating the development of a deciduous forest. The replacement of *D. ruderatus* by *D. rotundatus* is a characteristic feature of the early part of the interglacial malacological successions in the study area, indicating the transition from coniferous to deciduous forest (Limondin-Lozouet 2011). In the first part of the tufa the landscape recorded by the land snail populations can be described as a wetland bordered by open forest. Due to the local conditions, the forest fraction of the fauna remains modest in number, but its diversity (14 species) implies interglacial climatic conditions. In the upper part of the tufa the expansion of the marsh causes the disappearance of strictly forest species and greatly reduces the number of terrestrial species (Fig. 5). Whether this environmental change reflects the deterioration of climatic conditions remains hypothetical.

The Longpré tufa has been assigned to MIS 7 on morphostratigraphic grounds (Antoine 1990; Fig. 2). New malacological analyses show pioneer forest assemblages in the lower soil. In the tufa, the faunas, although

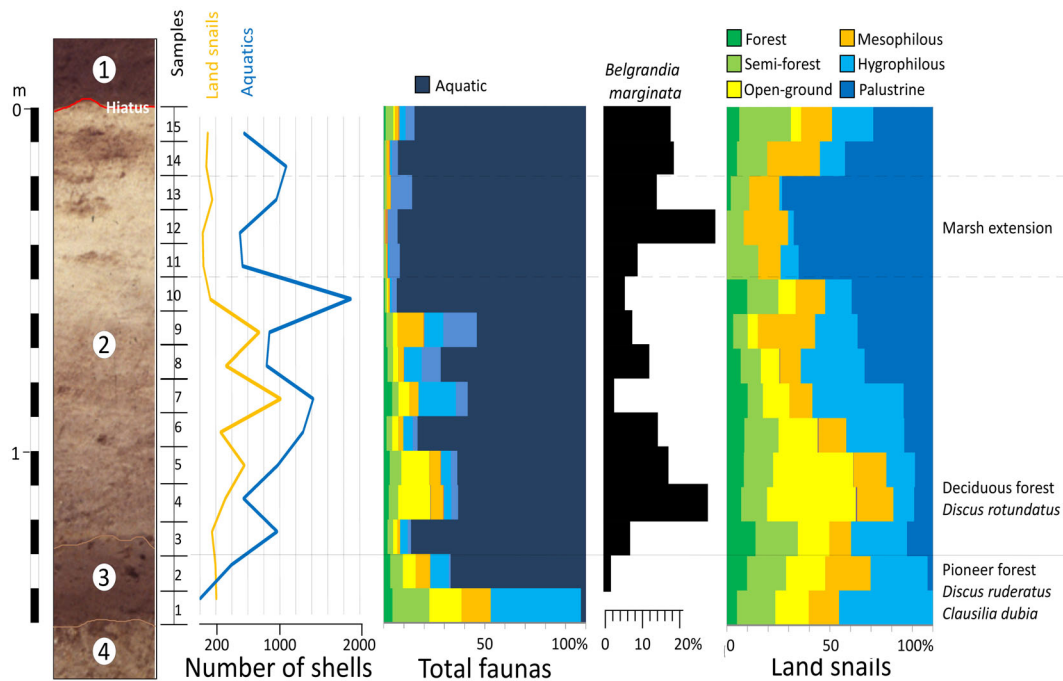


Fig. 5. Longpré-les-Corps-Saints: summarized malacological data. 1 = clayey humic soil horizon (Grey-forest soil); 2 = calcareous tufa; 3 = greenish marshy soil; 4 = fluvial calcareous sandy silt.

strongly influenced by local humid conditions, include a community of deciduous forest snails indicating an interglacial climatic context. However, the Longpré assemblages contain none of the diagnostic Eemian forest taxa identified at Caours, where the last interglacial reference malacological succession is defined (Limondin-Lozouet & Preece 2014). This observation is consistent with a MIS 7 age. U-series dating of mollusc shells and tufa material is in progress in order to validate this interpretation.

Late Middle Pleistocene pedosedimentary sequences

The aim of this section is to summarize the main features of seven of the best slope sequences from northern France encompassing the LMP: (i) Grâce-Autoroute, (ii) Cagny-Garenne, (iii) Gentelles, (iv) Mautort and (v) Etricourt-Manancourt for the Somme basin; (vi) Saint-Pierre-lès-Elbeuf for the Seine River and (vii) Villiers-Adam for the Oise River (Fig. 1).

Grâce-Autoroute reference record (Fig. 6A)

The long section of Grâce-Autoroute (Fig. 1), discovered and studied in 1994 during the excavation of the A-16 Paris–Amiens–Boulogne motorway trench, shows a long LPS overlying an alluvial formation corresponding to the oldest unit of the Quaternary stepped terrace system of the Somme River (Alluvial Formation X or

Grâce-Autoroute, relative altitude: +55 m, Fig. 2). These fluvial deposits, dated between 0.9 to 1 Ma by ESR and ESR/U-series (Bahain *et al.* 2007, 2010), are covered by a LPS exposed in a trench about 250 m long corresponding to a total thickness of more than 20 m (Antoine *et al.* 2020, 2021). The Grâce-Autoroute slope sequence thus represents the longest sub-continuous record of the Middle Pleistocene in both northern France and western Europe (Antoine *et al.* 2020, 2021). The LPS is composed of superimposed lenticular slope sub-sequences (silty sands then loess), separated by erosion discordances; each sub-sequence being terminated by a Bt horizon of brown leached palaeosol. The pedosedimentary and cyclostratigraphic approach leads to the distinction of eight successive glacial–interglacial cycles, three of which correspond to the LMP. Combined with ESR on quartz ages from the underlying alluvial sands, the cyclostratigraphic approach allows a correlation with global palaeoclimatic records showing that the oldest slope sediments were deposited at the beginning of the Cromerian Complex (MIS 18). The glacial–interglacial cycles recorded in the Grâce-Autoroute section are summarized below (Fig. 6A, Data S1).

Cycle I. – After the erosion of the top of the Bt horizon of the Grâce IV soil assigned to the MIS 11 interglacial (U7a), Cycle I begins with the formation of a humic soil complex on colluvial sandy silts during the transition between MIS 11 and MIS 10 (U7b to 7d). As during the

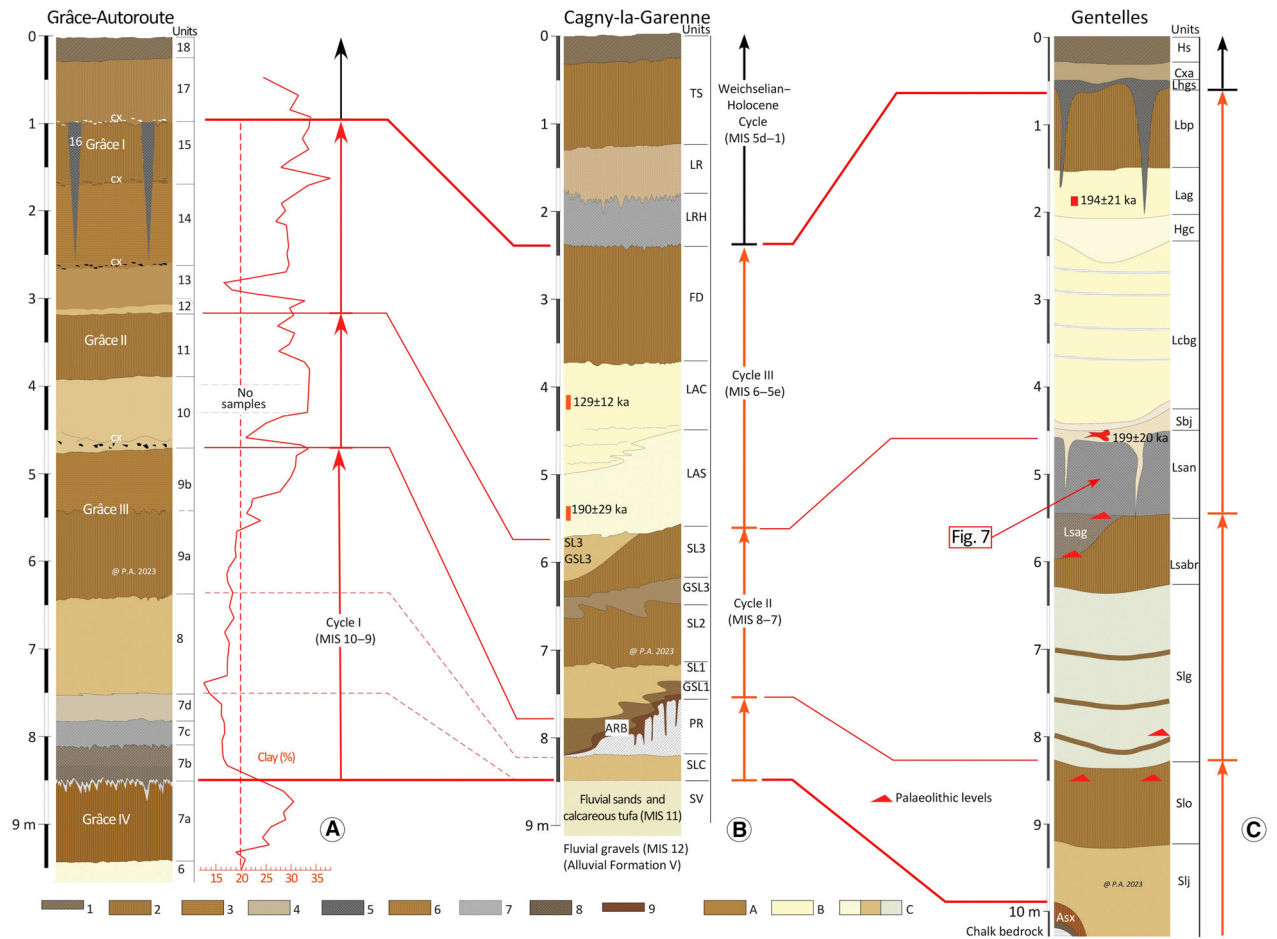


Fig. 6. A. Grâce-Autoroute (upper 10 m, according to Antoine *et al.* 2020). B. Cagny-la-Garenne (according to Haesaerts & Dupuis 1986, dating according to Balescu & Tuffreau 2004). C. Gentelles 1999: log of the LPS from the A-29 trench (redrawn from Antoine in Tuffreau *et al.* 1997) loess–palaeosol sequences (detailed description: see Data S1). Main litho- and pedological symbols used for Figs 6, 8: Soils: (1) Ap horizon of the topsoil; (2) Bt horizon of brown leached soils (Luvisols) including the topsoil; (3) weakly developed Bt or deep Bt horizons of Luvisols, locally banded B hz. or ‘doublets’; (4) hydromorphic horizons (Crysol-tundra gley); (5) Bw horizons boreal brown soils (Cambisols); (6) weak Ah of humic soil; (7) Ah horizon of isohumic steppe soil; (8) Bth horizon of Grey-forest soils (Greyzems) generally topped by an irregular light grey hydromorphic horizon with irregular subvertical cracks and root tracks; (9) B β clayey horizon at the boundary with the chalk bedrock. Sediments: (A) non-calcareous loess (decalcified); (B) typical calcareous loess: homogeneous or laminated, with locally thin layers of 2–3 mm chalk granule layers; (C) homogeneous sandy loess: various colours from beige to light brown or greenish (generally weakly calcareous).

Weichselian early-glacial, the humic soil complex (‘Grâce IV Soil Complex’) has recorded a step-by-step evolution of the climate and environment from a temperate continental climate with boreal forest (Grey-forest soil 7b) to colder but especially drier and more continental conditions (steppe soils 7c, 7d). Full glacial conditions are then attested by the deposition of sandy loess of U8, and the return to oceanic interglacial conditions at the end of Cycle I is marked by the formation of the brown leached soil (Bt horizon) of U9a, b.

Cycle II. – The second cycle begins with an erosion event that truncates the top of the previous Bt horizon marked by a thin gravel bed (Cx) and then goes on with the deposition of the homogeneous sandy loess of U10. The end of the cycle corresponds to a new interglacial period

recorded by the formation of the Bt horizon of brown leached soil Grâce II. According to the cyclostratigraphic analysis of the full Grâce LP record, this horizon would represent the whole MIS 7.

Whereas Cycles I and II are relatively well developed in the Grâce-Autoroute section, the following cycles are rather more compressed because the sedimentary trap is almost totally full at that time.

Cycle III. – The third cycle begins again with the erosion of the upper part of the previous interglacial soil and continues with the deposition of typical loess. However, due to the low thickness of this deposit, it was later completely decalcified during the formation of the brown leached soil during the Last interglacial (Bt horizon Grâce I, Eemian).

Weichselian–Holocene cycle. – The last climatic cycle, corresponding to the Weichselian–Holocene succession, is weakly developed in the Grâce sequence. It is mainly attested by the occurrence of a well-developed polygonal network (2 to 3 m) of soil veins (up to 1.5 m deep), infilled with dark grey humic soil material such as at Gentelles for example (see below), or in Saint-Acheul (Antoine 1990). Strong erosion events on the slope (cx) are probably responsible for the weakness of the record of the last glacial period. The end of the cycle is recorded by the brown leached soil Bt horizon of the Lateglacial–Holocene topsoil.

Cagny-la-Garenne

The Cagny area located on the left bank of the Avre, just before its confluence with the Somme to the southwest of Amiens (Fig. 1), is characterized by the exceptional preservation of the various alluvial deposits forming the Middle Terrace Complex and associated loess cover (Bourdier 1974; Haesaerts & Dupuis 1986; Antoine 1990). For more than a century, it has yielded famous Acheulean sites such as Cagny-la-Garenne, Cagny-Cimetière and Cagny-L'Épinette. The profiles at Cagny-la-Garenne are best known from the work of F. Bourdier (Bourdier 1969, 1974). This work has subsequently been supplemented by stratigraphic and micromorphological studies focusing mainly on the cover sequence (Sommé *et al.* 1984; Haesaerts & Dupuis 1986; Van Vliet-Lanoë 1989; Antoine 1990). Recent research carried out on the malacological assemblages of fluvial units has revealed a MIS 11 record that can be linked to that of the Saint-Acheul sequence, where it was first discovered (Limondin-Lozouet & Antoine 2006). The glacial–interglacial cycles recorded in the Cagny-la-Garenne section are summarized below (Fig. 6B, Data S1).

Cycle I. – Overlying the calcareous fluvial silts dated to the MIS 11 interglacial using ESR dating on quartz, the LMP cover sequence begins with the deposition of a sandy silt layer interbedded with gravel beds and cryogenic features (SLC). This is followed by the deposition of a thick lens made up of chalk blocks and flint nodules packed in a chalk mud matrix (the ‘Presle’ of former authors). A period of deep weathering of this chalky periglacial deposit is then recorded in a thick horizon of dark brown ‘chocolate’ clay (ARG) formed during an interglacial period that correspond to MIS 9 (Haesaerts *et al.* 1984; Antoine 1990).

