



HAL
open science

The last 750 ka in loess–palaeosol sequences from northern France: environmental background and dating of the western European Palaeolithic

Pierre Antoine, Sylvie Coutard, Jean-Jacques Bahain, Jean-luc Locht, David Hérison, Emilie Goval

► To cite this version:

Pierre Antoine, Sylvie Coutard, Jean-Jacques Bahain, Jean-luc Locht, David Hérison, et al.. The last 750 ka in loess–palaeosol sequences from northern France: environmental background and dating of the western European Palaeolithic. *Journal of Quaternary Science*, 2021, Special Issue: Pleistocene geoarchaeology and palaeoenvironments in European loess November 2021, 36 (8), pp.1293-1310. 10.1002/jqs.3281 . hal-03164133

HAL Id: hal-03164133

<https://hal.science/hal-03164133v1>

Submitted on 7 Dec 2021

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.

The last 750 ka in loess–palaeosol sequences from northern France: environmental background and dating of the western European Palaeolithic

PIERRE ANTOINE,^{1*} SYLVIE COUTARD,^{1,2} JEAN-JACQUES BAHAIN,³ JEAN-LUC LOCHT,^{1,2} DAVID HÉRISSON⁴ and EMILIE GOVAL⁵

¹UMR 8591 CNRS-Université Paris I & UPEC, Laboratoire de Géographie Physique, Environnements quaternaires et actuels, Meudon, France

²INRAP Hauts-de-France, Glisy, France

³UMR 7194 Histoire naturelle de l'Homme préhistorique HNHP, MNHN-CNRS-UPVD - IPH, Paris, France

⁴CNRS-UMR7041, MAE, 21 A. de l'Université, Nanterre, France

⁵Service Régional de l'Archéologie des Hauts-de-France, Amiens, France

Received 8 October 2020; Revised 23 January 2021; Accepted 27 January 2021

ABSTRACT: This study presents an overview of Middle Pleistocene loess–palaeosol sequences (LPS) in northern France and discusses the palaeoclimatic significance of the pedosedimentary record in the context of western European LPS and of global climatic cycles for the last 750 ka. In this area, the oldest loess deposits (early Middle Pleistocene) are preserved in sedimentary traps (leeward scarps of fluvial terraces and dissolution sinkholes). They result from local deflation processes reworking Pleistocene sandy fluvial deposits or relicts of Tertiary sands. A large extension of typical calcareous loess over the landscape, the *Loess Revolution*, is then observed during MIS 6, with heavy mineral assemblages testifying to long-distance transport from the polar desert area of the dried eastern Channel. A correlation scheme is proposed between the global records of northern France in continental environments and both global palaeoclimatic records and other main western European LPS. After 30 years of research, northern France LPS stand as a fundamental archive of the impact of interglacial–glacial climatic cycles as well as millennial events. Finally, these works provide a robust chronoclimatic framework for the study of the western European Late Acheulean and Middle Palaeolithic and for the relative dating of the various fluvial terraces that they fossilise. © 2021 John Wiley & Sons, Ltd.

KEYWORDS: loess; Palaeolithic; palaeosols; Pleistocene; western Europe

Introduction

On the scale of the northern hemisphere, loess deposits represent the largest and thickest correlative formations of the successive glacial stages of the Quaternary in the temperate latitudes (Pécsi, 1990) and especially in the great European plains (Haase *et al.*, 2007; Lehmkuhl *et al.*, 2016). In this large area (Fig. 1) loess–palaeosol sequences (LPS) can reach 40 to 60 m thick near the major rivers of central Europe like 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). Such LPS have long been recognised 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 climatic signal evidenced from the pedostratigraphic analysis of the LPS, then quantified by magnetic susceptibility and calibrated by palaeomagnetism, has been parallelised with deep sea records (Lisiecki and Raymo, 2005). This approach has been reinforced for 20 years by ⁴⁰Ar/³⁹Ar dating of tephra layers enclosed in these LPS (Van den Bogaard and Schmincke, 1990; Horvath, 2001; Fitzsimmons *et al.*, 2013; Jensen *et al.*, 2016) or more generally by luminescence dating of

silt particles from loess (Frechen and Dodonov, 1998; Marković *et al.*, 2015; Lomax *et al.*, 2019).

In the main European River basins, the cyclostratigraphic approach of LPS preserved as cover deposits of alluvial terraces has long been considered as a reliable tool for relative dating of the underlying fluvial deposits as, for example, in the terrace systems of the Danube (Kukla, 1977), the Rhine (Brunnacker *et al.*, 1975, 1982), the Somme and the Seine rivers (Bourdier *et al.*, 1974; Lautridou *et al.*, 1985, 1999; Antoine *et al.*, 2000, 2003a; Cliquet *et al.*, 2009; Antoine, 2019) (Fig. 2). In these last two river valleys, reference LPS such as Saint-Pierre-lès-Elbeuf (Lautridou, 1985; Cliquet *et al.*, 2009) or Cagny-la-Garenne (Haesaerts *et al.*, 1984; Antoine, 1990) exhibit a pedosedimentary record starting in the Middle Pleistocene around 400 ka ago. In the Seine River, older LPS likely going back to the Early Cromerian have been locally evidenced in deep sinkholes in the chalk substratum (Iville V & VI and Bosc-Hue VII: Lautridou, 1985). In the north of France, a few sequences showing up to three interglacial soils have been described at la Longueville by Sommé (1977) but are no longer accessible. Finally, in the Somme Valley (Fig. 2), well known since the end of the 19th century for its major role in the emergence of Quaternary geology and prehistory (see, for example, Bahain and Antoine, 2019), ‘old loess’ has been already mentioned at the beginning of the 20th century on the very high terrace (Commont, 1909).

During the last 30 years, an unprecedented development of rescue archaeological excavations has led to the discovery of

*Correspondence: P Antoine, as above.
E-mail: pierre.antoine@lgp.cnrs.fr

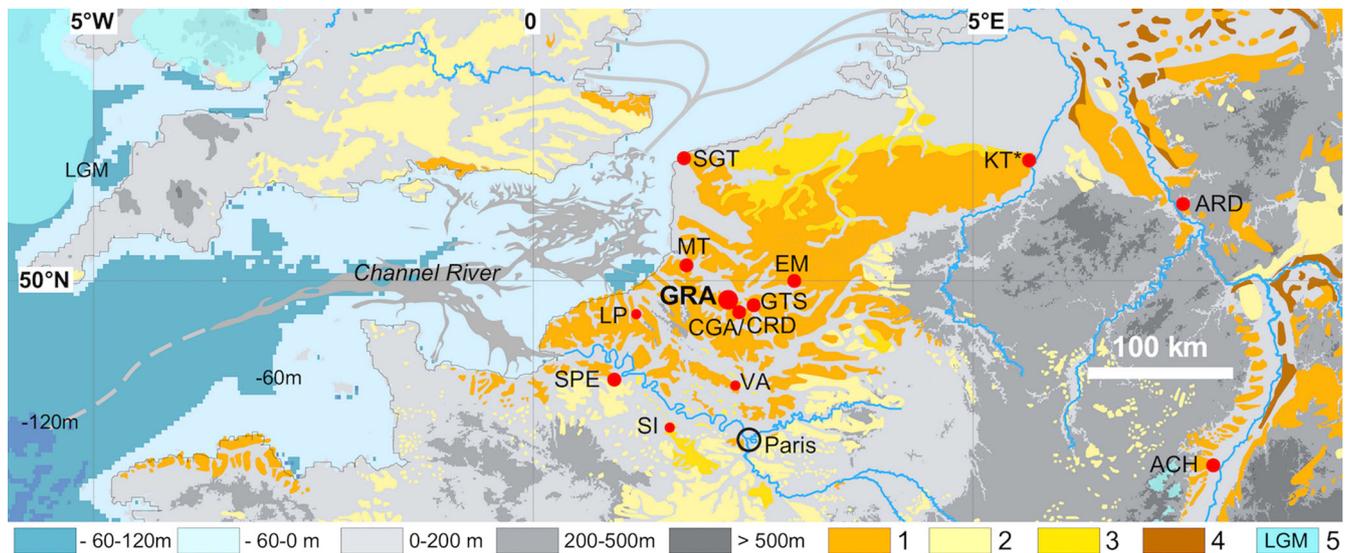


Figure 1. Location of the main reference pedosedimentary sequences in north-west Europe on a map of the western part of the European loess belt (from Antoine *et al.*, 2013, modified). 1) Loess (>1 m); 2) Loess (<1 m); 3) Sandy loess (>1 m); 4) Aeolian sand; Kesselt* (sites of: Nelissen, Op de Schans, Canal Albert West). Sites: GRA: Grâce-Autoroute, CGA: Cagny-la-Garenne, CRD: Cagny-Rocade, GTS: Gentelles, EM: Etrécourt-Manancourt, MT: Mautort, VA: Villiers-Adam, SI: Saint-Illiers, SPE: Saint-Pierre-lès-Elbeuf, SGT: Sangatte, KT: Kesselt, ARD: Ariendorf, ACH: Achenheim. [Color figure can be viewed at wileyonlinelibrary.com]