Cycle II. – Cycle II begins with the deposition of lenses of solifluction clayey gravels and sandy silts with a very high sand content at the base (50%), which then gradually decreases (GSL1 to SL3). The heavy mineral assemblage is dominated by ubiquitous minerals (rutile, zircon) and epidote, as in fluvial sands. According to the

micromorphology and geometry of the different units, this part of the sequence corresponds to two different pedosedimentary sub-cycles that can be assigned to the MIS 7 interglacial complex (‘Cagny Pedocomplex’; Haesaerts *et al.* 1984).

- *Sub-cycle IIa.* Deposition of silty sands and solifluction gravel beds SL1 to GSL2 reworking the brown clay developed at the top of the ‘Presle’ in a periglacial context evidenced by mass solifluction and cryoturbation. This first cold and wet period is followed by a first phase of interglacial pedogenesis marked by the formation of a reddish-brown Bt horizon with a strong prismatic structure and yellow then yellowish-brown clay coatings (SL2; Van Vliet-Lanoë 1989).
- *Sub-cycle IIb.* Deposition of the silty sands and solifluction gravel beds GSL3 to SL3 during a strong climatic degradation, followed by the formation of a brown leached soil (SL2) evidenced by yellow clay coatings affecting SL3, but less developed than the previous one.

According to thermoluminescence (TL) ages of the overlying calcareous loess (Balescu & Tuffreau 2004) and the cyclostratigraphic analysis of the Garenne LMP sequence, Sub-cycles IIa and IIb respectively represent the pedosedimentary budget of: MIS 8/MIS 7e and MIS 7d/MIS 7c–a.

Cycle III. – The beginning of the next climatic degradation, assigned to early MIS 6, is marked by a new erosion event characterized by the deposition of gravel beds and colluvial sandy loess locally preserved in a channel truncating the previous sequence (GSL4, SL4). This event is followed by the deposition of the first typical loess, initially non-calcareous (LAS), then calcareous (LAC) separated by a gravel bed and deep erosional features (thawing channels). LAC unit contains a *Pupilla* fauna typical of steppic loess environments. Heavy mineral assemblages from these loess layers are characterized by green hornblende and garnet in increasing proportions from the base of the LAS to the top of the LAC, in contrast to the previous deposits where green hornblende is never observed. LAC and LAS loess units have been dated to 129 ± 12 and 190 ± 29 ka, respectively, using infrared stimulated luminescence (IRSL) (Balescu & Tuffreau 2004).

Weichselian–Holocene cycle. – As in other sites where the sediment trap is already filled at the end of the Eemian, the last glacial–interglacial cycle is represented here only by a weak humic soil complex (LRH), then by an undifferentiated loess body (LR), finally topped by the Bt horizon of the topsoil (TS).

According to Haesaerts & Dupuis (1986), Balescu & Tuffreau (2004) and Antoine *et al.* (2021), the whole LPS, which overlies the fluvial sequence of the Middle

Terrace at Cagny-La-Garenne (~9 m thick), corresponds to the late Middle Pleistocene and to the succession encompassing MIS 10 to MIS 6. The two major phases of loessic deposition are separated by the intra-Saalian interglacial complex, which here is represented by two distinct climatic improvements (Bt horizons) separated by a cold phase corresponding to the ‘aborted glacial’ of MIS 7 (7d) and to GSL3–SL3 stratigraphic units.

Gentelles

The Gentelles sequence was studied on a 200-m-long section excavated in 1998–1999 on the route of the A-29 motorway (Amiens-Saint-Quentin). These earthworks crossed several large sinkholes opening up on the surface of the chalk (~45 m in diameter for a depth of 8.5 m for the largest). During the archaeological excavation, several Palaeolithic levels were discovered and studied (Tuffreau *et al.* 1997). In addition, the dating of a few horse teeth found in the sandy layer (Sbj) using the ESR-U series allowed the assignment of the immediately underlying humic soil horizon, named ‘Gentelles Soil’, to late MIS 7 to be confirmed. The successive glacial–interglacial cycles recorded in the Gentelles section are summarized below (Fig. 6C, Data S1).

Cycle I. – In the deepest part of the sinkhole, the sequence begins with the deposition of orange-brown silty-clayey sands (Slo), which have the characteristics of a Bt horizon of brown interglacial leached soil developed on sandy silts (Slj). This soil is later influenced by a phase of deep seasonal frost and strong terminal hydromorphy. The Slj-Slo sequence corresponds to a relatively poor budget of a first glacial–interglacial cycle attributable to the MIS 10 to MIS 9 succession, according to the cyclostratigraphic analysis of the overlying pedosedimentary succession and numerical ages.

Cycle II. – The sinkhole then trapped a 2-m-thick sequence of grey sandy silt with oxidation traces (Slg) including coarse flint gravel beds with a clayey sandy matrix. This climatic deterioration culminates in the development of a series of laminated sands with concentrated runoff structures including thin beds of pure clay. The brown leached soil (Lsab) that develops at the top of the previous sequence represents a new phase of environmental stabilization and an interglacial period (MIS 7).

Cycle III. – After a new climatic degradation, marked by the erosion of the Bt Lsab and by the deposition of colluvial sandy deposits, a thick grey-black humic soil horizon has developed (Lsan). The ESR dating of horse teeth from the sand layer (199 ± 20 ka; Bahain *et al.* 2015), and the IRSL ages of the overlying loess (194 ± 21 ka; Balescu & Tuffreau 2004) both support the

allocation of this soil horizon to the transition between MIS 7 and MIS 6 in accordance with the characteristics of the horse teeth collected in the sandy layer (Auguste in Tuffreau *et al.* 2017). The so-called ‘Sol de Gentelles’ is thus located at the beginning of the penultimate glacial–interglacial cycle (Cycle III) in the same stratigraphic position as other humic horizons described in northern France LPS such as at Mautort (Antoine 1990), Villiers-Adam (Antoine *et al.* 2003a) and Etricourt-Manancourt (Coutard *et al.* 2018). This isohumic steppe soil (Ah horizon) is then penetrated by deep sand wedges (~0.7 m depth for 5 cm at the opening) filled with yellow aeolian sands (Fig. 7A). In some areas large cryoturbation ‘pockets’ infilled by calcareous loess separated by cryo-injected humic soil Lsan are observed (Fig. 7B). These features undoubtedly indicate that permafrost first appeared in early MIS 6, as in the Mautort and Garenne sequences. The cold period corresponding to MIS 6 is then characterized by both the deposition of the first calcareous loess (Lbg) and the first major permafrost event. This calcareous loess, dated to 194 ± 21 ka using IRSL on feldspar (with fading correction), is capped by a typical Bt horizon of brown leached soil (Lbap), formed mainly during the Eemian (MIS 5e), but also partly during MIS 5a–5d, as shown by the occurrence of superimposed stratified clayey-humic to silto-humic coatings (polygenetic soil horizon).

Weichselian–Holocene cycle. – As the sinkhole was completely filled in at this time, the Last Glacial is recorded here only by the presence of a large network of humus-filled frost cracks (Lhgs), corresponding to those classically observed at the beginning of the Weichselian glacial (‘soil veins’) (Lautridou 1985; Antoine 1994; Antoine *et al.* 1999). Topsoil pedogenesis is here superimposed on the complex Bt horizon of Cycle III.

Mautort

Deep excavations (up to 13 m in the S1 test pit) carried out in 1988 at Mautort on the route of the A-28 motorway near Abbeville (Fig. 1), on the left bank of the Somme River, revealed a thick loess–palaeosol sequence overlying an alluvial sequence corresponding to the fluvial record of MIS 10 and MIS 9 (Antoine 1994). In addition, Mautort was the site where it was possible, for the first time in northern France, to detect a two-folded soil complex corresponding to the MIS 7 interglacial including two distinct Bt horizons separated by a 0.5-m-thick loess deposit (Antoine 1994). The successive glacial–interglacial cycles recorded in the Mautort section are summarized below (Fig. 8A, Data S1).

Cycle I. – At Mautort, due to the presence of two distinct Bt horizons (U14 and U12) separated by a colluvial sandy loess (U13), the first cycle from the late Middle

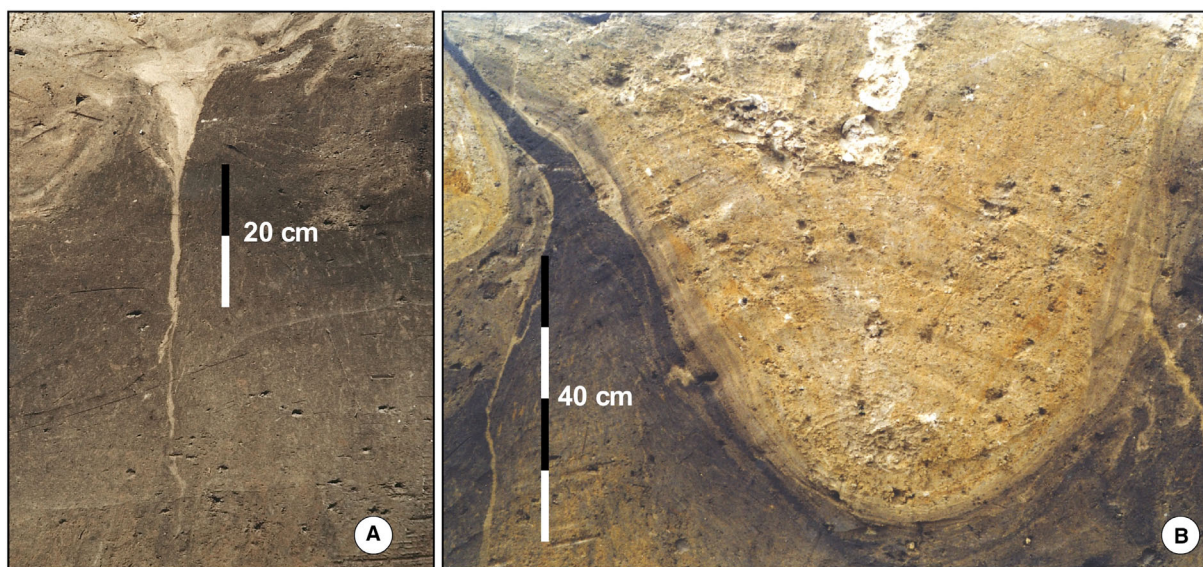


Fig. 7. ‘Gentelles soil’ and permafrost features. A. Frost crack with sandy infilling (Sbj) ‘sand wedge’ penetrating the humic soil horizon (‘Gentelles Soil’) Lsan. B. Large cryoturbation pocket developed at the boundary between Lsan humic soil and calcareous loess Lcbg.

Pleistocene is divided into two sub-cycles (as at Cagny-la-Garenne):

- *Sub-cycle Ia.* Erosion of the upper part of the alluvial sequence (gravel bed), followed by the deposition of sandy silts during a first cold phase. This sediment is then influenced by the formation of a typical Bt horizon of brown leached soil (U14) indicating the return to an interglacial period (MIS 7e).
- *Sub-cycle Ib.* Erosion of the upper part of the previous Bt horizon followed by deposition of a sandy silt layer (U13) indicating a strong climatic degradation and an open environment. A typical Bt horizon of brown leached soil (U12) then develops on this deposit during the following interglacial peak (MIS 7a–c).

Cycle II. – The second cycle begins with the hydromorphic degradation of the surface of the previous Bt horizon (glosses). This is followed by the deposition of massive colluvial sandy silts in which a weak greyish humic soil horizon (Ah, steppe soil) develops in the same stratigraphic position as in the Gentelles and Villiers-Adam LPS. A major climatic pejouration is then attested by the deposition of a massive sandy-loam deposit (U10) and of a thick set of bedded sandy-clay loam (U9). Deep frost cracks (~2 m), later infilled by solifluction gravels, are observed at the top of U9 (former ice wedge casts). They indicate the first period of permafrost aggradation during the LMP (as at Gentelles and Cagny-La-Garenne), but also the occurrence of a rapid thawing event. This led to intense erosion of the former ice wedge casts by thawing waters, followed by their infilling by massive solifluction gravels with clayey matrix

(thermokarst processes). Typical calcareous loesses, with a finely laminated structure, are then deposited (U8 to U6) but they still contain solifluction gravel beds indicating seasonal gelifluction events on the steep slope surrounding the site to the SW. The end of Cycle II is marked by the formation of a Bt horizon of brown leached soil, which testifies to full interglacial conditions. This soil is assigned to the Eemian interglacial.

Weichselian–Holocene cycle. – After the erosion of the Bt horizon of the last interglacial the Weichselian sequence begins with a succession of Grey-forest soil and steppe soil horizons as in the Weichselian early-glacial type section of Saint-Saulieu (Antoine *et al.* 2016). The Weichselian pleniglacial deposits are then formed by a succession of two calcareous loess units (laminated loess and homogeneous loess), at the top of which the postglacial Bt horizon is formed.

The LMP Mautort LPS is thus characterized by two sets of calcareous loess units (U10 and U9) and (U8 to U6) separated by a major erosion associated with a cycle of permafrost development (large ice wedges) and subsequent collapse (gelifluction and thermokarst). By their stratigraphic position, these two sets are equivalent to the LAS and LAC units at Cagny-La-Garenne, which are also separated by thawing channels.

Etrécourt-Manancourt

The LPS at Etrécourt-Manancourt, discovered during a rescue archaeological excavation, contains several Palaeolithic levels including an Acheulean occupation well dated by TL on heated flints around 280–300 ka (late MIS 9) (Hérisson *et al.* 2016; Coutard *et al.* 2018).

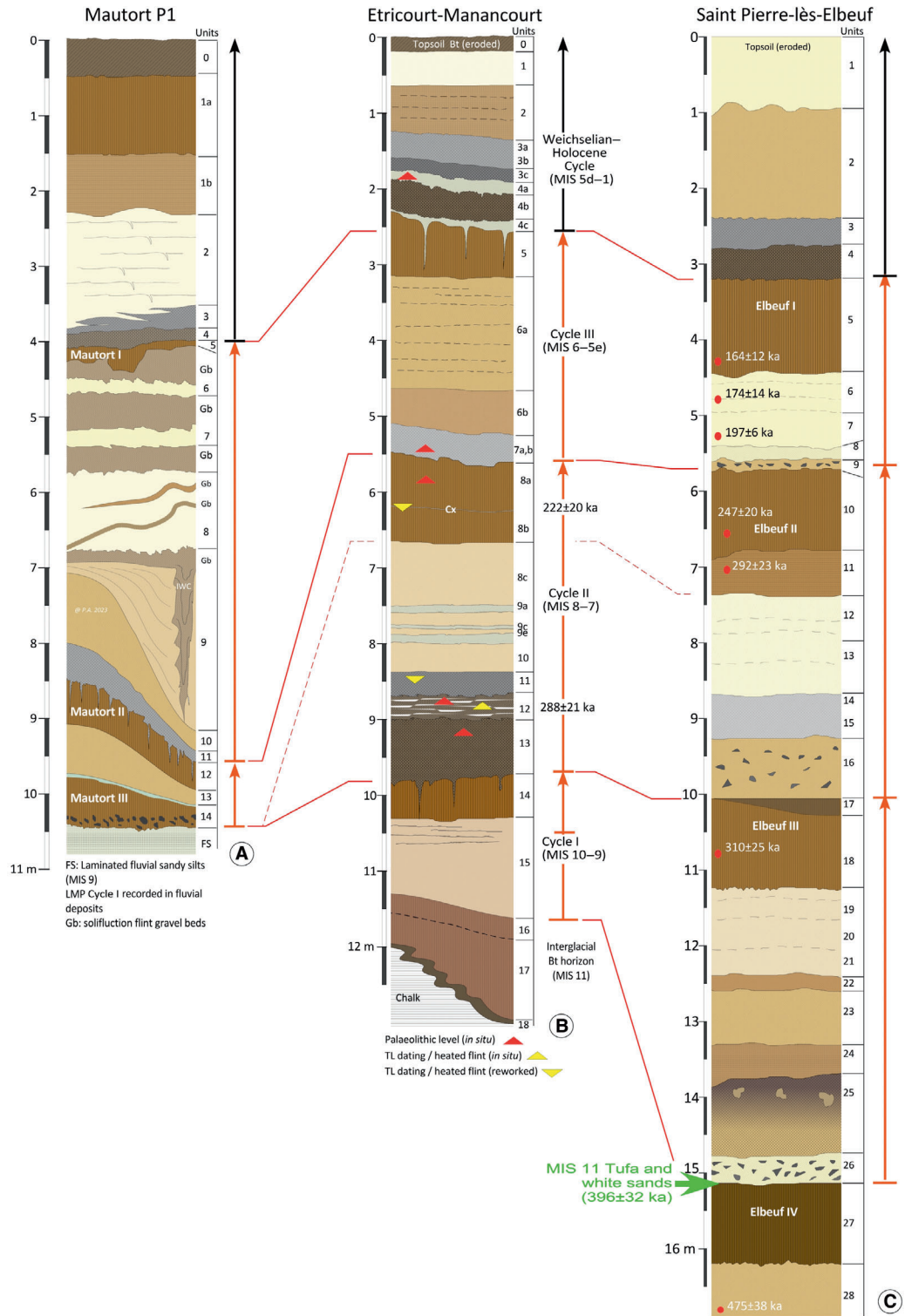


Fig. 8. A. Mautort S1 (according to Antoine 1990). B. Etricourt-Manancourt summarized profile (redrawn according to Coutard *et al.* 2018). C. Saint-Pierre-lès-Elbeuf (redrawn according to Cliquet *et al.* 2009 and Coutard *et al.* 2019, ages from Balescu 2013) (detailed description: see Data S1).

The archaeological excavation, located on the slope of a dry valley, led to the discovery of two deep sinkholes that developed in the Upper Cretaceous chalk bedrock. The

bottom of the deepest one is located at more than 11 m below the surface of the topsoil and 5 m below the average chalk surface. A 12-m-thick cumulative loess-

palaeosol succession corresponding to five stacked glacial–interglacial cycles has been identified here (Fig. 8B). The Etrécourt sequence includes five interglacial luvisols respectively assigned to MIS 11 (U17), MIS 9 (U14), to the two warm substages of the MIS 7 interglacial complex (U8b and 8a) and finally to MIS 5e (U5). The successive glacial–interglacial cycles recorded in the Etrécourt–Manancourt section are summarized below (Fig. 8B, Data S1).

Cycle I. – The first cycle is composed of the succession of a 1.5-m-thick non-calcareous homogeneous sandy loess (U15) at the top of which is a Bt horizon of brown leached soil indicating an interglacial period corresponding to the MIS 9 Interglacial (U14) according to both the pedosedimentary budget and the TL dates from U12. This first LMP pedosedimentary cycle overlies a compact clayey Bt horizon (U17–16) separated from the weathered chalk bedrock by a layer of pure clay and manganese oxides (B β horizon, U18). According to the overlying pedosedimentary record this horizon, formed on a non-calcareous loess body, would correspond to the long interglacial period of MIS 11.

Cycle II. – After the erosion of the top of the previous interglacial soil (thin gravel bed), the Etrécourt section shows an exceptionally thick (~1.5 m) humic soil complex (U13–U11) including a Bth horizon of Grey-forest soil and isohumic soil horizons (steppe soils) in which the main archaeological layer (Acheulean) included in U12 yields TL ages from heated flints of about 290 ka (average: 288 \pm 21 ka). This sequence indicates a step-by-step evolution towards more continental climatic conditions during the transition between the end of MIS 9 and the beginning of MIS 8, which shows great similarities with that evidenced for the Weichselian early-glacial (MIS 5d–5a; Antoine *et al.* 2016). The Etrécourt Humic Soil Complex is then covered by sandy loess deposits punctuated by small hydromorphic horizons during the later part of the MIS 8 glacial period. The cycle ends with the formation of a new interglacial soil composed of two weakly separated Bt horizons as in the ‘Garenne Soil Complex’. The TL date of 222 \pm 20 ka obtained from a (reworked) heated flint associated with the Levallois technique is in good agreement with the allocation of this soil complex to the MIS 7 Interglacial.

Cycle III. – As in Mautort and Gentelles, the younger MIS 7 Bt horizon is overlain by a humic soil horizon (LGS) assigned to the transition to early MIS 6. This cold period is then represented by a first homogeneous loess deposit and by a thick unit of finely laminated loess in which the heavy mineral content shows a strong increase in the green hornblende as in the LAS and LAC loess units of the Cagny-La-Garenne reference section. The end of Cycle III is marked by the formation of a new typical interglacial Bt horizon allocated to the Eemian.

Weichselian–Holocene cycle. – At Etrécourt, the Weichselian and Holocene cycle is relatively well developed, especially its lower part, which shows a humic soil complex typical of the Weichselian early-glacial in northern France (Bth horizons of Grey-forest soils then Ah horizons of steppe soils). The rest of the sequence is made up of undifferentiated pleniglacial loess deposits in which the Bt horizon of the topsoil is developed.

Saint-Pierre-lès-Elbeuf

The Saint-Pierre-lès-Elbeuf loess–palaeosol sequence is located at the confluence of the Seine and a small tributary, the Oison (Fig. 1). Known since the 1950s (see Lautridou 1985; Cliquet *et al.* 2009), it shows an LPS succession corresponding to the late Middle and Upper Pleistocene over an exceptional thickness (17 m, Fig. 8C), which constitutes a reference sequence for the Middle Pleistocene of northern France (Lautridou 1985). New research has been carried out on the loess sequence using OSL dating and micromorphology as well as on the malacological content of the interglacial calcareous tufa dated to MIS 11, which is intercalated at the base of the sequence above the Elbeuf IV soil (Cliquet *et al.* 2009). The sequence shows the succession of three LMP glacial–interglacial cycles overlying the MIS 11 interglacial calcareous tufa. The successive glacial–interglacial cycles recorded in the Saint-Pierre-lès-Elbeuf section are summarized below (Fig. 8C, Data S1).

Cycle I. – The first pedosedimentary cycle, which overlies both the Elbeuf IV palaeosol and the MIS 11 calcareous tufa deposit, begins with a strong erosional event evidenced by a thick flint gravel bed (U26). This is followed by the deposition of sandy loess in which a slightly humic soil develops in a steppic environment (U25) then by the deposition of non-calcareous sandy loess (U24 to U19) fed by aeolian deflation from the periglacial alluvial plain of the Seine. This first cycle ends with the development of the Bt horizon of brown leached soil named Elbeuf III (U17–18), for which an IRSL age of 310 \pm 25 ka is consistent with an allocation to MIS 9 (Coutard *et al.* 2019).

Cycle II. – The second cycle also starts with a strong erosion event shown by a thick flint gravel bed (U16). It is followed, as in the previous cycle, by a humic horizon with large crotovinas that were formed in a steppic environment under interstadial conditions (U14–15). Full glacial conditions are then characterized by the deposition of typical loess (U13–12), which would correspond to MIS 8. Cycle II ends with the Elbeuf II thick Bt horizon of brown leached soil (U11–10) dated by IRSL to about 247 \pm 20 ka.

Cycle III. – The third cycle also begins with an erosive event (gravel bed U9). The following glacial period is

evidenced by the deposition of aeolian sands, but then mainly by typical calcareous loess (U6–5), characterized by some laminations (doublet horizon). The IRSL ages (average around 180 ka) are probably slightly over-estimated for deposits that should date back to the MIS 6 glacial period. The Elbeuf I brown leached soil, allocated to the Eemian and mainly to MIS 5e, registers the end of Cycle III.

Weichselian–Holocene cycle. – Although very reduced (3 m thick), the Weichselian shows here a typical succession of the main units of this period in northern France: (i) a humic soil complex including a Grey-forest soil (U4) and a steppe soil horizon (U3) (early-glacial), followed by (ii) a brownish loess and boreal soil complex (Lower and Middle Pleniglacial) and (iii) typical calcareous loess (Upper Pleniglacial). However, a much more detailed record of the Last glacial has been described in a lateral profile (Antoine *et al.* 1999).

Villiers Adam

At Villiers-Adam, about 35 km north of Paris, highway excavation works and associated rescue archaeological operations were carried out between 1995 and 1999 (Fig. 1). They revealed a loess–palaeosol sequence corresponding to the last two glacial–interglacial cycles with a total thickness of about 20 m (Fig. 9). The deposits are preserved on the north-northeast facing slope of an asymmetric dry valley tributary on the left bank of the River Oise. Multidisciplinary research carried out in the area, including sedimentology, soil micromorphology, malacology and organic carbon $\delta^{13}\text{C}$, is summarized in Antoine *et al.* (2003a). The oldest cycle of the LMP (Cycle I: MIS 10–MIS 9) is not recorded here, probably due to the strong erosion occurring before the deposition of the oldest loess at Villiers-Adam. The two LMP glacial–interglacial cycles recorded in the Villiers-Adam section are summarized below (Fig. 9, Data S1).

Cycle II. – The second cycle was preceded by a period of intense erosion that resulted in the formation of a deep gully perpendicular to the present dry valley forming a sediment trap. This incision feature was later infilled by a thick body of regularly laminated silty sands, deposited by runoff from the Tertiary sands in a cold and open environment (U21). The upper part of this unit is then affected by a brown leached soil characterized by a sharp increase in the clay content, the presence of reddish-brown clay coatings and numerous biogalleries (Bt horizon, U20a–b). The variation in clay proportion through this unit reflects a complex soil resulting from the superposition of two Bt horizons separated by a weak sedimentary episode. According to the cyclostratigraphic analysis of the Villiers-Adam LPS and to optically stimulated luminescence (OSL) ages from the

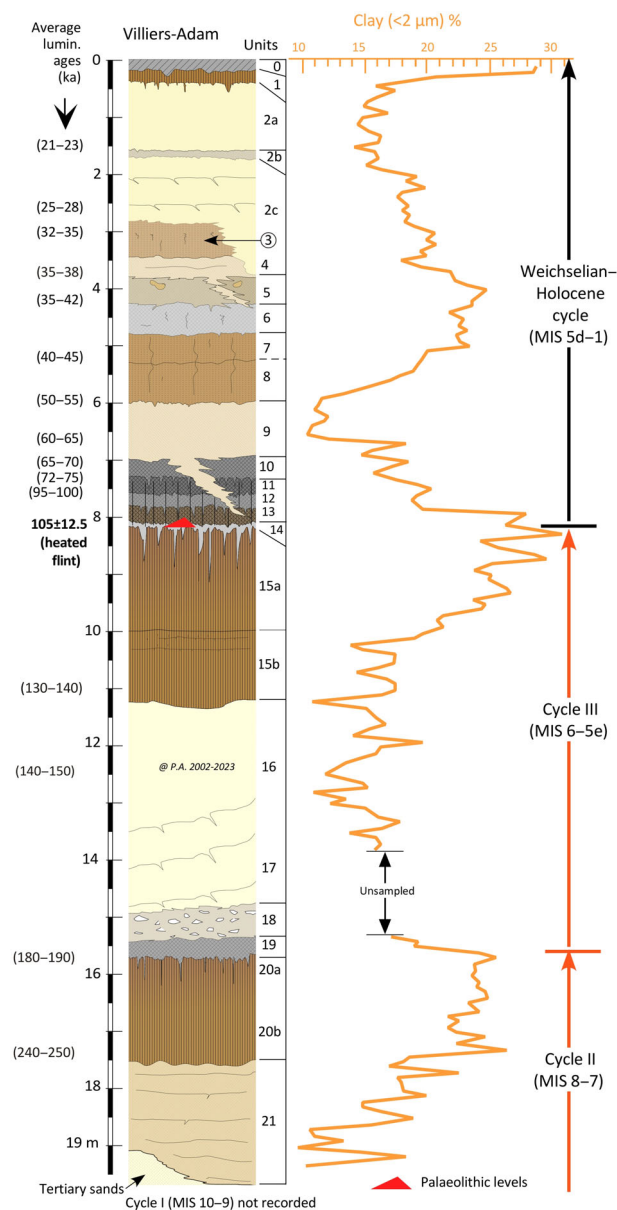


Fig. 9. Villiers-Adam summarized profile, average luminescence ages and variation in clay percentage (according to Antoine *et al.* 2003a) (detailed description: see Data S1).

directly overlying deposits U20a, b, this soil probably reflects the pedosedimentary response to the two main climatic improvements of the MIS 7 ‘interglacial complex’, as already shown for the Somme basin at Mautort, Cagny and Etrécourt (Antoine 1994).

Cycle III. – The third cycle begins with a small greyish humic horizon (steppe soil facies) comparable to the Mautort or Gentelles humic soils, which occurs in the same stratigraphic position. Just above this soil, a phase of intense erosion led to the formation of a deep gully, the base of which is underlain by a gravel bed that contain

reworked Tertiary rock elements from the plateau (U18). This structure is then infilled by laminated calcareous loess with desiccation micro-cracks (U17), then to the top, by homogeneous calcareous loess (U16) reflecting extremely cold and arid conditions. A full glacial environment is highlighted here both by the malacological content (*Pupilla* fauna indicating a dry steppic environment: Limondin-Lozouet & Gauthier 2003) and by organic carbon $\delta^{13}\text{C}$ values (Hatté in Antoine *et al.* 2003a). Luminescence ages (around 175 ka) obtained from these deposits confirm their assignment to the Upper Saalian (MIS 6) and strengthen their correlation with sequences from neighbouring regions such as the Somme. A particularly well-developed (1.5-m-thick) brown-leached soil, reflecting mainly full interglacial conditions (U15), then developed throughout the upper part of this MIS 6 calcareous loess. This soil is characterized by a very complex multi-phased facies highlighted by a gradual increase in clay content from 15 to 30%, but only the initial phase of which is attributable to the Eemian interglacial (5e). Thin section analysis shows that the pedological features of the upper horizons (U15b and especially U15a) are typical for Grey-forest soils and later deep seasonal frost, associated with the initial phases of the Weichselian early-glacial (MIS 5d–5a). In general, the Saalian sequence at Villiers-Adam is thus characterized by a succession of loessic facies and environmental conditions that appear to be very similar to those that prevailed during the deposition of the loess of the Upper Weichselian Pleniglacial. This observation confirms the importance of the change that appears in the dynamics of loess deposition at the beginning of MIS 6 in northern France (massive appearance of typical allochthonous calcareous loess).