new reference LPS in the Somme Basin (Fig. 1): Mautort (Antoine, 1994; Antoine *et al.*, 2000); Grâce-Autoroute (Antoine *et al.*, 2003a, 2020) (Fig. 3A); Cagny-Rocade (Tuffreau *et al.*, 1997; Antoine *et al.*, 2000) (Fig. 3B); Gentelles (Tuffreau *et al.*, 2017) and lastly Etrécourt-Manancourt (Coutard *et al.*, 2018).

The objective of this paper is to present an overview of these Middle Pleistocene LPS in northern France with the following aims:

- (1) To discuss the palaeoclimatic significance of the summarised pedosedimentary record for this area in the context of the main western European LPS and of global climatic cycles for the last 750 ka.
- (2) To provide reliable chronoclimatic and dating frames for the western European Lower and Middle Palaeolithic.

To achieve these goals, this contribution will start with a review of three of the most complete sequences of the Somme Basin: Grâce-Autoroute, Cagny-Rocade and Etrécourt-Manancourt (Fig. 1). Other well-known LPS of northern France formerly studied and published in detail, such as Cagny-la-Garenne (Bourdier *et al.*, 1974; Haesaerts and Dupuis, 1986; Antoine, 1990) or Saint-Pierre-lès-Elbeuf (Normandy: Lautridou, 1985, Cliquet *et al.*, 2009), will be used as comparison sequences in the discussion. Finally, a short summary of the last interglacial-glacial record, which represents a fundamental reference for the interpretation of more condensed pedosedimentary records of the older cycles, will precede the discussion.

Middle Pleistocene pedosedimentary sequences from the Somme Basin

Grâce-Autoroute reference record

The long section of Grâce-Autoroute, evidenced in 1994 during the excavation of the A-16 Paris-Amiens-Boulogne motorway cutting, exhibits a thick LPS overlying an alluvial formation corresponding to the oldest unit of the Quaternary stepped terrace system of the River Somme (Alluvial Formation X or Grâce-Autoroute, relative altitude: + 55 m; Fig. 2). This fluvial formation, dated by electron spin resonance (ESR) and ESR/U-series from 1 to 0.9 Ma ago (Bahain *et al.*, 2007, 2010),

is covered by an LPS exposed by roadworks in a trench about 250 m in length and corresponding to a total thickness of more than 20 m (Antoine *et al.*, 2020).

The Grâce-Autoroute LPS is made up by superimposed lenticular slope sub-sequences (silty sands then loess), separated by erosion discordances. The pedosedimentary and cyclostratigraphic approach leads to the distinction of eight successive glacial–interglacial cycles. Each sub-sequence is terminated by a brown leached palaeosol horizon (soils Grâce I to Grâce VII) (Figs. 3A and 4). Combined with quartz-ESR ages obtained from the underlying alluvial sands, it is possible to propose a correlation with global palaeoclimatic records and the allocation of the oldest slope deposits to the beginning of the Cromerian Complex (MIS 18).

At Grâce-Autoroute, as generally in the Somme Valley, most of the sediments forming the Middle Pleistocene slope sequence result from short-distance transport of sandy silts reworked from the alluvial plain by aeolian processes. In addition, other sources of fine sands are present in the direct environment and could have been reworked by hillwash processes. This includes marine Tertiary sands (Thanetian), preserved as relict mounds scattered on the plateau overlooking the Somme Valley, as well as weathered Lower Pleistocene fluvial sediments bordering the plateau (plateaux gravels, Fig. 2). Typical (allochthonous) loess only occurs during the penultimate cycle (MIS 6) and later.

The Grâce-Autoroute slope sequence is the longest sub-continuous record of the Middle Pleistocene highlighted to date both in northern France and western Europe (Antoine *et al.*, 2020). It therefore represents the central reference, allowing robust correlations with the other long LPS of north-western Europe like Saint-Pierre-lès-Elbeuf, Kesselt, Achenheim or Ariendorf.

Summary of the pedosedimentary record

The LPS of Grâce-Autoroute is composed of sandy to sandy-silty deposits, most often laminated, then of more clearly loessic units, interbedded with seven, more or less truncated, palaeosols of interglacial rank (Bt horizons of leached brown soils). It can be divided into two sub-sequences separated by a

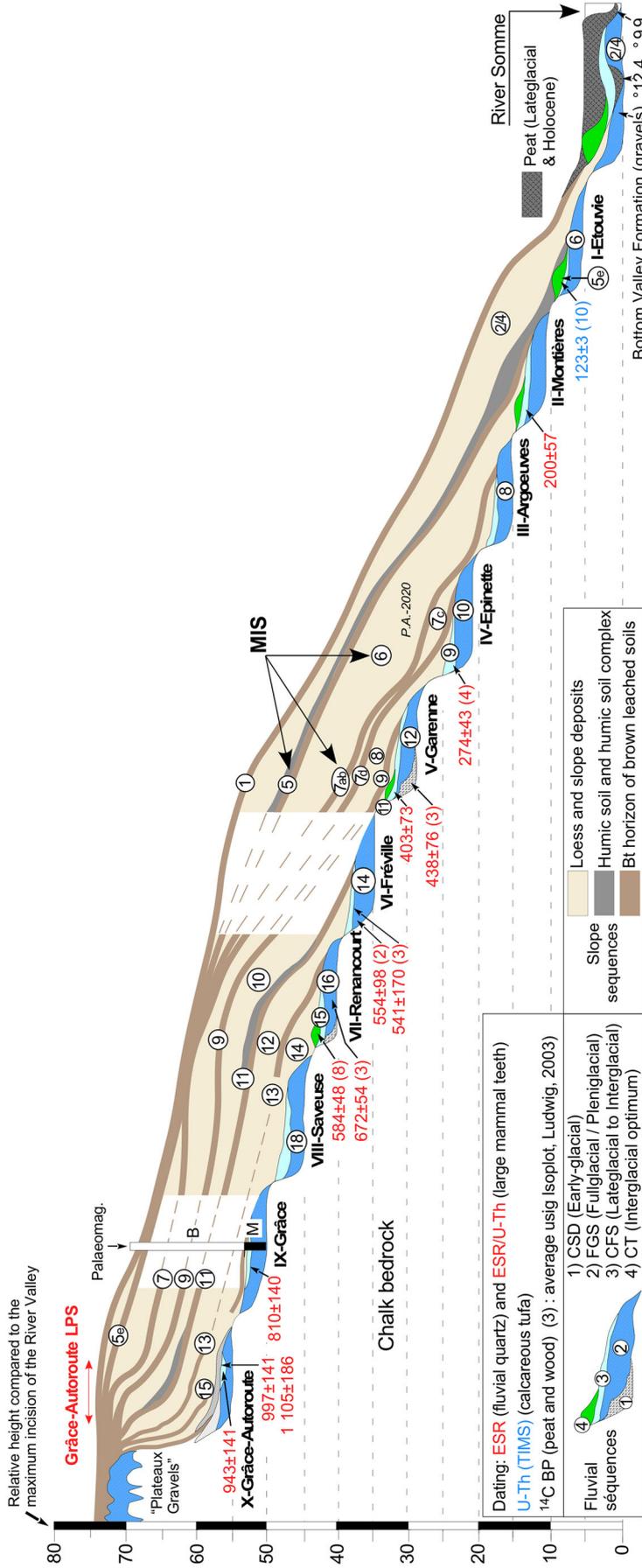


Figure 2. Global transect of the stepped terrace system of the Somme Basin and of its LPS cover sequences (according to Antoine *et al.*, 2007, 2019, modified). Fluvial sequences CSD: Coarse slope deposits including chalk and flint blocks and fluvial silt lenses; FGS: Periglacial fluvial sands and gravels (braided river system); CFS: Calcareous fluvial silts (overbank deposits linked to a single meandering fluvial system); CT: Calcareous tufa. [Color figure can be viewed at wileyonlinelibrary.com]



Figure 3. (A) General view of the south-west part of the large Grâce-Autoroute cross-section between test pits S1 and S3. (B) Cagny-Rocade 1995 general view of the LPS sequence backing onto the chalk talus to the south. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

strong slope erosion event preceding the deposition of thick laminated silty sands (Fig. 4).