Weichselian–Holocene cycle. – The last glacial–interglacial cycle is very well developed here (~8 m thick) and presents one of the best Last glacial sequences in the area, including: (i) a well-developed early-glacial soil complex (U13–U10), (ii) a particularly rich Middle Pleniglacial soil complex including two boreal brown soil horizons (the ‘Villiers-Adam Soil Complex’), and (iii) two units of calcareous Upper Pleniglacial loess. The sequence ends with the Bt horizon of the topsoil.

Discussion

Unlike the Weichselian loess (mainly MIS 2) and, to a lesser extent, the late Saalian ones (MIS 6), which form a sub-continuous cover in northern France, Middle Pleistocene loess deposits are rare and only preserved in local sediment traps. These traps are either sinkholes associated with the dissolution of the chalky Cretaceous substratum (e.g. at Gentelles, Revelles, Etricourt-Manancourt and Le Pucheuil), or formed by the junction between the surface of alluvial terraces (former alluvial plains) and overhanging slopes and terrace scarps (e.g. at

Saint-Pierre-lès-Elbeuf, Grâce-Autoroute, Cagny-Rocade, Cagny-la-Garenne and Mautort). This last configuration is particularly well illustrated by the Middle Pleistocene reference sequence of Grâce-Autoroute where the LPS forms the cover slope deposits of the oldest alluvial formation of the stepped terrace system of the Somme valley (MIS 22; Antoine *et al.* 2000, 2020). As developed above, the chronostratigraphic interpretation of the LPS is mainly based on the demonstration of a cyclic glacial–interglacial signal and its comparison with global climatic references such as the stacked oceanic $\delta^{18}\text{O}$ curve of Lisiecki & Raymo (2005). In some of the sequences, direct dating of loess sediments using luminescence techniques and/or TL dating of archaeological heated flint artefacts from the numerous Palaeolithic sites included in the LPS sequences of the area (Hérisson *et al.* 2023) have strengthened this cyclostratigraphic approach. The cyclostratigraphic interpretation of the LPS is also supported by: (i) the relative position of the different LPS within stepped alluvial terrace systems of the Somme and Seine River valleys (Figs 2, 3) and (ii) the geochronology of fluvial sediments from the alluvial terraces on which they are deposited (ESR on quartz and ESR/U-series on large mammal teeth and U-series on calcareous tufa).

MIS 11: long interglacial and lower boundary of the late Middle Pleistocene

The Grâce IV soil horizon is integrated into a soil complex (Grâce IV Soil Complex; Fig. 10) that includes not only a Bt horizon of typical interglacial brown leached soil, but also a degraded Grey-forest soil horizon (Bth) overlain by an isohumic steppe layer (Ah) (only preserved at Grâce). This soil complex shows the same evolution as the soil complexes recorded during the Eemian/Weichselian early-glacial period in northern France, such as at Saint-Saufieu (Antoine *et al.* 1994), and at Remicourt, Belgium (Haesaerts *et al.* 2016) and Garzweiler, Germany (Schirmer 2016).

Whether at Grâce-Autoroute or Cagny-Rocade, the position of the Grâce IV Soil Complex in relation to the number of younger pedosedimentary cycles and the ESR ages available in the underlying fluvial levels (Bahain *et al.* 2007), means that this soil complex can be assigned to the pedosedimentary budget of the MIS 11 interglacial (Holsteinian) and the beginning (early-glacial phase) of MIS 10 (first glacial of the Saalian complex). Only the Ariendorf sequence, on the right bank of the Rhine in Germany (Brunnacker *et al.* 1975), recently re-examined by Haesaerts *et al.* (2019), clearly shows a soil complex comparable to the Grâce IV soil complex including an interglacial soil (Bt) allocated to MIS 11 (Ariendorf IV), fossilized by the Rieden Tephra dated at 420 to 450 ka by $^{40}\text{Ar}/^{39}\text{Ar}$ (van den Bogaard & Schmincke 1990), then covered by two humic horizons assigned to early MIS 10, including one Grey-forest soil

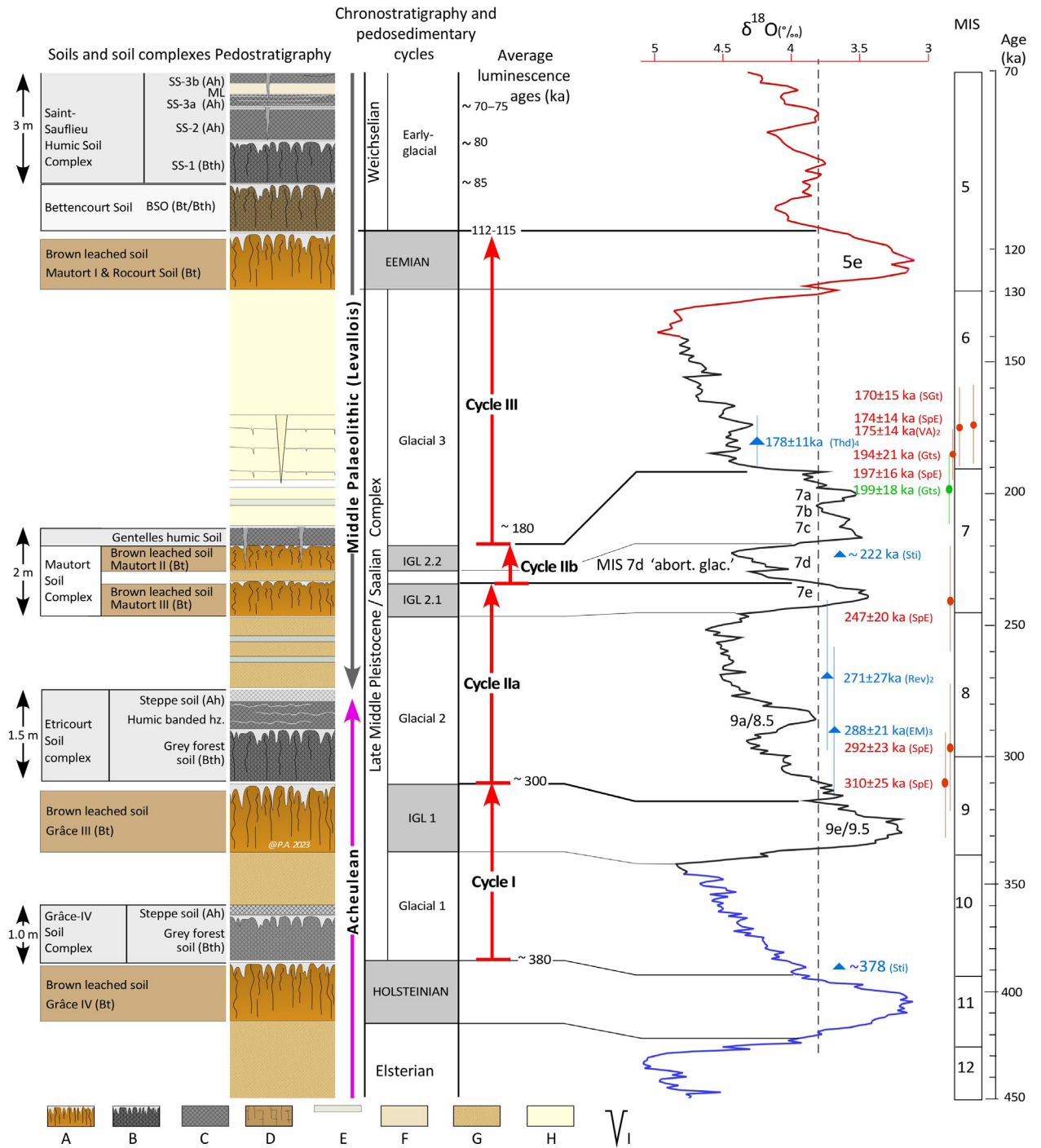


Fig. 10. The late Middle Pleistocene from northern France LPS: summarized pedosedimentary record, dating, and correlation with global oceanic $\delta^{18}\text{O}$ variations. A. Bt horizon of brown leached soil with upper greyish leached glossic horizon. B. Bth horizon of isohumic steppe soil with strong prismatic to lamellar structure and upper whitish leached glossic horizon. C. Ah horizon of isohumic steppe soil. D. Bw horizons of interstadial brown soils (boreal to arctic brown soils). E. Greyish tundra gley horizon with periglacial deformations and oxidized root tracks (Gelic Gleysol). F. Local aeolian loam and non-calcareous loess. G. Non-calcareous to weakly calcareous sandy loess. H. Typical calcareous loess (laminated or homogeneous). I. Ice wedge casts with loess infilling (permafrost). Ages: according to Antoine *et al.* (2018) and Coutard *et al.* (2018, 2019) (exponent: number of individual dating results used for the calculation of the averaged age). $\delta^{18}\text{O}$: data according to Lisiecki & Raymo (2005) and Railsback *et al.* (2015). Various chronological scales: red: 0–140 ka, black: 140–340 ka, blue: 340–450 ka.

horizon (Bth). To the west, the Elbeuf IV soil (Lautridou 1985) is well dated to the Holsteinian interglacial (MIS 11) by geochronological data (U-series, IRSL, ESR, ESR/U-series) and the malacological content of the directly overlying calcareous tufa (*Lyrodiscus* fauna; Cliquet *et al.* 2009) (Figs 8C, 11).

In the fluvial record, the MIS 11c interglacial is represented by several well-dated and shelly calcareous tufas not only in northern France but also in southwest England (Preece *et al.* 2007). The development of the *Lyrodiscus* fauna, characteristic of humid temperate forest environments, is best recorded in the La Celle sequence where it is associated with southern trees and temperate mammal species. The *Lyrodiscus* fauna is particularly diverse and rich in allochthonous taxa of current central and southern European origin, which appear in the latest stages of the forest extension during MIS 11c. A close correlation between increases in both temperature and humidity, and the evolution of forest snail communities, is demonstrated by the combined malacological and isotopic record from La Celle, culminating in the interglacial optimum (Limondin-Lozouet *et al.* 2020).

Late Middle Pleistocene (MIS 10–6)

Cycle I (MIS 10–9). – Beginning with the first cold stage after the long MIS 11 interglacial at about 370 ka, the LMP sequence from northern France is always represented by loessic materials characterized by a strong sandy component (fine sands: 30 to 40%). These sandy loess accumulations are mainly the result of the reworking by wind (aeolian deflation) of sands and silts from the surface of the islands of the braided channel networks occupying the alluvial plain of the Somme River during glacial periods. During MIS 10 the sandy loess deposition is restricted to local sediment traps such as dissolution sinkholes (Etrécourt) or external parts of fluvial terraces sheltered by former terrace scarps, such as at Cagny-la-Garenne, Grâce Autoroute and Saint-Pierre-lès-Elbeuf (Figs 2, 6A, B, 8A, C, 11).

On a regional scale, the next interglacial (MIS 9) is characterized by the formation of a typical leached brown soil called Grâce III Soil (Figs 2, 10). This soil was also observed in the lower part of the Etrécourt-Manancourt doline infilling, where it is covered by the Etrécourt Humic Soil Complex. TL dates on heated flint obtained from archaeological Acheulean material found in this humic soil complex (HUD) confirm the assignment of this soil to a period extending between the end of MIS 9 and early MIS 8 (Hérisson *et al.* 2016; Coutard *et al.* 2018). Given its stratigraphic position and these dates, the brown leached soil Grâce III would therefore be correlated with the brown leached soil of Elbeuf III in Normandy (based on pedomorphology and on IRSL dates; Cliquet *et al.* 2009), at Montenaeken, Belgium (pedostratigraphy; Meijs *et al.* 2012), at

Erbach, Germany (Schirmer 2016), or with the (non-leached) brown interglacial soil from the base of the Achenheim III Soil Complex in eastern France (Lautridou *et al.* 1985).

In the fluvial archives of the Seine Basin, MIS 9 is rare and is only described at Soucy in the River Yonne, south of the area. Although erosion has removed a significant part of the interglacial record, the Soucy malacofauna contains several central European thermophilous species including the extinct species *Aegopis klemmi*, which together form a MIS 9 specific assemblage (Fig. 4). Despite the limited extent of the forest biotope indicated by the mollusc record in the valley floor, the presence of these particular species suggests either a more pronounced forest cover nearby or a declining closed canopy community at the end of the interglacial optimum. Although not included in the fluvial record of the Seine or Somme River basins, it is also important to refer to the Sangatte sequence located on the coast of the eastern Channel (Strait of Dover or ‘Pas-de-Calais’) where beach sands, leaning against the fossil cliff, correspond to a MIS 9 sea-level highstand and have been dated to 350 ± 50 ka by OSL (quartz) (Pawley in Coutard *et al.* 2019).

Cycle II MIS 8–7. – The next cold stage (MIS 8) is characterized by deposits that are slightly less sandy in the Somme sequences, but more clearly loessic at sites located further away from potential sand sources (large periglacial rivers) such as Etrécourt-Manancourt. However, the MIS 8 sedimentary budget can be much larger in some sinkholes such as at Revelles near Amiens where a more than 10-m-thick LPS has been preserved in a large (25 m in diameter) dissolution doline in chalk (Coutard *et al.* 2019; Lamotte *et al.* 2019). According to TL dating on Palaeolithic heated flints preserved at the base of this sequence in silty-clayey deposits (mean: 271 ± 21 ka; Coutard *et al.* 2019), as well as the analysis of the pedosedimentary record including two horizons of interglacial brown leached soils, the first phases of chalk dissolution leading to the formation of the doline date back to the MIS 9 interglacial and/or to the transition between MIS 10 and 9. At this site, therefore, an exceptional accumulation of about 7 m of clayey–sandy silt can be dated to the MIS 8 glacial period. A similar situation was observed in Normandy at Le Pucueil (Fig. 1), where a 50-m-wide and 10-m-deep doline has trapped two superimposed sequences of Saalian loess associated with several Palaeolithic occupations (Delagnes & Ropars 1996). Another interesting LPS, including MIS 10 to 6 loess layers interbedded with interglacial horizons of brown leached soils, was studied at Saint-Illiers-la-Ville on a northeast-facing slope at about 7 km southwest of the Seine (Fig. 1). At this site, the MIS 7 interglacial has been dated to about 222 ka using TL on heated archaeological flints contained in the soil horizon (Blaser & Chaussé 2016).

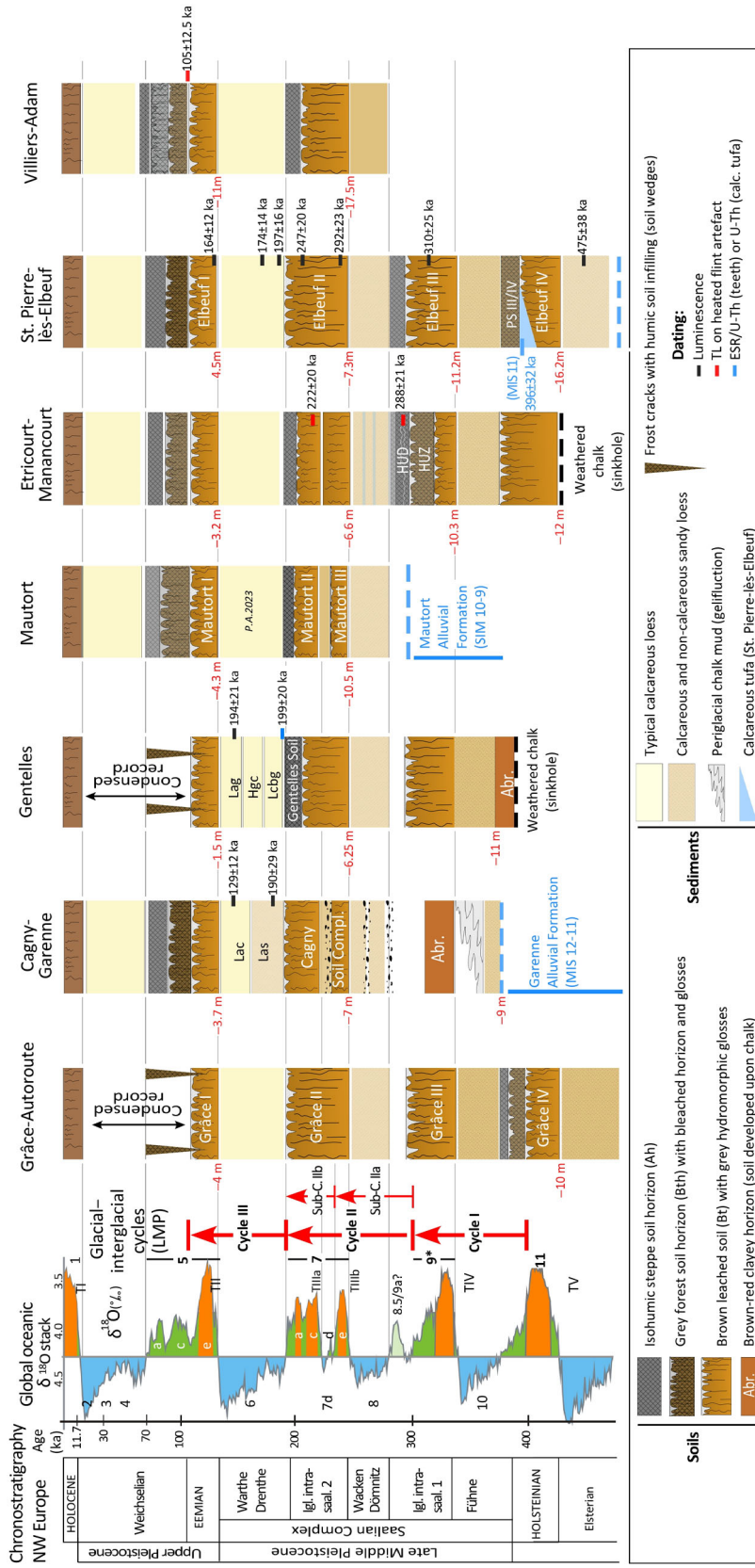


Fig. 11. The main LPS from northern France: correlation with isotopic stages (according to Antoine *et al.* 2020, modified). Northwestern Europe chronostratigraphy according to Cohen & Gibbard (2020), generalized curve of the oceanic $\delta^{18}O$ variations (SPECMAP), according to Lisiecki & Raymo (2005).

The Grâce II Soil, which represents the following interglacial, has pedological characteristics and a stratigraphic position that allow it to be paralleled with the leached brown soils assigned (and/or) dated to MIS 7, such as the Cagny Soil Complex (Haesaerts & Dupuis 1986), the Elbeuf II Soil in Normandy, the Hees soil in Belgium (Meijs *et al.* 2012) and the Ariendorf Ib-II complex in Germany. However, in some sequences, a clear subdivision of this soil into two distinct Bt horizons has been demonstrated, as in Mautort (Mautort III and II Soils; Antoine 1990), Cagny-la-Garenne (Haesaerts & Dupuis 1986) and Etrécourt-Manancourt (Coutard *et al.* 2018). The most illustrative example of this subdivision is represented by the complex formed by the succession of the Mautort III and Mautort II soils at the base of the overlying sequence of the fluvial deposits of the Mautort Formation (Figs 8A, 11). Indeed, at this site, two Bt horizons of typical leached brown soils are clearly separated by a homogeneous sandy loess deposit about 0.5 m thick (Antoine 1994). This particular feature of MIS 7 is also found in some famous LPS of the Danube basin such as Paks in Hungary (Basaharc double soil complex: BD1 & BD2), Mošorin in Serbia (Marković *et al.* 2015) and Mircea Voda in Bulgaria (Balescu *et al.* 2010; Timar-Gabor *et al.* 2011).

The loess layer located in between the two MIS 7 soils is reflected in the fluvial record of the Somme basin by a periglacial gravel body (gravels of the Alluvial Formation II or Low Terrace) allocated to the cold stage of MIS 7d at about 230 ka (Antoine *et al.* 2007). In the Paris Basin the mollusc faunas attributed to MIS 7 are less diverse and much poorer in forest taxa compared to other Pleistocene interglacials (Fig. 4). Among these, species outside their modern range, especially central European taxa that form the malacological signature of past interglacials, are not recorded during this period. Furthermore, closed canopy assemblages are not observed and temperate mollusc faunas during MIS 7 indicate the development of open wooded areas rather than dense forests. At Tourville the woodland snail community, which represents up to 43% of the mollusc population (Fig. 4), is dominated by the most tolerant species of this group, which belong to the semi-forest ecological category (Puisségur 1983). This observation is corroborated by the other bio-indicators, pollen and large mammals, which form mosaic landscape communities where woodland and steppe often coexist. In the lowest part of the Biache sequence, the presence of *Corbicula fluminalis*, a bivalve mollusc recorded only in interglacial deposits (Meijer & Preece 2000), is a strong argument in favour of fully temperate conditions. On the other hand, the upper part of the Biache sequence as well as the Longpré tufa, contain very limited populations of forest snails, suggesting to a lesser extent improved climatic conditions. Studies of the Weichselian Lateglacial have demonstrated the influence of cold climate oscillations on malacological recolonization, slowing or

stopping the spread of species depending on their duration (Limondin-Lozouet & Antoine 2001). Furthermore, a comparison between Pleistocene and Holocene interglacial malacological records has highlighted the absence of central European forest species during the Holocene, which is associated with much drier conditions, particularly during the climatic optimum (Dabkowski & Limondin-Lozouet 2022). However, in the study area there are no reconstructions of the humidity conditions of MIS 7 from geochemical data that can be compared with those of other interglacials, but it is worth noting that the lower warming of stages 7e and especially 7a–c, compared with other interglacials, and the duration and intensity of the climatic deterioration of stage 7d, could have played an important role in the recolonization of the molluscs, limiting the spread of thermophilic species and preventing that of the most demanding taxa. In long continental pollen records from MIS 7, strong temperature oscillations are expressed as an expansion of deciduous forest cover, thus with interglacial rank, separated by steppe episodes reflecting cooling phases (e.g. Follieri *et al.* 1988; Reille *et al.* 2000; Sadori *et al.* 2016). However, most of these reference series are located further south of the study area. At a similar latitude the Schöningen sequence provides a significantly different pollen succession for MIS 7 where the first peak of tree expansion corresponds to an interglacial deciduous forest (Schöningen Interglacial), but the next two peaks belong to an interstadial boreal forest or tree steppe category (Büddenstedt I and II) (Urban 2007). This scheme is consistent with the malacological record of northern France, assuming that Tourville and the lower part of Biache correspond to MIS 7e, and the upper part of Biache and Longpré to MIS 7a–c (Fig. 4).

Finally, the malacological signal of less pronounced temperate conditions during MIS 7 compared to more intense interglacials such as MIS 11 and the Eemian can be paralleled with observations from fluvial series from southern Britain, where the Waverley Wood interval, equivalent to MIS 7, corresponds to a more continental temperate episode (Gibbard & West 2020).

In the LPS records the upper Bt horizon (Mautort II soil) allocated to the later part of 7a–c is capped by a homogeneous grey isohumic steppe soil horizon. The same type of humic soil, although more developed, was observed at the Gentelles sinkhole site (Tuffreau *et al.* 2017), where the ESR/U-series dates obtained on two horse teeth from the directly overlying loess (199±20 ka) also support the attribution of the ‘Sol de Gentelles’ to the transition between MIS 7 and early MIS 6 (Bahain *et al.* 2010). Other examples of humic horizons corresponding to the same climatic transition have been recognized at Le Pucueil in Normandy (Delagnes & Ropars 1996), at Villiers-Adam near the Oise valley (Antoine *et al.* 2003a), and at Etrécourt-Manancourt in the Somme basin (Hérisson *et al.* 2016).

At this last site, the remains of the humic soil are overlain by a loess layer dated by IRSL to between 180 and 144 ka (Coutard *et al.* 2018). Finally, at Therdonne, close to the Thérain river valley (Fig. 1), a 20-cm-thick humic steppe soil horizon (TOC: 0.2%) occurs in the same stratigraphic position (Locht *et al.* 2010) and has been dated to 178 ± 11 ka by TL of archaeological heated flints (Locht *et al.* 2010). This soil has yielded remains of cf. *Citellus superciliosus*, a continental steppe rodent, suggesting a cold and dry climate as well as an open environment.

At Gentelles, a few kilometres southeast of Amiens, the humic soil attributed to the MIS 7–MIS 6 transition is affected by periglacial structures (sand wedges) of more than a metre deep, as well as by large-scale cryo-injection features (Fig. 7A, B), both features representing the oldest evidence of permafrost in the area (Coutard *et al.* 2019). The remnant of a former large ice wedge, subsequently deformed by hillwash processes and infilled by solifluction gravels, has also been described at Mautort within the MIS 6 loess sequence (Antoine 1994).

Cycle III (MIS 6–5e) and the MIS 6 ‘Loess Revolution’. – In contrast to the loess facies preceding MIS 7, the typical late Saalian (or late Wolstonian, Gibbard & West 2020) calcareous loess dated to MIS 6 is much more widespread in the landscape and is therefore much more frequently described, especially from rescue archaeological test pits and also better dated by OSL.

For the area of northern France, the main sequences (Fig. 1) are: Cagny-la-Garenne (LAS & LAC, average 160 ± 20 ka), Etricourt-Manancourt (U6), Gentelles (Lcbg to Lag, average: 196 ± 20 ka), Sangatte (U2, average: 170 ± 14 ka), Villiers-Adam (U17 & U16, average 146 ± 12 ka) and Saint-Pierre-lès-Elbeuf (U8 to U6, average 178 ± 11 ka) (Fig. 11).

The appearance of typical calcareous loess facies (CaCO_3 : ~15–18%) with an unprecedented extent over the whole landscape at the end of the Saalian, while previous aeolian deposits are represented by sandy facies of local origin limited to sedimentary traps, is a common feature in northern France (Antoine *et al.* 2020). In the Villiers-Adam sequence, located close to the southern margins of the northern French loess zone, the appearance of thick and typical calcareous loess (4 m), in an area where the sandy substrate dominates the geological context, is a clear marker of the unprecedented spread of allochthonous loess during MIS 6.

This strong increase in calcareous loess deposition rates at the end of MIS 6 is also observed in Belgium at Kesselt (Nelissen), where the ‘B Loess’ reaches a thickness of 6 to 10 m (Meijs 2002), in Alsace at Schaffhouse (Wuscher & Moine in Antoine *et al.* 2018) and at Achenheim (Lautridou *et al.* 1985), as well as in Germany with the Wetterau Formation (Schirmer 2016), at Böckingem (Bibus 2002) and at Nussloch (Antoine *et al.* 2001).

This major change in aeolian sedimentation is a marker of this glacial period in the whole western part of the European loess belt. It is marked by a significant change in the heavy mineral composition with high concentrations of green hornblende (Haesaerts *et al.* 1984; Balescu 1988; Meijs 2002; Pirson *et al.* 2018). This rapid change in both sedimentation rates, carbonate content and heavy mineral composition is difficult to interpret as the result of a purely climatic forcing since much more intense and longer glacial periods such as MIS 16 or 12 did not result in the same intensification of aeolian processes and loess sedimentation.

The MIS 6 ‘Loess Revolution’ thus probably indicates a significant increase in the volume of the detrital sediments available for aeolian deflation processes from the braided channels of the Channel River draining the eastern Channel in a configuration where it is connected to the southwest of the North Sea basin (Antoine *et al.* 2003b). Indeed, during the Lower Pleistocene and early Middle Pleistocene, before 450 ka, a chalk land bridge connected France and England and then bounded to the southwest the proglacial lake that occupied the south of the North Sea during glacial periods. During MIS 12 this barrier underwent a catastrophic erosion event causing the first opening of the Strait of Dover or ‘Pas-de-Calais’ (Gibbard 1995; Gupta *et al.* 2007). A similar process could have occurred later during MIS 6 (Gupta *et al.* 2007), causing a major reorganization of the drainage network from northwestern Europe towards the Atlantic Ocean (Toucanne *et al.* 2009).

However, even if such a catastrophic event was necessary to open the way for a southwestward drift of meltwater and associated sediments from the Scandinavian Ice Sheet, it is not sufficient to fully explain the unprecedentedly high loess sedimentation rates observed in western Europe during MIS 6. This implies a significant increase in the production of silt-sized particles by glacial grinding and their subsequent transport towards the deflation area of the southern North Sea and the English Channel. Such a process could have occurred during severe (full) glacial periods of such as MIS 12, 6 or 2. However, no typical loess was deposited in northern France during MIS 12, and aeolian deposits at that time were derived from local reworking of sandy material, highlighting the absence of an extensive deflation source in the Channel during MIS 12.

In addition, very strong similarities in facies succession, loess structures and mineralogy between MIS 6 (~150–140 ka) and MIS 2 (~30–17 ka) from northern France to western Germany through Belgium have been demonstrated following numerous field observations (Antoine *et al.* 2016). These common features are: (i) the systematic occurrence of a thick body of laminated calcareous loess with micro-crack networks covered by a thinner unit made up of homogeneous loess (Hesbayan–Brabantian succession in Belgium; Gullentops 1954),

(ii) the development of several tundra gley horizons corresponding to former permafrost active layers, (iii) the occurrence of large ice wedge cast networks, the latter being extremely rare or absent before MIS 6, and (iv) high concentrations of green hornblende in heavy mineral assemblages (Pirson *et al.* 2018). These observations show that both palaeoclimatic and palaeogeographical conditions were similar during the MIS 6 ‘Loess Revolution’ (~180–140 ka) and late MIS 3 and MIS 2 (~30–17 ka).