Sub-sequence 1 is represented by the first three pedosedimentary cycles (H, G, F) each time terminated by interglacial soils named Grâce VII, VI and V (cumulative thickness: ≈ 5 m). This part of the LPS is exclusively preserved at the bottom of the chalky slope representing the left bank of the former river Somme Valley. Sub-sequence 1 begins with the deposition of aeolian silty sands representing the sedimentary matrix in

which the oldest interglacial soil horizon (Bt horizon) named Grâce VII is formed (Cycle H).

The subsequent cycle (Cycle G) begins with an intense erosive event, including gullies formed by concentrated hillwash processes, resulting in a truncation of the underlying upper horizons of Grâce VII interglacial soil. The formation of this sequence was favoured by the occurrence of the steep chalky slope of the former riverbank (Fig. 3A). The sediments originate from short-distance reworking

mainly by runoff (and aeolian processes?) of former fluvial deposits from the plateaux gravels formation and of Tertiary sand patches still abundant on the overlooking plateau edge at that time. Cycle G then ends with the formation of the interglacial brown leached soil horizon (Bt) Grâce VI.

The beginning of the third cycle (Cycle F) is again marked by a phase of erosion by hillwash processes on the slope, which has severely truncated Grâce VI interglacial soil. This was followed by the deposition of a new unit of silty sands and ends with the formation of a new brown leached soil Bt horizon of interglacial rank named Grâce V.

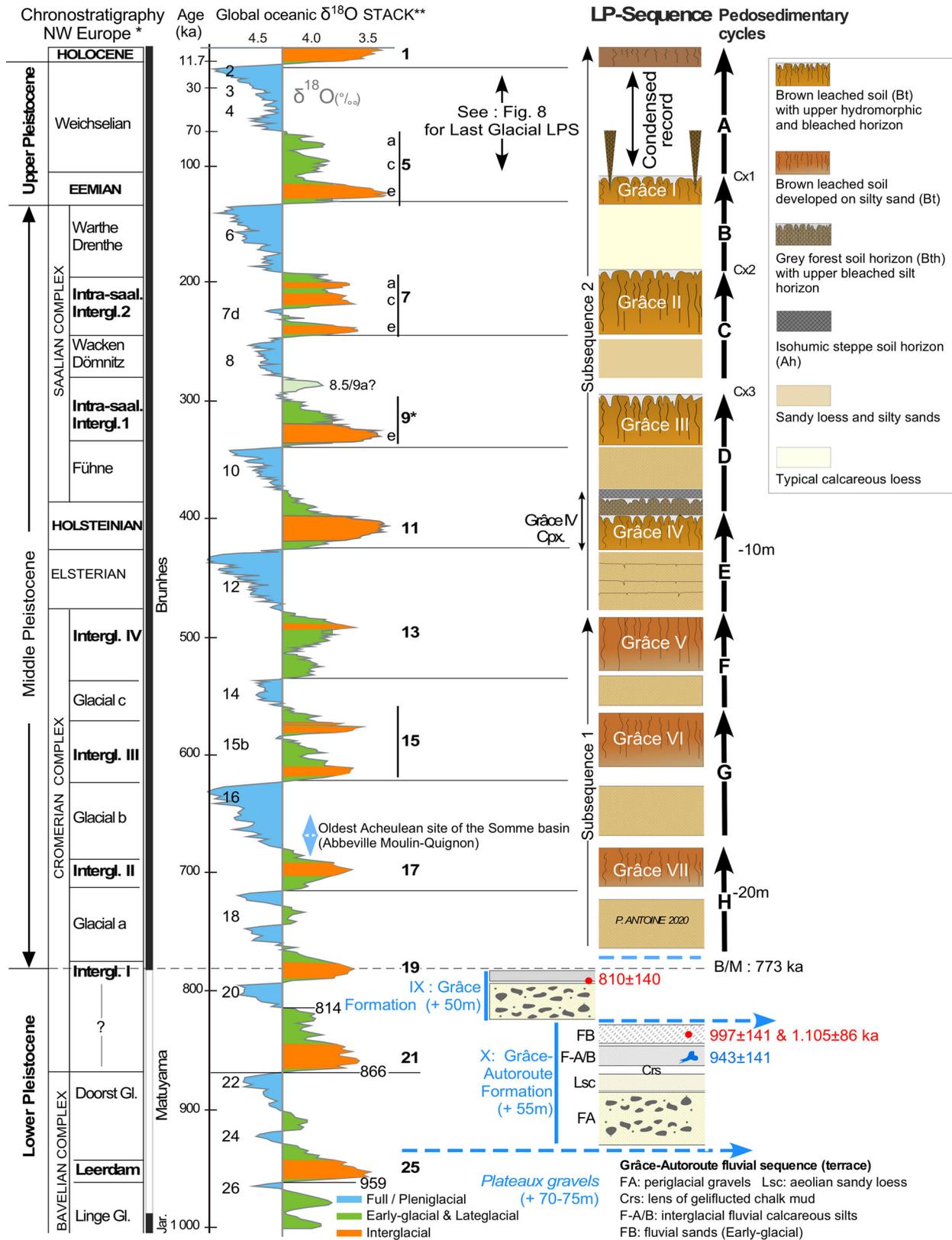


Figure 4. Grâces-Autoroute: summarised sequence, pedosedimentary cycles and correlation proposal with isotopic stages and chronostratigraphy of north-western Europe. * Stratigraphy of north-western Europe (Cohen and Gibbard, 2020). ** Generalised curve of the oceanic $\delta^{18}\text{O}$ variations SPECMAP (Lisiecki & Raymo, 2005; Railsback *et al.*, 2015). [Color figure can be viewed at wileyonlinelibrary.com]

Sub-sequence 2, formed by the following five cycles (E, D, C, B, A), begins with a thick unit of laminated sandy silts and then develops as a succession of large and discordant lenses separated by erosion discontinuities locally underlined by thin gravel beds of frost-shattered flints (cumulative thickness: ≈ 15 m).

At the start of Cycle E, an intense hillwash erosion period resulted in the formation, over more than 200 m in length, of an erosive contact, discordant on all previous deposits. This event was followed by the deposition of a thick sequence (5 to 6 m) of finely laminated silty sands evolving towards more homogeneous sandy loess in the upper 1.5 m. Bulk grain size of these sandy silts is dominated by fine sands ($\geq 60\%$) but the deposit incorporates silty loessic layers (≤ 1 cm) for which an aeolian origin is likely (grain size ratio > 1). The deposition of this unit filled a large part of the space remaining in the original sedimentary trap explaining the much lower thickness of the following cycles. The pedosedimentary cycle ends with the formation of an interglacial leached brown soil horizon (Sol Grâce IV). The latter appears better preserved than the previous horizons and shows deep bioturbation tracks by earthworms and a freeze–thaw structure much more typical for this area of the soils from the Middle Pleistocene (Coutard *et al.*, 2019) or of the Last Interglacial (Antoine *et al.*, 2016). Furthermore, the soil complex formed by the succession of sub-units represents an important pedomorphological marker-horizon in the stratigraphy of Grâce-Autoroute (Grâce IV Soil Complex, Fig. 4).