According to Toucanne *et al.* (2009) these periods were characterized by the connection of the Channel River to the drainage system of the Fennoscandian Ice Sheet and the rerouting of the Elbe–Weser river network to the southwest through the southern North Sea to the North Atlantic. This situation results from the coalescence of the British and Scandinavian ice sheets, which occurred during the Weichselian between ~30 and ~25 ka (Scourse *et al.* 2009; Sejrup *et al.* 2009). This time-span corresponds exactly to the period in which the highest sedimentation rates are depicted in western European loess sequences (Antoine *et al.* 2001, 2016; Haesaerts *et al.* 2016; Moine *et al.* 2017; Rousseau *et al.* 2017). Finally, it is therefore very likely that the unprecedented volume of loess deposited in northern France during MIS 6 is the signature of an original palaeogeographical pattern characterized by the coalescence of the northern European ice sheets in the North Sea basin, inducing a rerouting of the drainage system and associated sediments to the eastern Channel deflation area. However, the question of the exact timing of late Saalian loess deposition in relation to the two glacial advances of MIS 6 (Drenthe then Warthe stadials) is still open. In the Somme system, at Cagny-la-Garenne two successive loess units are described between MIS 7 and 5 interglacial soils (Fig. 6A: LAS and LAC), which are dated at 190 ± 29 and 129 ± 12 ka, respectively. Elsewhere, for example at Sangatte, a calcareous loess typical of the Saalian was dated by OSL to about 170 ± 14 ka; at Saint-Pierre-lès-Elbeuf relatively old IRSL ages were obtained (178 ± 10 ka), and finally at Villiers-Adam, the age of the calcareous laminated loess is about 150–130 ka.

It is therefore likely that typical calcareous loess was deposited during early MIS 6, probably during the Drenthe Stadial, but also during a younger stadial around 150–130 ka. However, due to the small number of luminescence ages currently available and to the large error bars that characterize them, it is still speculative to distinguish loess units deposited in relation to the Drenthe and (or) Warthe stadials. Furthermore, since fluvial activity is required to transport sediments from the southern North Sea to the eastern Channel area, which is the source of loess in northern France, the link between glacial dynamics and loess deposition is not immediate. It is therefore possible that silty sediments accumulated in the eastern Channel during the first episode of coalescence of the British and Scandinavian

ice sheets (Drenthe) were still available for aeolian deflation and loess deposition during the Warthe stage.

Conclusions

Our review, based on the cyclostratigraphic analysis of both loess–palaeosol records and fluvial terrace systems in combination with palaeoecological data (mainly molluscs) from the LMP (MIS 10–6) of northern France, leads to the following conclusions:

- In the malacological record of fluvial environments, the most demanding land snail species of central European origin, which characterize developed forest biotopes during the major Pleistocene interglacial periods, such as MIS 11c and MIS 5e, are present during MIS 9, whereas they are absent from MIS 7 series. This indicates that the forest was less developed during MIS 7, suggesting that climatic conditions were either drier and/or cooler than during other Pleistocene interglacial periods. According to the malacofauna, within MIS 7 there may be a difference in the intensity of the warming between 7e (*Corbicula fluminalis* at Biache and developed wood biotope at Tourville) and 7a–c, characterized by very low numbers of forest molluscs. In the fluvial sequences, marker species define the malacological signatures of each interglacial optimum for MIS 11, MIS 9 and MIS 5e.
- In the Somme stepped terrace system, the stratigraphic record shows that two alluvial formations can be detected during the ~110 ka time-span between MIS 8 and MIS 7 (Cycles IIa & II b MIS 8/7e and 7d/7a–c). This seems to be a unique situation during the last 1 Ma in the terrace systems.
- In some LPS, MIS 7 is recorded as a soil complex including two Bt horizons of brown leached soils assigned to MIS 7e and 7c–a respectively, separated by the deposition of a sandy loess layer. The occurrence of two pedosedimentary sub-cycles (IIa and IIb), separated by a relatively long (~12 ka) and very cold period corresponding to a kind of ‘aborted glacial’ (MIS 7d), emphasizes the complex pattern of this unusual ‘interglacial’. As discussed above, this specific twofold pattern of MIS 7 is also reflected in the fluvial record of this period by the occurrence of sub-cycles IIa and IIb.
- Overall, it is important to note that during the LMP each soil complex corresponding to the interglacial and early-glacial periods from MIS 11 to MIS 5 presents broadly the same soil facies (Bt horizon of brown leached soils, Bth horizon of Grey-forest soils and Ah horizon of humic soils), but with a specific succession pattern or signature.
- During interglacial periods bio-indicators allow the individualization of intra-interglacial climatic evolution whereas the pedosedimentary approach of soil

complexes can only describe the evolution of the environments over longer time-spans such as full interglacial or early-glacial periods.

- LPS from northern France show a huge change occurring in both deposition rates and geographical extent of typical calcareous loess at the beginning of MIS 6, compared to local sandy loess deposits trapped locally in terraces systems or dissolution sinkholes during earlier stages. This so-called MIS 6 'Loess Revolution' is probably related to a change in the palaeogeography of the southern North Sea and eastern Channel source areas at times marked by the coalescence of the British and Scandinavian ice sheets. Finally, this period is also characterized by the occurrence of large ice wedge casts, which are the oldest irrefutable evidence of permafrost development in the area.

In the future, our main objective will be to strengthen the geochronological control of fluvial sequences (especially using the U-series on the MIS 9 and 7 calcareous tufas) and loess deposits using luminescence techniques. On the latter point, this study shows that a close link between loess research and Palaeolithic archaeology can be of great help in enabling the use of TL dating of heated flints, a reliable and accurate dating approach for loess sequences.

Acknowledgements. – This paper is a contribution to ANR research programme 'NeandRoots' coordinated by Dr Marie-Hélène Moncel (CNRS-MNHN, Paris). The authors thank all the colleagues who contributed to various fieldwork campaigns on northern France LMP sequences and Palaeolithic sites: Jean-Luc Loch and Sylvie Coutard (INRAP northern France), David Hérison (CNRS), Emilie Goval (northern France archaeological survey), Dominique Cliquet (Normandy archaeological survey), and Jean-Jacques Bahain (MNHN, Paris), Sanda Balescu (Univ. Lille) and Nick Debenham (Nottingham) for ESR/U-series, OSL and TL dating contributions. We are grateful to Phil Gibbard and an anonymous reviewer for their very constructive comments that helped us to greatly improve this manuscript. The authors have no conflict of interest to declare.

Author contributions. – PA: stratigraphy, sedimentology, conceptualization, writing and editing, illustrations; NLL: malacology, writing and editing, illustrations.

Data availability statement. – The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Antoine, P. 1990: *Chronostratigraphie et Environnement du Paléolithique du bassin de la Somme*. 231 pp. Publication du Centre de Recherches et d'Études Préhistoriques de l'Université de Lille, Lille.

Antoine, P. 1994: The Somme Valley terrace system (Northern France); a model of river response to Quaternary climatic variations since 800 000 BP. *Terra Nova* 6, 453–464.

Antoine, P. 2019: Le Quaternaire de la vallée de la Somme (terrasses fluviales, loess et paléosols): une contribution à l'Inventaire National du Patrimoine Géologique. *Quaternaire* 30, 257–270.

Antoine, P. & Limondin-Lozouet, N. 2004: Identification of MIS 11 Interglacial tufa deposit in the Somme valley (France): new

results from the Saint-Acheul fluvial sequence. *Quaternaire* 15, 41–52.

Antoine, P., Bahain, J. J., Chaussé, C., Cliquet, D., Coutard, S., Deschodt, L., Despriée, J., Dubar, M., Laforge, M., Liard, M., Loch, J.-L., Moigne, A.-M., Moine, O., Monnier, J.-L., Perrenoud, C., Saos, T., Tissoux, H., Voinchet, P. & Wuscher, P. 2018: Quaternaire et géoarchéologie Pléistocène de la France. Quoi de neuf depuis 1976? In Djindjian, F. (ed.): *La Préhistoire de la France*, 38–84. Éditions Hermann, Paris.

Antoine, P., Bahain, J.-J., Coutard, S. & Limondin-Lozouet, N. 2020: La séquence de Grâce-Autoroute (Somme, France): une référence pour l'enregistrement des variations climatiques quaternaires depuis 1 Ma à l'Ouest de l'Europe. *Quaternaire* 31, 205–230.

Antoine, P., Bahain, J.-J., Debenham, N., Frechen, M., Gauthier, A., Hatté, C., Limondin-Lozouet, N., Loch, J.-L., Raymond, P. & Rousseau, D.-D. 2003a: Nouvelles données sur le Pléistocène du Nord du Bassin Parisien: les séquences loessiques de Villiers-Adam (Val d'Oise, France). *Quaternaire* 14, 219–235.

Antoine, P., Catt, J., Lautridou, J.-P. & Sommé, J. 2003b: The loess and coversands of Northern France and Southern England. *Journal of Quaternary Science* 18, 309–318.

Antoine, P., Coutard, S., Bahain, J.-J., Loch, J.-L., Hérison, D. & Goval, E. 2021: The last 750 ka in loess-palaeosols sequences from Northern France: environmental background and dating of the Western European Palaeolithic. *Journal of Quaternary Science* 36, 1293–1310.

Antoine, P., Coutard, J.-P., Gibbard, P., Hallegouet, B., Lautridou, J.-P. & Ozouf, J.-C. 2003c: The Pleistocene rivers of the Channel Region. *Journal of Quaternary Science* 18, 227–243.

Antoine, P., Coutard, S., Guérin, G., Deschodt, L., Goval, E., Loch, J.-L. & Paris, C. 2016: Upper Pleistocene loess-palaeosols records from Northern France in the European context: environmental background and dating of the Middle Palaeolithic. *Quaternary International* 411, 4–24.

Antoine, P., Lautridou, J.-P. & Laurent, M. 2000: Long-Term Fluvial archives in NW France: response of the Seine and Somme rivers to tectonic movements, climatic variations and Sea level changes. *Geomorphology* 33, 183–207.

Antoine, P., Limondin-Lozouet, N., Auguste, P., Loch, J.-L., Ghaleb, B., Reyss, J.-L., Escudé, E., Carbonel, P., Mercier, N., Bahain, J.-J., Falguères, C. & Voinchet, P. 2006: Le tuf de Caours (Somme, Nord de la France): mise en évidence d'une séquence de tufs calcaires eemien et d'un site paléolithique associé. *Quaternaire* 17, 281–320.

Antoine, P., Limondin-Lozouet, N., Chaussé, C., Lautridou, J. P., Pastre, J.-F., Auguste, P., Bahain, J.-J., Falguères, C. & Ghaleb, B. 2007: Pleistocene fluvial terraces from northern France (Seine, Yonne, Somme): synthesis, and new results from interglacial deposits. *Quaternary Science Reviews* 26, 2701–2723.

Antoine, P., Limondin-Lozouet, N., Dabkowski, J., Bahain, J.-J., Auguste, P., Sevéque, N., Ghaleb, B., Reyss, J.-L., Jamet, G., Carbonel, P., Gauthier, A., Jolly-Saad, M.-C., Lebreton, L. & Loch, J.-L. 2024: Last interglacial and Neanderthal occupation in Western Europe: 20 years of multidisciplinary research on the reference Eemian (MIS5e) calcareous tufa sequence at Caours (Somme Basin, France) – a review. *Boreas*, <https://doi.org/10.1111/bor.12654>.

Antoine, P., Moncel, M.-H., Loch, J.-L., Bahain, J.-J., Voinchet, P., Hérison, D. & Hurel, A. 2019: The earliest record of Acheulean Human occupation from Northern Europe and the rediscovery of the Moulin Quignon site. *Nature Scientific Reports* 9, 13091.

Antoine, P., Munaut, A.-V. & Sommé, J. 1994: Réponse des environnements à l'évolution climatique du Début Glaciaire weichselien: données de la France du Nord-Ouest. *Quaternaire* 5, 151–156.

Antoine, P., Munaut, A.-V., Van Kolfschoten, T. & Limondin-Lozouet, N. 1995: Une occupation du Paléolithique moyen en contexte fluviale dans la séquence de la très basse terrasse de la Somme à Saint-Sauveur (Somme). *Bulletin de la Société Préhistorique Française* 92, 201–212.

Antoine, P., Rousseau, D.-D., Degeai, J.-P., Moine, O., Lagroix, F., Kreutzer, S., Fuchs, M., Hatté, C., Gauthier, C., Svoboda, J. & Lisa, L. 2013: High-resolution record of the environmental response to climatic variations during the last interglacial-glacial cycle in Central