Indeed, if the Grâce V to Grâce VII soils are made up of strongly truncated Bt horizons of brown leached soils, a definitely much more complete pedosedimentary record appears at the base of Cycle D. Above a classic Bt horizon of brown leached soil attributable to interglacial temperate oceanic conditions (Grâce IV), we observe the development of a grey forest soil on colluvial deposits corresponding to still temperate but much more continental climatic conditions, comparable to the climate described for the Weichselian Early Glacial, and marking the boundary between Cycles E and D. Then an isohumic soil formed in a more continental

environment and finally a gley, testifying to the transition to a periglacial environment. During Cycle D, typically periglacial conditions are shown by the deposition of laminated hillwashed sands including thin flint gravel beds, then by homogeneous sandy silts (fine sands: $\approx 40\%$), the deposition of which is more clearly dominated by aeolian processes (a strong rise in the ratio between silt and sand percentages). A new interglacial brown leached soil, marking the upper boundary of Cycle D, is then overprinted on the former sandy loess. This typical Bt horizon, showing clay coatings on biopores, earthworm biotubules and diapause chambers, is named Grâce III. In its upper part, a slightly more greyish clayey horizon likely corresponds to a former humic horizon strongly degraded and partly reworked by colluvial processes.

Cycle C, preserved in the form of a lens less than 2 m thick, is separated from the previous cycle by a markedly erosive discordance underlain by a flint gravel bed including numerous frost-shattered fragments (Cx3). The deposition of the overlying loessic deposit showing scattered laminations at the lower part testifies to a new cold period. A sharp drop in sand inputs (fine sand $< 2\%$) and a concomitant increase in coarse silt proportion, typical of loess are then observed in this deposit. The following interglacial period is recorded by a new Bt horizon of brown leached soil with well-preserved clay coatings on biopores and a marked prismatic to lamellar structure; it is named Grâce II soil.

The penultimate cycle (Cycle B) is distinguished by a more significant development than the previous one. It starts with a laminated sands bed, witness to the erosion of the top of the Grâce II Bt horizon, followed by the deposition of non-calcareous loess characterised by a drop in sand percentages and a strong rise in coarse silt fraction corresponding to typical loess deposits (ratio: coarse silt/fine silt+clay > 1). Cycle B ends with the formation of a Last Interglacial brown leached soil horizon (Bt horizon) named Grâce I soil. The decalcification processes linked to the Grâce I interglacial soil has deeply penetrated the underlying loess and fully leached the calcareous particles (about 15% of the sediment) typical for loess from the Penultimate Glacial period (Antoine *et al.*, 2016).

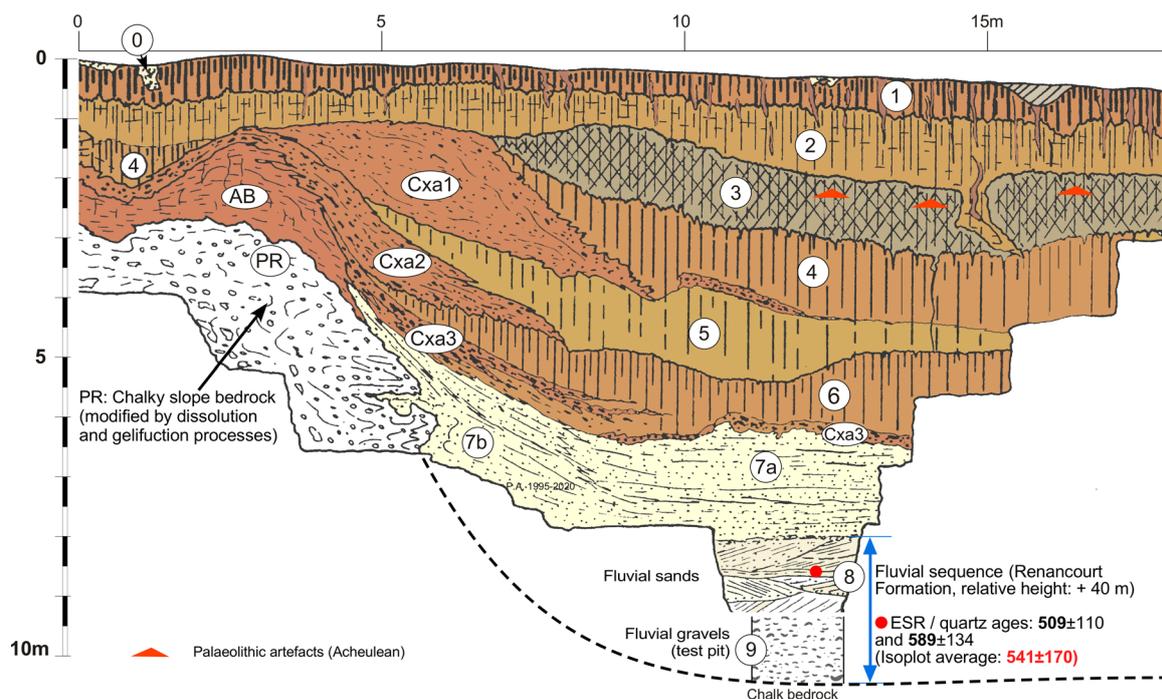


Figure 5. Cagny-Rocade: cross-section showing the LPS sequence overlying the fluvial deposits of alluvial formation VII. [Color figure can be viewed at wileyonlinelibrary.com]

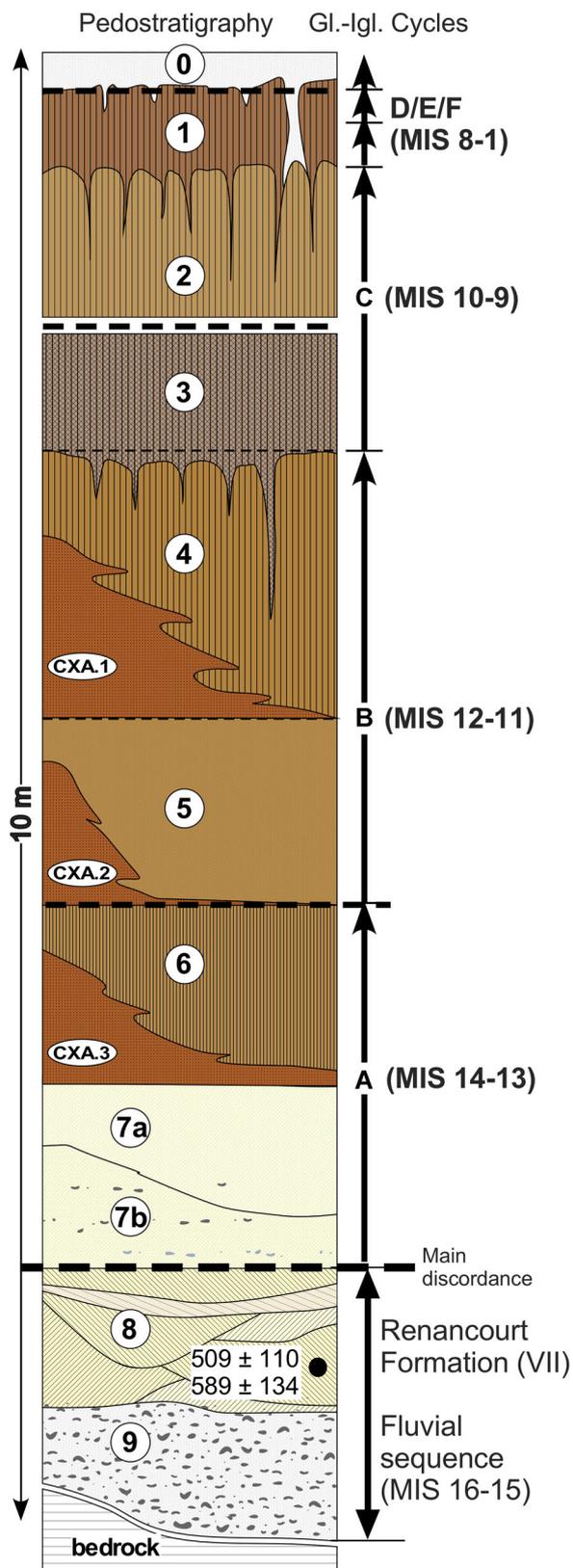


Figure 6. Cagny-Rocade: summarised pedosedimentary sequence, ESR dating and chronoclimatic interpretation. [Color figure can be viewed at wileyonlinelibrary.com]

A comparison with other regional sequences, where this palaeosol is better preserved, shows that at Grâce-Autoroute the Grâce I soil was strongly truncated by multiple erosion phases that marked the Last Glacial period on the slope. A network of fine frost wedges with clayey-humic infilling (soil-veins) penetrating this Bt horizon over more than 1.5 m

on average was observed, as in several other profiles of the Somme (Saint-Acheul, Antoine, 1990; Cagny-Rocade, Tuffreau *et al.*, 1997; Sourdon, Antoine, 1990), where it constitutes the signature of an extremely condensed budget of the Weichselian Early Glacial chronoclimatic interval (≈ 112 –70 ka ago). Finally, the strong prismatic to polyhedral structure of the Bt horizon of the Grâce I soil indicates an intense impact of deep freeze–thaw processes during the Last Glacial. The formation of the Bt horizon is therefore essentially attributable to the Last Interglacial (Eemian), i.e. to isotopic sub-stage 5e. Grâce I soil can be correlated with the soils recording the Last Interglacial as Mautort I in the Somme (Antoine, 1994), Rocourt in Belgium (Gullentops, 1954) or Elbeuf I in Normandy (Lautridou, 1985).

Finally, in the profile of Grâce-Autoroute, the pedosedimentary balance attributable to the last glacial–interglacial cycle (Weichselian–Holocene; Cycle A) is particularly reduced (≤ 1 m), compared with the 5 to 6 m of calcareous loess that are preserved, for the same period, at the bottom of the slope of the Somme Valley exposed to the north-east (Antoine *et al.*, 2016; 2020), and more generally in northern France (Antoine *et al.*, 2016). This is the result of the final filling of the sediment trap structure of the Grâce-Autoroute formation and the formation of a large erosion surface *glacis* exposed to wind deflation and hillwash processes at the end of the Penultimate Glacial.

Cagny-Rocade

The sequence of Cagny-Rocade (Fig. 1) was observed during road-building work on the left bank of the lower Avre River, about 3 km upstream of its confluence with the Somme (9.5 km to the east–south-east of the Grâce-Autoroute section). Exposed to the east–north-east, the LPS (≈ 8 m thick) is here preserved in a sedimentary trap formed by the junction between the chalky slope and the surface of the fluvial deposits of a former ‘high terrace’ of the Avre, overlying the chalk bedrock at 58–59 m (Figs. 3B, 5). According to its relative altitude (+ 40 m), the fluvial sequence is allocated to alluvial formation VII of the Somme system (Fig. 2), dating from the succession of isotopic stages 16 and 15 (Antoine *et al.*, 2000). At Cagny-Rocade, two ESR dates were obtained on quartz grains extracted from fluvial sands (509 ± 110 and 589 ± 134 ka; Bahain *et al.*, 2007) and support this interpretation. It is also in agreement with the strong difference in relative altitude (10 m) separating the bedrock steps at Cagny-Rocade and at Cagny-la-Garenne where fluvial deposits were dated to the MIS 12–11 succession (Laurent *et al.*, 1994; Antoine *et al.*, 2007; Bahain *et al.*, 2007).

Description of the pedosedimentary record (Figs. 5 and 6)

The oldest pedosedimentary cycle (Cycle A) begins with the deposition of laminated sandy deposits (units 7a–b), the facies and geometry of which both argue for a strong input of Tertiary sands reworked by hillwash processes from the slope (Fig. 5). The deposition of these sandy slope sediments indicates a first marked climatic deterioration following the lateral shift of the river and then the incision of a new bedrock step. This event was followed by the deposition of a lens of clayey and variably sized flint gravels resulting from the reworking by periglacial processes of former weathered fluvial terrace sediments preserved on the chalk plateau above the site (unit Cxa3). This first cold period ends with the deposition of sandy-clayey silts in which was developed the first typical Bt horizon of interglacial brown leached soil of the sequence (unit 6, MIS 13).

The next glacial–interglacial cycle (Cycle B) started with a strong climatic degradation, first underlined by the erosion of the upper part of the underlying Bt horizon, and then by the deposition of a complex sequence of slope deposits: soliflucted clayey gravels (Cxa2), a sandy colluvial unit (unit 5), a lens of clayey gravels (Cxa1) and finally a new lens of sandy silts (matrix of unit 4). The formation of a typical leached brown soil with thick clay coatings represented by an orange-brown Bt horizon (unit 4) with deep clay illuviation on biopores and earthworm biotubules is indicative of the interglacial period that marks the end of slope Cycle B.

After a new climatic deterioration, marked by greyish hydromorphic patches and small frost cracks, a third cycle (Cycle C) began with the deposition of sandy colluvium (unit 3), including reworked small soil nodules from unit 4. This unit, however, shows superimposed pedogenetic features identifying a clayey–humic soil (grey forest soil or Greyzem), overprinted by deep seasonal frost processes (strong polyhedral to thick lamellar structure with white silt coatings on aggregate surfaces, numerous Fe–Mn concretions and degradation tracks of organic matter). According to its palaeopedological features, and by comparison with the pedosedimentary evolution evidenced for the Weichselian Early Glacial, unit 3 would therefore point to a boreal forest environment associated with a cool continental climate and strong seasonal contrasts (Antoine *et al.* 1994; 2016). The next step in the climatic deterioration is recorded by the formation of large frost cracks (former ice wedges?) and then by concentrated hillwash erosion gullies (channels at the base of 2), followed by the deposition of a sandy loess with scattered small flint gravel. The end of Cycle C is marked by the development of a new interglacial Bt horizon (unit 2). However, by the end of this stage the initial sedimentary trap is almost totally filled. The uppermost part of the sequence is represented by a complex succession of pedogenesis superimposed in a thin sequence of loessic deposits that are difficult to distinguish despite the presence of gravel layers indicating the main erosive hiatuses.

In this part of the sequence, the strongly polygenetic interglacial soil of unit 1 (deep clay illuviation made by a succession of various clay coatings) seems to correspond to at least three superimposed cycles (D/E/F). At the top, the last glacial–interglacial cycle is marked only by a thick and cryoturbated gravel layer including numerous frost-shattered flints and by a final phase of clay illuviation overprinted in the topsoil Bt horizon (unit 0).

Finally, we note that the characteristics of the fine frost cracks penetrating unit 1 and unit 2 are fairly typical of the soil-vein networks marking the end of the Weichselian Early Glacial in plateau positions or in slope sequences where Last Glacial sedimentation is poorly represented (as in Grâce-Autoroute). We therefore interpret the polygenetic Bt horizon of unit 1 as representing the superimposition of multiple pedogenesis corresponding to the last three interglacial periods (MIS 7, 5e and 1). According to this reasoning, unit 2, whose pedogenetic features are less marked, would represent the pedosedimentary balance of Cycle C, correlated with the succession of MIS 10 and 9. The Cagny-Rocade LPS thus likely includes the record of six pedosedimentary glacial–interglacial cycles in good accordance with both the position of the alluvial formation within the Somme system and the available ESR ages around 600–550 ka ago (Bahain *et al.*, 2007) (Fig. 6).

Finally, the interpretation of this sequence allows its correlation with the reference sequence of Grâce-Autoroute where the Grâce IV Soil Complex, allocated to MIS 11 and early MIS 10, shows a pedosedimentary record comparable

with the succession of units 4 and 3 of Cagny-Rocade and occurring in the same stratigraphic position.

Etricourt-Manancourt

Another loess–palaeosol sequence uncovered during an archaeological rescue excavation at Etricourt-Manancourt integrates several Palaeolithic layers, including an Acheulean layer dated by thermoluminescence (TL) on heated flints around 300–280 ka ago (late MIS 9) (Hérisson *et al.*, 2016, Coutard *et al.*, 2018) (Fig. 7). The archaeological excavation, located on the slope of a dry valley, was opened on more than 4500 m² and led to the discovery of two deep sinkholes developed in the chalk bedrock. The bottom of the deepest one is located more than 11 m from the surface of the topsoil and 5 m below the average chalk surface. The study of four reference profiles and their correlation using well-defined pedological marker levels led to the definition of a ≈12 m thick cumulative loess–palaeosol succession including 18 main stratigraphic units and corresponding to five stacked glacial–interglacial cycles. This approach allowed the construction of the pedosedimentary sequence of the Etricourt site.

The Etricourt sequence includes five luvisols (units 17, 14, 8a, 8b and 5), each testifying for full interglacial conditions. They are respectively allocated to MIS 11 (unit 17), MIS 9 (unit 14), to the two warm sub-stages of the MIS 7 interglacial complex (units 8b and 8a) and finally to MIS 5e (unit 5). The pedosedimentary records corresponding to MIS 9 and MIS 5 are represented by well-developed pedocomplexes corresponding to the superimposition of a truncated Luvisol and a humic soil complex including a grey forest soil (Greyzem).