- Europe: the loess-palaeosol sequence of Dolní Věstonice (Czech Republic). *Quaternary Science Reviews* 67, 17–38.
- Antoine, P., Rousseau, D.-D., Lautridou, J. P. & Hatte, C. 1999: Last Interglacial–Glacial climatic cycle in loess-palaeosol successions of north-western France. *Boreas* 28, 551–563.
- Antoine, P., Rousseau, D.-D., Zöller, L., Lang, A., Munaut, A. V., Hatté, C. & Fontugne, M. 2001: High-resolution record of the last Interglacial–glacial cycle in the Nussloch loess-palaeosol sequences, Upper Rhine Area Germany. *Quaternary International* 76–77, 211–229.
- Auguste, P. 2009: Évolution des peuplements mammaliens en Europe du Nord-Ouest durant le Pléistocène moyen et supérieur. Le cas de la France septentrionale. *Quaternaire* 20, 527–550.
- Auguste, P. 2023: Dynamique des renouvellements de la grande faune mammalienne et évolution des contextes paléoenvironnementaux et biochronologiques de la Normandie durant le Pléistocène. In Cliquet, D. & Coutard, J. P. (eds.): *Les environnements des occupations humaines pléistocènes de Normandie (France) et des îles anglo-normandes dans leur cadre chronologique*, 339–356. Eraul 145, Liège.
- Bahain, J.-J. & Antoine, P. 2019: Les recherches préhistoriques à Abbeville (Somme) de 1875 à 1939, ou la mise en place d'une approche géologique des gisements paléolithiques. *Actes du XXVIII Congrès Préhistorique de France, Société préhistorique de France 1*, 41–54.
- Bahain, J.-J., Falguères, C., Dolo, J.-M., Antoine, P., Auguste, P., Limondin-Lozouet, N., Locht, J.-L. & Tuffreau, A. 2010: ESR/U-series dating of teeth recovered from well-stratigraphically age-controlled sequences from Northern France. *Quaternary Geochronology* 5, 371–375.
- Bahain, J.-J., Falguères, C., Laurent, M., Dolo, J.-M., Shao, Q., Auguste, P. & Tuffreau, A. 2015: ESR/U-series dating of faunal remains from the paleoanthropological site of Biache-Saint-Vaast (Pas-de-Calais, France). *Quaternary Geochronology* 30, 541–546.
- Bahain, J.-J., Falguères, C., Laurent, M., Voinchet, P., Dolo, J.-M., Antoine, P. & Tuffreau, A. 2007: ESR chronology of the Somme River Terraces system and of the first human settlements of Northern France. *Quaternary Geochronology* 2, 356–362.
- Balescu, S. 1988: *Apports de la thermoluminescence à la stratigraphie et à la sédimentologie des loess du Nord-Ouest de l'Europe*. Thèse de doctorat, Université des Sciences, 343 pp.
- Balescu, S. 2013: Chronologie des loess du Pléistocène moyen de Normandie. *Quaternaire* 24, 237–245.
- Balescu, S. & Tuffreau, A. 2004: La phase ancienne du Paléolithique moyen dans la France septentrionale (stades isotopiques 8 à 6): apports de la datation par luminescence des séquences loessiques. *Archeologicheskii almanach, Donetsk* 16, 5–22.
- Balescu, S., Lamothe, M. & Lautridou, J.-P. 1997: Luminescence evidence for two Middle Pleistocene interglacial events at Tourville, northwestern France. *Boreas* 26, 61–72.
- Balescu, S., Lamothe, M., Panaiotu, C.-G. & Panaiotu, C.-E. 2010: La chronologie IRSL des séquences loessiques de l'est de la Roumanie. *Quaternaire* 21, 115–126.
- Benabdellouahed, M., Dugué, O., Tessier, B., Thinon, I. & Guénnoc, P. 2013: Evolution pléistocène de la Seine fluviale préservée en Baie de Seine. *Quaternaire* 24–3, 267–277.
- Bibus, E. 2002: Zum Quartär im mittleren Neckarraum: Reliefentwicklung, Löss/ Paläobodensequenzen, Paläoklima. *Tübinger Geowissenschaftliche Arbeiten, Reihe D, Geoökologie und Quartärforschung D08*, 1–236.
- Blaser, F. & Chaussé, C. 2016: Saint-Illiers-la-Ville and the Micoquian of Weichselian sequences of the Paris basin. *Quaternary International* 411, 163–178.
- Bourdier, F. 1969: Étude comparée des dépôts quaternaires des bassins de la Seine et de la Somme. *Bulletin d'Information des Géologues du Bassin de Paris* 21, 169–231.
- Bourdier, F. 1974: Quaternaire et Paléolithique des bassins de la Somme et de la Basse Seine. *Bulletin de l'Association Française pour l'Étude du Quaternaire* 3–4, 103–273.
- Bridgland, D.-R. 1994: *Quaternary of the Thames*. 441 pp. Chapman & Hall, London.
- Bridgland, D.-R. & Schreve, D. C. 2004: Quaternary lithostratigraphy and mammalian biostratigraphy of the Lower Thames terrace system, south-east England. *Quaternaire* 15, 29–40.
- Brunnacker, K., Lohr, H., Boenick, W., Puisségur, J. J. & Poplin, F. 1975: Quartär-Aufschlüsse bei Ariendorf am Unteren Mittelrhein. *Mainzer Naturwissenschaftliches Archiv* 14, 93–141.
- Brunnacker, K., Löscher, M., Tillmans, W. & Urban, B. 1982: Correlation of the Quaternary terrace sequence in the Lower Rhine valley and Northern Alpine foothills of central Europe. *Quaternary Research* 18, 152–173.
- Chaussé, C., Limondin-Lozouet, N., Occhiotti, S., Voinchet, P. & Bacon, J. C. 2000: La nappe alluviale de Soucy-Les-Grandes-Pièces (Yonne, France): reconstitution pluridisciplinaire du fonctionnement d'un cours d'eau du Pléistocène moyen. *Géographie Physique et Quaternaire* 54, 187–208.
- Chaussé, C., Voinchet, P., Bahain, J.-J., Connet, N., Lhomme, V. & Limondin-Lozouet, N. 2004: Middle and Upper Pleistocene evolution of the river Yonne valley (France). First results. *Quaternaire* 15, 53–64.
- Choudhury, D., Timmermann, A., Schloesser, F., Heinemann, M. & Pollard, D. 2020: Simulating Marine Isotope Stage 7 with a coupled climate-ice sheet model. *Climate of the Past* 16, 2183–2201.
- Cliquet, D., Lautridou, J.-P., Antoine, P., Lamothe, M., Leroyer, M., Limondin-Lozouet, N. & Mercier, N. 2009: La séquence loessique de Saint-Pierre-lès-Elbeuf (Normandie, France): nouvelles données archéologiques, géochronologiques et paléontologiques. *Quaternaire* 20, 321–343.
- Cohen, K. M. & Gibbard, P. 2011: *Global Chronostratigraphical Correlation Table for the Last 2.7 Million Years*. Subcommittee on Quaternary Stratigraphy (International Commission on Stratigraphy), Cambridge. Available at: <http://quaternary.stratigraphy.org/charts>.
- Cohen, K. M. & Gibbard, P. L. 2020: Global chronostratigraphical correlation table for the last 2.7 million years v2020. Mendeley Data. <https://doi.org/10.17632/dtsn3xn3n6.3>.
- Commont, V. 1909: *Saint-Acheul et Montières. Notes de Géologie, de Paléontologie et de Préhistoire*. 68 pp. Mémoire de la Société géologique du Nord VI (Mém. III), Lille.
- Coutard, J. P. 2023: Le Pléistocène moyen de Normandie. In Cliquet, D. & Coutard, J. P. (eds.): *Les environnements des occupations humaines pléistocènes de Normandie (France) et des îles anglo-normandes dans leur cadre chronologique*, 161–188. Eraul 145, Liège.
- Coutard, S., Antoine, P., Deschodt, L., Jamet, G. & Pawley, S. 2019: Stratigraphie et chronologie des formations du Pléistocène moyen récent (MIS 10–6) du nord de la France, un cadre pour l'étude des occupations paléolithiques. *Actes du XXVIII Congrès Préhistorique de France, Société préhistorique de France 1*, 63–90.
- Coutard, S., Antoine, P., Hérisson, D., Pirson, S., Balescu, S., Brisson, L. F., Spagna, P., Debenham, N., Bare, M., Chantreau, Y., Giros, R. & Lamothe, M. 2018: La séquence loessique pléistocène moyen à supérieur d'Étrécourt-Manancourt (Picardie, France): un enregistrement pédo-sédimentaire de référence pour les derniers 350 ka. *Quaternaire* 29, 311–346.
- Dabkowski, J. 2014: High potential of calcareous tufas for integrative multidisciplinary studies and prospects for archaeology in Europe. *Journal of Archaeological Science* 52, 72–83.
- Dabkowski, J. & Limondin-Lozouet, N. 2022: Comparison of temperature and humidity during MIS 11 and MIS 5e interglacials with the Holocene using stable isotopes in tufa deposits from northern France. *Quaternary Research* 107, 147–158.
- Delagnes, A. & Ropars, A. 1996: *Paléolithique moyen en Pays De Caux (Haute-Normandie)*. 246 pp. Documents d'Archéologie Française, Ed. *Maison des Sciences de l'Homme* 56, Paris.
- Demir, T., Westaway, R. & Bridgland, D. 2018: The influence of crustal properties on patterns of quaternary fluvial stratigraphy in Eurasia. *Quaternary* 1, 28. <https://doi.org/10.3390/quat1030028>.
- Dodonov, A. E., Zhou, L. P., Markova, A. K., Tchepalyga, A. L., Trubikhin, V. M., Aleksandrowski, A. L. & Simakova, A. N. 2006: Middle-Upper Pleistocene bio-climatic and magnetic records of the Northern Black Sea Coastal Area. *Quaternary International* 149, 44–54.

- Dutton, A., Bard, E., Antonioli, F., Esat, T. M., Lambeck, K. & McCulloch, M. T. 2009: Phasing and amplitude of sea-level and climate change during the penultimate interglacial. *Nature Geoscience* 2, 355–359.
- Evlogiev, Y. 2007: Evidence for the Aeolian origin of loess in the Danubian Plain. *Geologica Balcanica* 36–34, 31–39.
- Fedorowicz, S., Lanczont, M., Bogucki, A., Kusiak, J., Mroczek, P., Adamiec, G., Bluszcz, A., Moska, P. & Tracz, M. 2013: Loess-palaeosol sequence at Korshiv (Ukraine): chronology based on complementary and parallel dating (TL, OSL), and lithopedosedimentary analyses. *Quaternary International* 296, 117–130.
- Fitzsimmons, K., Hambach, U., Veres, D. & Iovita, R. 2013: The Campanian Ignimbrite eruption: new data on volcanic ash dispersal and its potential impact on human evolution. *PLoS One* 8, e65839, <https://doi.org/10.1371/journal.pone.0065839>.
- Follieri, M., Magri, D. & Sadori, L. 1988: 250,000-year pollen record from Valle di Castiglione (Roma). *Pollen et Spores* 30, 329–356.
- Frechen, M. & Dodonov, A. E. 1998: Loess chronology of the Middle and Upper Pleistocene in Tadjikistan. *Geologische Rundschau* 87, 2–20.
- Gibbard, P. L. 1994: *Pleistocene History of the Lower Thames Valley*. 239 pp. Cambridge University Press, Cambridge.
- Gibbard, P. L. 1995: Formation of the strait of Dover. In Preece, R.-C. (ed.): *Island Britain: A Quaternary Perspective*, 15–26. Geological Society Special Publication 96, London.
- Gibbard, P. & West, R. G. 2020: Late Middle Pleistocene temperate and associated events in lowland England. *Quaternary International* 546, 170–184.
- Gilbertson, D. D. 1980: The palaeoecology of Middle Pleistocene Mollusca from Sugworth, Oxfordshire. *Philosophical Transactions of the Royal Society of London B* 289, 107–118.
- Green, C. P., Coope, G. R., Jones, R. L., Keen, D. H., Boxen, D. Q., Currant, A. P., Holyoak, D. T., Ivanovitch, M., Robinson, R. E., Rogerson, R. J. & Young, R. C. 1996: Pleistocene deposits at stoke Goldington, in the valley of the Great Ouse, UK. *Journal of Quaternary Science* 11, 59–87.
- Gullentops, F. 1954: Contribution à la Chronologie du Pléistocène et des Formes de Relief en Belgique. *Mémoires de l'Institut géologique de l'université de Louvain XVIII*, 125–252.
- Gupta, S., Collier, J. S., Palmer-Felgate, A. & Potter, G. 2007: Catastrophic flooding origin of shelf valley systems in the English Channel. *Nature Letters* 448, 342–345.
- Haase, D., Fink, J., Haase, G., Ruske, R., Pécsi, M., Richter, H., Altermann, M. & Jäger, K. D. 2007: Loess in Europe – its spatial distribution based on a European Loess Map, scale 1:2 500,000. *Quaternary Science Reviews* 26, 1301–1312.
- Haesaerts, P., Balescu, S., Dupuis, C. & Van Vliet, B. 1984: Contribution à la stratigraphie des gisements paléolithiques de Cagny (Somme). *Cahiers de Géographie Physique, Lille* 5, 77–94.
- Haesaerts, P. & Dupuis, C. 1986: Contribution à la stratigraphie des nappes alluviales de la Somme et de l'Avre dans la région d'Amiens. *Supplément du Bulletin de l'Association française pour l'étude du Quaternaire* 26, 171–186.
- Haesaerts, P., Dambon, F., Gerasimenko, N., Spagna, P. & Pirson, S. 2016: The Late Pleistocene Loess-Palaeosol sequence of middle Belgium. *Quaternary International* 411, 25–43.
- Haesaerts, P., Dupuis, C., Spagna, P., Dambon, F., Balescu, S., Jadin, I., Lavachery, P., Pirson, S. & Bosquet, D. 2019: Révision du cadre chronostratigraphique des assemblages Levallois issus des nappes alluviales du Pléistocène moyen dans le bassin de la Haine (Belgique). *Actes du XXVIIIe Congrès Préhistorique de France, Société préhistorique de France* 1, 179–199.
- Hérisson, D., Coutard, S., Goval, É., Loch, J.-L., Antoine, P., Chantreau, Y. & Debenham, N. 2016: A new key-site for the end of Lower Palaeolithic and the onset of Middle Palaeolithic at Étrécourt-Manancourt (Somme, France). *Quaternary International* 409, 73–91.
- Hérisson, D., Loch, J.-L., Goval, E., Antoine, P. & Coutard, S. 2023: Archaeological sequences, framework, and lithic overview of the late Middle Pleistocene of northern France. In Scott, B., Shaw, A., Scott, K. & Pope, M. (eds.): *Repeopling la Manche*, 131–145. *Prehistoric Society Research Paper 10*. Oxbow Books, Oxford.
- Hinnov, L. A. 2013: Cyclostratigraphy and its revolutionizing applications in the earth and planetary sciences. *GSA Bulletin* 125, 1703–1734.
- Horvath, E. 2001: Marker horizons in the loesses of the Carpathian Basin. *Quaternary International* 76–77, 157–163.
- Jamet, G. 2014: *Réponses sédimentaires d'un bassin versant côtier aux variations glacio-eustatiques et au soulèvement plio-quaternaire, l'exemple du bassin versant côtier de la Baie de Seine (Seine, Touques et Dives)*. Thèse de Doctorat, Université de Caen Basse Normandie, 420 pp.
- Jensen, B. J. L., Evans, M. E., Froese, D. J. & Kravchinsky, V. A. 2016: 150,000 years of loess accumulation in central Alaska. *Quaternary Science Reviews* 135, 1–23.
- Jipa, D. C. 2014: The loess-like deposits in the Lower Danube basin. Genetic significance. *Geo-Eco-Marina* 20, 7–18.
- Kerney, M. P. 1971: Interglacial deposits in Barnfield Pit, Swanscombe and their molluscan fauna. *Journal of the Geological Society of London* 127, 69–93.
- Kukla, G. 1977: Pleistocene land-sea correlations. 1: Europe. *Earth-Science Reviews* 13, 307–374.
- Lamotte, A., Deschodt, L., Antoine, P., Guerlin, O. & Debenham, N. 2019: Le gisement acheuléen en contexte de doline de Revelles (Somme, France) et ses caractéristiques communes à l'Acheuléen méridional. *L'Anthropologie* 123, 695–723.
- Lautridou, J.-P. 1985: *Le cycle périglaciaire pléistocène en Europe du Nord-Ouest et plus particulièrement en Normandie*. Thèse de doctorat d'État, Université de Caen, 908 pp.
- Lautridou, J.-P., Auffret, J. P., Baltzer, A., Clet, M., Lécalle, F., Lefebvre, D., Lericolais, G., Roblin-Jouve, A., Balescu, S., Carpentier, G., Cordy, J.-M., Descombes, J.-C., Occhietti, S. & Rousseau, D.-D. 1999: Le fleuve Seine, le fleuve Manche. *Bulletin de la Société Géologique de France* 170, 545–558.
- Lautridou, J.-P., Sommé, J., Heim, J., Puisségur, J.-J. & Rousseau, D.-D. 1985: La stratigraphie des loess et formations fluviatiles d'Achenheim (Alsace): nouvelles données bioclimatiques et corrélations avec les séquences pléistocènes de la France du Nord-Ouest. *Bulletin de l'Association française pour l'étude du Quaternaire* 22, 125–132.
- Lehmkuhl, F., Nett, J. J., Pötter, S., Schülte, T., Sprafke, P., Jary, Z., Antoine, P., Wacha, L., Wolf, D., Zerboni, A., Hošek, J., Marković, S. B., Obrecht, I., Sümegei, P., Veres, D., Zeeden, C., Boemke, B., Schaubert, V., Viehweger, J. & Hambach, U. 2021: Loess landscapes of Europe, mapping, geomorphology and zonal differentiation. *Earth Science Reviews* 215, 103496, <https://doi.org/10.1016/j.earscirev.2020.103496>.
- Lehmkuhl, F., Zens, J., Krauß, L., Schulte, P. & Kels, H. 2016: Loess-palaeosol sequences at the northern European loess belt in Germany: distribution, geomorphology and stratigraphy. *Quaternary Science Reviews* 153, 11–30.
- Lhomme, V., Connet, N., Chaussé, C., Bemilli, C., Bahain, J.-J. & Voinchet, P. 2004: Les sites et les industries lithiques du Paléolithique inférieur, moyen et supérieur de la basse vallée de l'Yonne dans leurs contextes chronostratigraphiques. *Bulletin de la Société préhistorique française* 101, 701–739.
- Limondin-Lozouet, N. 2001: Une malacofaune nouvelle du Pléistocène moyen à Soucy (Yonne, France): biogéographie et paléocécologie. *Géobios* 34, 303–313.
- Limondin-Lozouet, N. 2011: Successions malacologiques à la charnière Glaciaire/Interglaciaire: du modèle Tardiglaciaire-Holocène aux transitions du Pléistocène. *Quaternaire* 22, 211–220.
- Limondin-Lozouet, N. 2017: "L'assemblage à *Lyrodiscus*", marqueur paléoenvironnemental et biostratigraphique des formations du SIM 11 en Europe du Nord-Ouest. *Quaternaire* 28, 231–238.
- Limondin-Lozouet, N. & Antoine, P. 2001: Palaeoenvironmental changes inferred from malacofaunas in the Lateglacial and early Holocene Fluvial sequence at Conty, northern France. *Boreas* 30, 148–164.
- Limondin-Lozouet, N. & Antoine, P. 2006: A new *Lyrodiscus* (Mollusca, Gastropoda) assemblage at Saint-Acheul (Somme Valley): reappraisal of stage 11 malacofaunas from Northern France. *Boreas* 35, 622–633.