Description of the pedosedimentary record

In the lower part of the sequence, a Luvisol (unit 14) is developed on loessic deposits. This soil is attributed to MIS 9e, the only sub-stage of MIS 9 that was sufficiently warm and long for the formation of an interglacial soil. The truncation of this Bt horizon (unit 14) and its degradation by hydromorphy and solifluction, indicate a phase of climatic degradation following the interglacial optimum, which could be correlated with sub-stage 9d. The ‘Lower Humic Soil Complex’ or Etricourt Soil Complex (ESC) begins then with a thick layer of dark clayey silts including scattered flint gravels (unit 13). It is characterised by a strong increase in total organic carbon (TOC) concentrations (0.18%), compared with the underlying Bt horizon, and by important biological activity indicated by numerous earthworm chambers (diapause?), partially filled with clayey pellets. Two types of clay coatings are superimposed within this soil unit: the first corresponds to light brown to orange clay coatings and the second to brownish red to blackish micro-laminated clay coatings. The last feature is typical of grey forest soils (Greyzems), a soil type today associated with forest-steppe environments and continental cool climates. The overlying horizon (unit 12), in which is preserved the Acheulean level HUD, is represented by a compacted grey-brownish loam showing a marked banded fabric of cryogenic origin. However, the lithic artefacts are well preserved and not gelifRACTED.

This Acheulean level has been dated to around 288 ± 21 ka ago using TL on heated flints (mean of three TL ages). The overlying dark brown horizon (11) is then characterised by a strong biological activity attested by large burrows and a peak in TOC values (0.20%) indicating a typical humic steppe soil (Ah) horizon, likely of the Chernosol type. According to these palaeo-pedological data, the ESC thus exhibits a progressive transition in environments from continental forest to forested

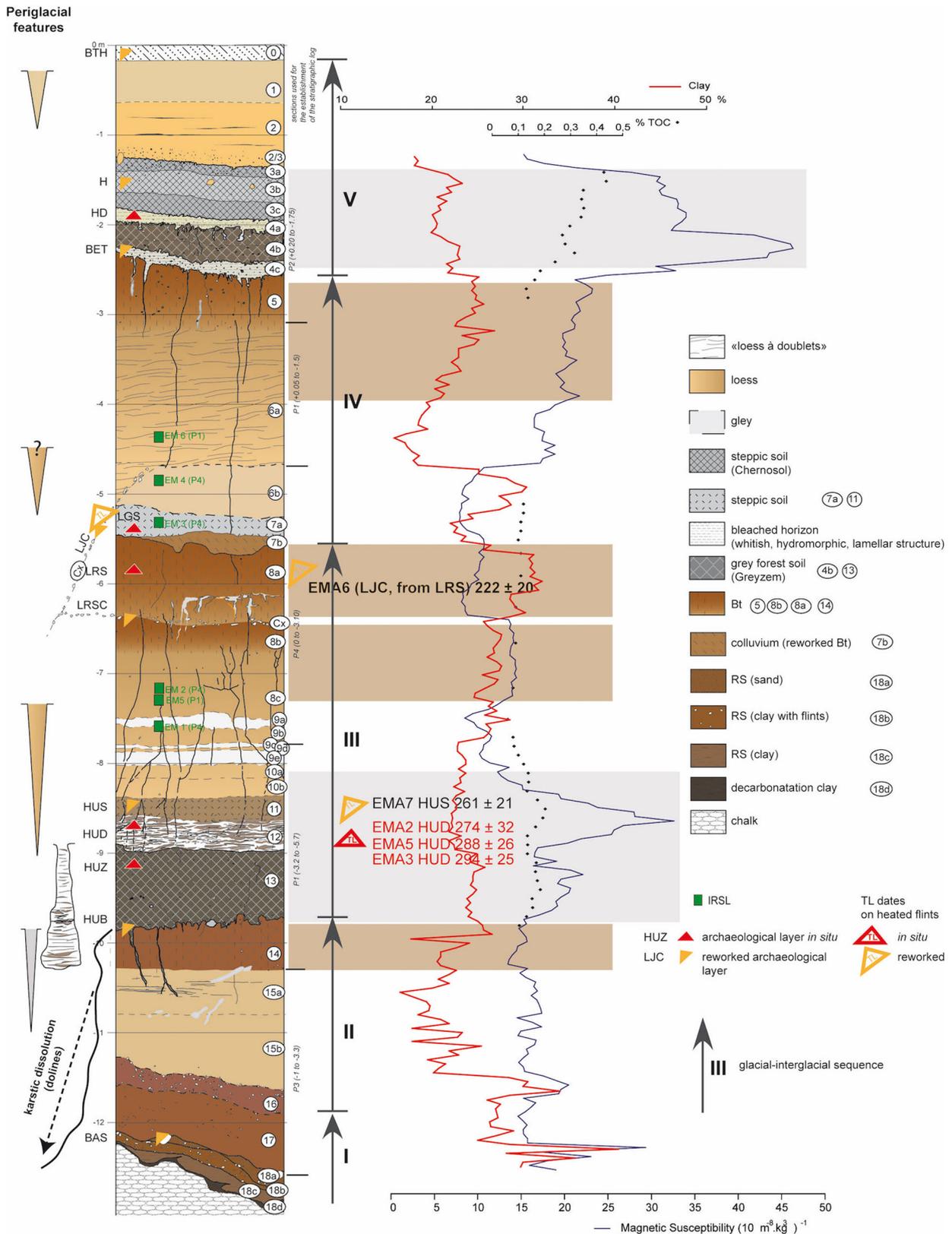


Figure 7. Etricourt-Manancourt (Somme): Synthetic log with pedosedimentary cycles, analytical results, TL ages on heated flints and archaeological layers (after Coutard *et al.*, 2018, modified). [Color figure can be viewed at wileyonlinelibrary.com]

steppe or steppe associated with a progressive climatic degradation directly following an interglacial stage (early glacial phase). According to both the location of the soil complex within the full sequence and TL dating results, this phase is allocated to the transition between MIS 9 and MIS 8.

Within the ESC there is an indication that an intense frost episode is responsible for the banding of unit 12. Since the

lithic artefacts from HUD are not gelifracted, this episode of freeze–thaw must have occurred after the burial of the Palaeolithic artefacts. The following sequence of events may thus be proposed: (1) erosion and degradation of the interglacial Bt horizon (unit 14) at the end of MIS 9e and during 9d; (2) formation of unit 13 during MIS 9c (HUZ occupation); (3) erosion of unit 13 during MIS 9b; (4) formation

of steppe soils (units 12 to 10b) during MIS 9a; (5) intense freeze–thaw episode responsible for the cryoturbation of unit 12 and transition to gleys and loess at the transition between MIS 9a and 8.

The following glacial period, which can be allocated to MIS 8, is recorded by the deposition of a non-calcareous loess (unit 8c). The overlying Luvisol (unit 8b) shows mainly layered grainy clay coatings including alternations of limpid orange clays and layers of quartz grains similar to the surrounding sediment. The subsequent erosion (truncation) of this interglacial Bt horizon is marked by a flint gravel bed (Cx) and by a strong decrease in magnetic susceptibility values. The overlying horizon (unit 8a) shows numerous pedo-relics, papules and large soil aggregates resulting from the erosion and the reworking of the underlying Bt (unit 8b). A new illuviation phase then took place in the channels and inter-aggregate spaces indicating the formation of a Luvisol on the colluvium produced by the erosion of the underlying Bt. It is proposed that the first Luvisol (unit 8b) correlates with the first peak of the MIS 7 record corresponding to a temperate phase dated around 240 ka ago (MIS 7e), while the second one (unit 8a) could be correlated with the two peaks MIS 7c and MIS 7a, following a pattern already evidenced in two other sequences of the Somme Basin, at Mautort (Antoine, 1994) and Cagny-la-Garenne (Haesaerts and Dupuis, 1986).

The subsequent erosion of this MIS 7 soil complex resulted in the deposition of a further colluvial unit (7b). The overlying greyish unit (7a), including a Middle Palaeolithic archaeological level, appears in the same stratigraphic position as the humic soil layers described in other regional sequences such as Mautort (top of Mautort II soil) or Gentelles (Gentelles humic soil), at the transition between MIS 7 and MIS 6. At Etrécourt, the Upper Saalian stage (MIS 6) is represented by clayey loess (unit 6b), and *limons à doublets* (wavy banded fabric, unit 6a), separated by a strong erosion phase indicated by a bed of gelifRACTED flints containing reworked flint artefacts. The distinction between loessic sediments from MIS 8 and 6 appears clearly in the IRSL ages. However, compared with other sites from northern France where MIS 6 loess is systematically carbonated, at Etrécourt, MIS 6 loess is fully decalcified owing to the dissolution processes associated with the overlying interglacial Bt horizon.

Finally, the Last Interglacial optimum (MIS 5e) is recorded at the top of the Saalian loess as a typical argillic Bt horizon of Luvisol (unit 5). The overlying Upper Humic Soil Complex exhibits the same pedo-stratigraphic succession as the Weichselian Early Glacial reference sequence of Saint-Sauflieu (Antoine *et al.*, 1994; 2016).

Using litho-pedostratigraphy and the available geochronological data (TL and IRSL dating), the lower humic soil complex, or ESC, corresponding to MIS 9–8 transition, is definitely better expressed at Etrécourt than in the other sections of northern France and can be proposed as a reference for this period. To the west, at Saint-Pierre-lès-Elbeuf (Normandy), micromorphological study also highlights the development of a grey forest soil during the MIS 9–8 transition (Cliquet *et al.*, 2009). This period could also be represented by the Achenheim III pedocomplex in the Rhine Valley, composed of a non-leached reddish brown soil and one or more humic soil horizons (Lautridou *et al.*, 1985).

The last climatic cycle (Eemian–Weichselian)

In the environments of western Europe, loess sedimentation rates have been controlled by the distance to dust sources (generally periglacial braided river valleys) and by the

occurrence of sedimentary traps (leeward slopes, terraces scarps, bedrock sinkholes).

Generally, the best-developed Upper Pleistocene LPS are found when such sedimentary traps have been created just before the loess deposition. In northern France, the bedrock is formed by Upper Cretaceous chalk, in which dissolution processes can produce deep sinkholes and dolines favourable to the accumulation of thick LPS (e.g. Etrécourt, Revelles or Gentelles). Another process can also create accumulation spaces: retrogressive thermokarst processes resulting from rapid collapse/melting of former ice-wedge networks and associated permafrost (Antoine, 2012, Antoine *et al.*, 2016). The prevalence of these processes during the Last Glacial can explain why in some places young Weichselian loess (≤ 25 ka ago) can overlie truncated Eemian–Weichselian Early Glacial soil sequences or even lie directly on the chalk bedrock (Antoine, 1990).

Description of the pedosedimentary record

In northern France the Last Glacial (Weichselian) is represented by a sub-continuous loess cover up to 7–8 m in thickness in the best locations such as leeward slopes. In this area, pedostratigraphic sequences from this period have been intensely studied, especially in the framework of rescue archaeological programmes that have provided hundreds of individual sequences from test pits or excavations and numerous archaeological layers. The resulting global pedostratigraphic sequence from the last interglacial–glacial cycle exhibits a regular pedosedimentary pattern including well-established pedological and periglacial marker horizons that can be followed eastwards at least in Belgium and in Germany. This approach allows the building of a detailed pedostratigraphic and chronostratigraphic framework that represents a unique database to discuss the relationship between Palaeolithic occupations and environments in Europe. As detailed records of the last interglacial–glacial cycle in northern France have been recently published (Coutard *et al.*, 2018; Antoine *et al.*, 2014, 2016, 2019), here we will provide only a summary of the main features of this record which can be divided into four chronoclimatic phases following the erosion of the brown leached soil of the Last Interglacial (MIS 5e) during MIS 5d (Fig. 8):

- Stage 1: Early Glacial (112–72 ka ago) including a phase with grey forest soils (Early Glacial A: \approx MIS 5d to 5a) and a phase with steppe-like soils (Early Glacial B: end of MIS 5a).
- Stage 2: Lower Pleniglacial (≈ 70 –58 ka ago) with the first typical homogeneous loess deposits marking the onset of typical periglacial conditions.
- Stage 3: Middle Pleniglacial (≈ 58 –30 ka ago), marked by intense and short erosive episodes (thermokarst), the deposition of bedded colluvium completely reworking the whole underlying units, the development of a brown soil complex and weak aeolian deposition.
- Stage 4: Upper Pleniglacial (≈ 30 –17 ka ago), characterised by several successive networks of large ice-wedge casts and a drastic increase in loess sedimentation including tundra gley horizons.

In this context, the human occupation of northern France was discontinuous, with a clear concentration of Palaeolithic sites during the Early Glacial in forest-steppe contexts under continental climate. Only a few occupations are then attributed to the Lower Pleniglacial and to the Middle Pleniglacial and a gap in human settlement occurs between ≈ 25 and 15 ka ago, during the period of maximal loess

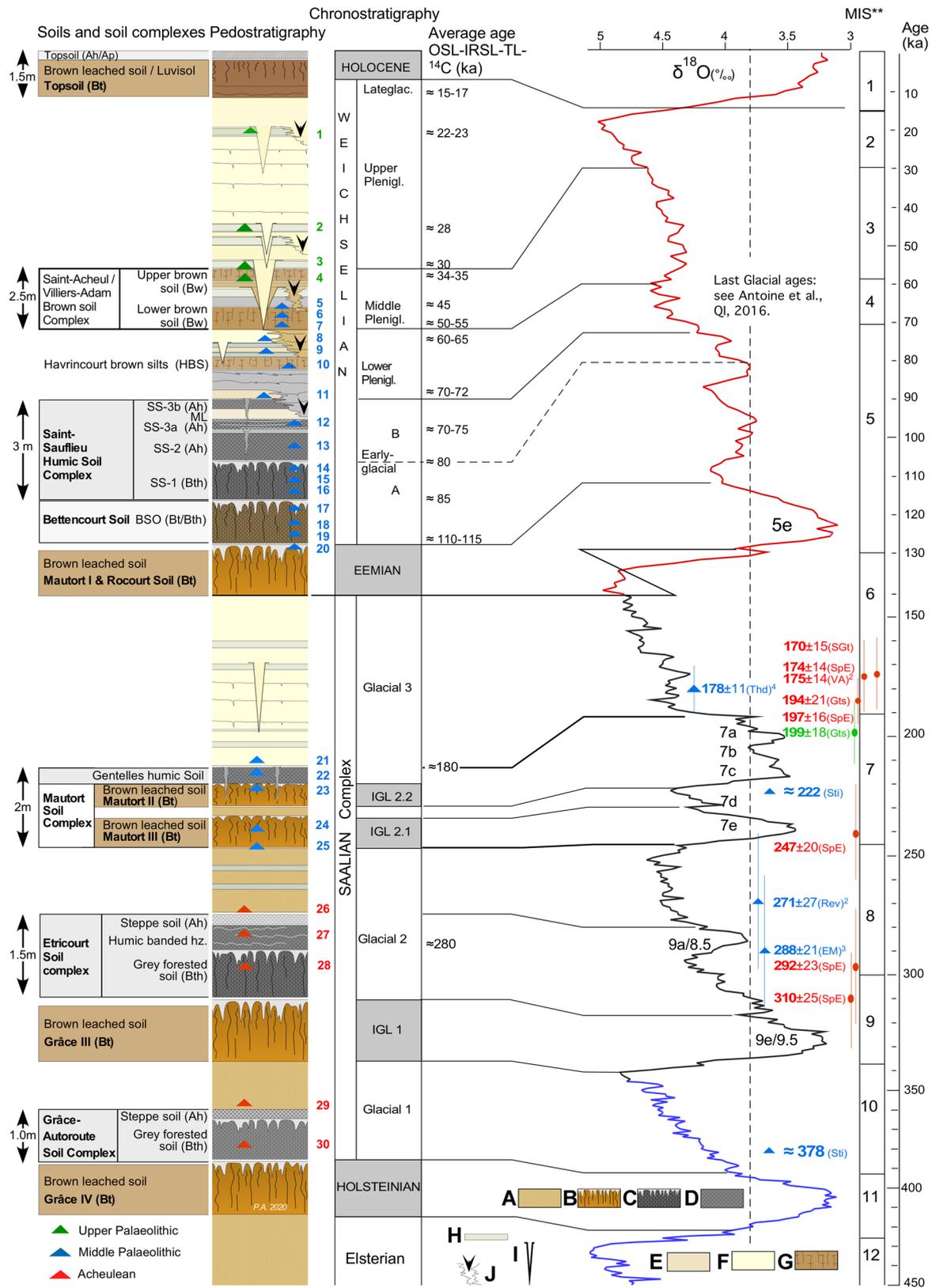


Figure 8 Continued.

deposition. A strong relationship between the intensity of human occupation and the climatic and environmental context is thus evident. This was probably conditioned by the relative availability of large fauna, itself linked to vegetation density, as indicated by the extremely sparse biomass estimates for this period contemporaneous with the Upper Pleniglacial loess deposition. Even if data are much more scattered for the Middle Pleistocene, a marked concentration of Palaeolithic occupation is also observed during Early Glacial transitional phases (Early Glacial MIS 11/10, 9/8 and 7/6).