- Limondin-Lozouet, N. & Gauthier, A. 2003: Biocénoses pléistocènes des séquences loessiques de Villiers-Adam (Val d'Oise, France): études malacologique et palynologique. *Quaternaire* 14, 237–252.
- Limondin-Lozouet, N. & Moine, O. 2023: Malacofaunes pléistocène de Normandie. In Cliquet, D. & Coutard, J. P. (eds.): *Les environnements des occupations humaines pléistocènes de Normandie (France) et des îles anglo-normandes dans leur cadre chronologique*, 279–313. Eraul 145, Liège.
- Limondin-Lozouet, N. & Preece, R. C. 2014: Quaternary perspectives on the diversity of land snail assemblages from NW Europe. *Journal of Molluscan Studies* 80, 224–237.
- Limondin-Lozouet, N., Antoine, P., Bahain, J.-J., Cliquet, D., Coutard, S., Dabkowski, J., Ghaleb, B., Locht, J.-L., Nicoud, E. & Voinchet, P. 2015: Northwest European MIS 11 malacological successions: a key for the timing of Acheulean settlements. *Journal of Quaternary Science* 30, 702–712.
- Limondin-Lozouet, N., Dabkowski, J. & Antoine, P. 2020: Palaeoenvironmental dynamics of the MIS 11 interglacial in north-western Europe based on the malacological succession from La Celle (Seine Valley, France): relationship with glacial refugia and palaeobiodiversity. *Palaeogeography Palaeoclimatology Palaeoecology* 560, 110044, <https://doi.org/10.1016/j.palaeo.2020.110044>.
- Lindner, L., Bogutsky, A., Gozhik, P., Marciniak, B., Marks, L., Lanczont, M. & Wojtanowicz, J. 2002: Correlation of main climatic glacial-interglacial and loess-palaeosol cycles in the Pleistocene of Poland and Ukraine. *Acta Geologica Polonica* 52, 459–469.
- Lisiecki, L. E. & Raymo, M. E. 2005: A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. *Paleoceanography* 20, PA1003, <https://doi.org/10.1029/2004PA001071>.
- Locht, J.-L., Antoine, P., Hérison, D., Gadebois, G. & Debenham, N. 2010: Une occupation de la phase ancienne du Paléolithique moyen à Therdonne (Oise): chronostratigraphie, production de pointes Levallois et réduction des nucléus. *Gallia Préhistoire* 52, 1–32.
- Locht, J.-L., Coutard, S., Antoine, P., Sellier, N., Ducrocq, T., Paris, C., Guerlin, O., Kiefer, D., Defaux, F., Deschodt, L. & Limondin-Lozouet, N. 2013: Données inédites sur le Quaternaire et le Paléolithique du Nord de la France. *Revue Archéologique de Picardie* 3, 5–10.
- Lomax, J., Fuchs, M., Antoine, P., Rousseau, D.-D., Lagroix, F., Hatté, C., Taylor, S., Till, J., Debret, M., Moine, O. & Jordanova, D. 2019: Luminescence chronology of the Harletz loess sequence, Bulgaria. *Boreas* 48, 179–194.
- Marković, S. B., Stevens, T., Kukla, G., Hambach, U., Fitzsimmons, K., Gibbard, P., Bugge, B., Zech, M., Guo, Z., Hao, Q., Wu, H., O'hara Dhand, K., Smalley, I. J., Ujvári, G., Sümegi, P., Timar-Gabor, A., Veres, D., Sirocko, F., Vasiljević, D., Jary, Z., Svensson, A., Jović, V., Lehmkuhl, F., Kovács, J. & Svirčev, Z. 2015: Danube loess stratigraphy – towards a pan-European loess stratigraphic model. *Earth Science Reviews* 148, 228–258.
- Meijer, T. & Preece, R. C. 2000: A review of the occurrence of *Corbicula* in the Pleistocene of North-West Europe. *Geologie en Mijnbouw, Netherlands Journal of Geosciences* 79, 241–255.
- Meijs, E. P. M. 2002: Loess stratigraphy in Dutch and Belgian Limburg. *Eiszeitler und Gegenwart* 51, 114–130.
- Meijs, E. P. M., Van Peer, P. & De Warrimont, J.-P. 2012: Geomorphologic context and proposed chronostratigraphic position of Lower Palaeolithic artefacts from the Op de Schans pit near Kesselt (Belgium) to the west of Maastricht. *Geologie en Mijnbouw/Netherlands Journal of Geoscience* 91, 137–157.
- Moine, O., Antoine, P., Hatté, C., Landais, A., Mathieu, J., Prud'Homme, C. & Rousseau, D.-D. 2017: The impact of Last Glacial climate variability in west-European loess revealed by radiocarbon dating of fossil earthworm granules. *PNAS* 114, 6209–6214.
- Munaut, A. V. 1988: Etude palynologique. In Tuffreau, A. & Sommé, J. (eds.): *Le gisement Paléolithique Moyen de Biache-Saint-Vaast (Pas-de-Calais)*, vol. 21, 77–88. Mémoires de la Société Préhistorique Française.
- Past Interglacials Working Group of PAGES 2016: Interglacials of the last 800,000 years. *Reviews of Geophysics* 54, 162–219.
- Pecsi, M. 1990: Loess is not just the accumulation of dust. *Quaternary International* 7–8, 1–21.
- Pirson, S., Baele, J.-M., Balescu, S., Haesaerts, P., Juvigné, E., Meijs, E. & Spagna, P. 2018: Green amphibole distribution as a stratigraphic tool in loess sequences from Belgium: a review. *Quaternary International* 485, 183–198.
- Preece, R. C., Parfitt, S. A., Bridgland, D. R., Lewis, S. G., Rowe, P. J., Atkinson, T. C., Candy, I., Debenham, N. C., Penkman, K. E. H., Rhodes, E. J., Schwenninger, J.-L., Griffiths, H. I., Whittaker, J. E. & Gleed-Owen, C. 2007: Terrestrial environments during MIS 11: evidence from the Palaeolithic site at West Stow, Suffolk, UK. *Quaternary Science Reviews* 26, 1236–1300.
- Puisségur, J.-J. 1983: Faunes malacologiques pléistocènes de Normandie. In Lautridou, J. P. (ed.): *Le Quaternaire de Normandie*, 151–160. Département de Géologie, Université de Rouen, Rouen.
- Railsback, L. B., Gibbard, P. L., Head, M. J., Voarintsoa, N. R. G. & Toucanne, S. 2015: An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages. *Quaternary Science Reviews* 111, 94–106.
- Reille, M., de Beaulieu, J.-L., Svobodova, H., Andrieu-Ponel, V. & Goeyry, C. 2000: Pollen stratigraphy of the five last climatic cycles in a long continental sequence from Velay (Massif Central, France). *Journal of Quaternary Science* 15, 665–685.
- Rousseau, D.-D. & Puisségur, J.-J. 1988: Analyse de la malacofaune continentale. In Tuffreau, A. & Sommé, J. (eds.): *Le gisement paléolithique moyen de Biache-Saint-Vaast (Pas de Calais)*, 89–102. Mémoires de la Société préhistorique française 21.
- Rousseau, D.-D., Boers, N., Sima, A., Svensson, A., Bigler, M., Lagroix, F., Taylor, S. & Antoine, P. 2017: (MIS 3 & 2) millennial oscillations in Greenland dust and Eurasian aeolian records – a palaeosol perspective. *Quaternary Science Reviews* 169, 99–113.
- Rousseau, D.-D., Puisségur, J.-J. & Lécalle, F. 1992: West-European terrestrial mollusc assemblages of isotopic stage 11 (Middle Pleistocene): climatic implications. *Palaeogeography Palaeoclimatology Palaeoecology* 92, 15–29.
- Sadori, L., Koutsodendris, A., Panagiotopoulos, K., Masi, A., Bertini, A., Combourieu-Nebout, N., Francke, A., Kouli, K., Joannin, S., Mercuri, A.-M., Peyron, O., Torri, P., Wagner, B., Zanchetta, G., Sinopoli, G. & Donders, T. H. 2016: Pollen-based paleoenvironmental and paleoclimatic change at Lake Ohrid (south-eastern Europe) during the past 500 ka. *Biogeosciences* 13, 1423–1437.
- Schirmer, W. 2016: Late Pleistocene loess of the Lower Rhine. *Quaternary International* 411, 44–61.
- Scourse, J. D., Haapaniemi, A. I., Colmenero-Hidalgo, E., Peck, V. L., Hall, I. R., Austin, W. E. N., Knutz, P. C. & Zahn, R. 2009: Growth, dynamics and deglaciation of the last British-Irish ice sheet: the deep-sea ice-rafted detritus record. *Quaternary Science Reviews* 28, 3066–3084.
- Sejrup, H. P., Nygård, A., Hall, A. M. & Hafliðason, H. 2009: Middle and Late Weichselian (Devensian) glaciation history of south-western Norway, North Sea and eastern UK. *Quaternary Science Reviews* 28, 370–380.
- Siddal, M., Rohling, E. J., Almogi-Labin, A., Hemleben, C., Meischner, D., Schmelzer, I. & Smeed, D. A. 2003: Sea-level fluctuations during the last glacial cycle. *Nature* 423, 853–858.
- Smalley, I., O'Hara-Dhand, K., Wint, J., Machalett, B., Jary, Z. & Jefferson, I. 2009: Rivers and loess: the significance of long river transportation in the complex event-sequence approach to loess deposit formation. *Quaternary International* 198, 7–18.
- Sommé, J. 1978: Géomorphologie et lithostratigraphie du gisement paléolithique de Biache-Saint-Vaast (Pas-de-Calais). *Bulletin de l'Association française pour l'Etude du Quaternaire* 1–3, 27–67.
- Sommé, J., Fagnart, J. P., Léger, M., Munaut, A. V., Puisségur, J.-J. & Tuffreau, A. 1984: Terrasses fluviales du Pléistocène moyen en France septentrionale: signification dynamique et climatique. *Bulletin de l'Association française pour l'étude du Quaternaire* 1–3, 52–58.
- Sommé, J., Munaut, A. V., Puisségur, J.-J., Cunat-Bogé, N., Heyvaert, F. & Leplat, J. 1996: L'Eemien sous les formations fluviales weichséliennes et holocènes d'Erquinheim (Nord de la France) dans la plaine de La Lys. *Quaternaire* 7, 15–28.
- Timar-Gabor, A., Vandenberghe, D. A. G., Vasiliniuc, S., Panaoitu, C. E., Panaiotu, C. G., Dimofte, D. & Cosma, C. 2011: Optical dating of

- Romanian loess: a comparison between silt-sized and sand-sized quartz. *Quaternary International* 240, 62–70.
- Toucanne, S., Zaragosi, S., Bourillet, J. F., Cremer, M., Eynaud, F., Van Vliet-Lanoë, B., Penaud, A., Fontanier, C., Turon, J. L., Cortijo, E. & Gibbard, P. 2009: Timing of massive 'Fleuve Manche' discharges over the last 350 kyr: insights into the European Ice Sheet oscillations and the European drainage network from MIS 10 to 2. *Quaternary Science Reviews* 28, 1238–1256.
- Tuffreau, A. & Sommé, J. 1988: *Le gisement paléolithique moyen de Biache-Saint-Vaast (Pas de Calais)*. 340 pp. Mémoires de la Société préhistorique française 21.
- Tuffreau, A., Auguste, P., Balescu, S. & Bahain, J.-J. 2017: Gentelles-Le Mont de l'Évangile (département de la Somme, France): un site de plateau occupé de l'Acheuléen au Micoquien. *L'Anthropologie* 121, 394–427.
- Tuffreau, A., Lamotte, A., Antoine, P. & Parcy, J.-L. 1997: Le gisement acheuléen de la Ferme de l'Épinette (Somme, France). *Archäologisches Korrespondenzblatt* 27, 513–530.
- Urban, B. 2007: Interglacial pollen records from Schöningen, North Germany. In Sirocko, F., Claussen, M., Sanchez-Goni, M. F. & Litt, T. (eds.): *The Climate of the Past Interglacials*, 417–444. Developments in Quaternary Science 7. Elsevier Scientific Publishing, Amsterdam.
- Van den Bogaard, P. & Schmincke, H. U. 1990: Die Entwicklungsgeschichte des Mittelrheinraums und die Eruptionsgeschichte des Ost-Eifel-Vulkanfeldes. In Schirmer, W. (ed.): *Rheingeschichte Zwischen Mosel und Maas*, 166–190. Deuqua Führer 1, Deutsche Quartärvereinigung, Annover.
- Van Vliet-Lanoë, B. 1989: Dynamique périglaciaire actuelle et passée: apport de l'étude micromorphologique et de l'expérimentation. *Bulletin de l'Association française pour l'étude du Quaternaire* 24, 113–132.
- Wendt, K. A., Li, X., Edwards, R. L., Cheng, H. & Spötl, C. 2021: Precise timing of MIS 7 substages from the Austrian Alps. *Climate of the Past* 17, 1443–1454.

Supporting Information

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

Data S1. Detailed description of the main LPS sequences (Figs 6, 8, 9).