Finally, as for older periods, it must be underlined that in the chalky area of northern France, the Weichselian Early Glacial period experienced particularly intense episodes of dissolution of the bedrock reported from many sites (examples in Antoine *et al.*, 2016). This process induced the formation of localised dissolution pockets or sinkholes that can reach over 3 m in depth and in which pedosedimentary sequences have been progressively trapped during the early stages of the Weichselian (between about 112 and 75 ka ago). These sequences are made by cumulic grey forest soils, the development of which is contemporaneous of the deposition of clayey colluvial deposits resulting from hillwash colluvial processes reworking former soil horizons and loess deposits on slopes. This process is important because it was responsible for the preservation of very detailed pedosedimentary records and associated Palaeolithic layers such as at Bettencourt-Saint-Ouen for MIS 5a to 5d (Antoine, 2002). At Havrincourt, for example (Antoine *et al.*, 2014), the formation of these sinkholes began at the end of the Eemian Interglacial, as shown by the deformations of the Bt horizon collapsed on the edges of the structures and its redeposition into the depressions. The cumulic soils stacked in the sinkholes are indicative of intense freeze–thaw and brutal soil drainage processes during the melting of snow cover in continental climatic conditions with strong seasonal contrasts (Van Vliet-Lanoë, 1987; Antoine *et al.*, 1994). During the first part of the Weichselian Early Glacial (Fig. 8), dissolution processes were enhanced under coniferous forests (acidification of precipitations through humic soil horizons) and also by the strong leaching processes associated with spring snow-melting events (thick coatings of bleached silts on aggregates). This dynamic, which related to the specific climatic conditions of the forested part of the Early Glacial (Early Glacial A: Fig. 8), ended with the formation of the first steppe soils around 70 ka ago in a markedly more arid environment. Similar dissolution processes and sinkholes are visible in the same stratigraphic position in Belgium in the Romont sequence, which also developed on chalky substra-

tum (Juvigné *et al.*, 2008). They occur also in older Early Glacial transition periods, as previously described in the Etricourt (humic) Soil Complex for the MIS 9–8 transition.

Discussion: the pedosedimentary record of northern France and its correlations with other western European LPS and global palaeoclimatic references

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 is rare and only preserved in localised sedimentary traps. These traps can be either sinkholes linked to the dissolution of the chalky Cretaceous substratum (e.g. at Gentelles, Revelles or Etricourt-Manancourt), or formed by the junction between the surface of alluvial terraces (former alluvial plains) and overhanging slopes and terrace scarps (e.g. at Grâce-Autoroute, Cagny-Rocade, Cagny-la-Garenne or Mautort).

This last configuration is particularly well illustrated by the Middle Pleistocene reference sequence of Grâce-Autoroute. The oldest part of the LPS forms the cover slope deposits of the oldest alluvial formation of the stepped terraced system of the Somme Valley (MIS 22, Antoine *et al.*, 2000, 2020). This sequence will therefore represent the basis for the definition of the local pedosedimentary evolution and cycles for the whole Middle Pleistocene period in the following discussion (Fig. 9).

The oldest part of Grâce-Autoroute LPS (sub-sequence 1), represented by the pedosedimentary cycles H, G and F, is bracketed between the alluvial deposits dated to the end of the Lower Pleistocene at around 0.9–1.0 Ma, and the first four glacial–interglacial pedosedimentary cycles recorded in this area. This sub-sequence is thus logically related to the beginning of the Middle Pleistocene and to the Cromerian Complex (Cohen and Gibbard, 2020). In the absence of geochronological data for these earliest sandy loess deposits, the chronostratigraphic attribution of this part of the LPS is based on the evidence for a cyclic glacial–interglacial signal and its comparison with global climatic curves such as the stacked oceanic $\delta^{18}\text{O}$ curve of Lisiecki and Raymo (2005). This cyclostratigraphic approach is reinforced by the direct dating (ESR on quartz and ESR/U-series on large-mammal teeth) of various levels of fluvial terraces on which LPS are deposited (Fig. 8). Palaeomagnetic data displaying the record of the BM boundary are also available for the next Alluvial Formation (IX) of the Somme system (Biquand, 1974). According to these

Figure 8. The global LPS in northern France from MIS12: pedosedimentary record, dating, location of Palaeolithic levels (1 to 30) and correlation with the generalised curve of Oceanic $\delta^{18}\text{O}$ variations. Soils and sediments: A) Non-calcareous sandy loess, B) Bt horizon of brown leached soil with upper greyish leached glossic horizon, C) Bth horizon of grey forest soil with strong prismatic to lamellar structure and upper whitish leached glossic horizon, D) Ah horizon of isohumic steppe soil, E) Local aeolian loam and non-calcareous loess, F) Typical calcareous loess (laminated or homogeneous), G) Bw horizons of interstadial brown soils (boreal to arctic brown soils), H) Greyish tundra gley horizon with periglacial deformations and oxidised root tracks (Gelic Gleysol). Features: I) Ice-wedge casts with loess infilling (permafrost), J) Deep and localised erosion gullies (thermokarst features). Dates: according to Antoine *et al.*, 2018 and Coutard *et al.*, 2018 (exponent: number of individual dating results used for the calculation of the averaged age). $\delta^{18}\text{O}$: data according to Lisiecki and Raymo (2005). Various chronological scales: red: 0–140 ka, black: 140–340 ka, blue: 340–450 ka. Palaeolithic sites and levels: according to Antoine *et al.*, 2018 (modified): 1) Chézy-sur-Marne, 2) Ren1: Renancourt-1, 3) Corbehem Upp., Hermies Canal-Cimetière, 4) Renancourt 2, Havrincourt Hav2-N2, 5) Hénin-sur-Cojeul, 6) Gauville (80), Attilly 1–2, St. Amand-les-Eaux, 7) Ploisy 1, Savy, Saint-Illiers 1, 8) Beauvais 1–2, Fitz-James, Sains-en-Amiénois, Ault, Catigny, 9) Hermies Tio-Marché, 10) Havrincourt Hav2-N1 /Hav1-N3, 11) Hermies Champ-Bruquette, 12) Blangy-Tronville, Gouy-Saint-André, Auteuil Upp., Soindres A and B, 13) Bettencourt-Saint-Ouen-N1, Amiens rue Saint-Honoré, Soindres C, Chavignon LBG, 14) Rencourt-les-Bapaume CA, Mauquenchy WA1, Bettencourt-Saint-Ouen N2a, 15) Bettencourt-Saint-Ouen N2b, Fresnoy-au-Val-N1, Chavignon SGF, Mauquenchy. WA2, 16) Soindres D, Hermies Champ-Bruquette Low., 17) Bettencourt-Saint-Ouen N3a, Revelles (Camp Féron), Villiers-Adam, 18) Fresnoy-au-Val N2, Bettencourt-Saint-Ouen N3b, Saint Hilaire-sur-Helpe, Soindres-F 19) Cuvilly, Saint-Illiers-2, Soindres-F, 20) Scattered reworked interglacial artefacts, 21) Menchecourt-Upper level, 22) Etricourt-Manancourt LGS, Therdonne, 23) Etricourt-Manancourt LRS, 24) Saint-Illiers N-4, 25) Saint-Valery-sur-Somme, 26) Plachy-Buyon Low., 27) Etricourt-Manancourt HUD, Clairy-Saulchoix, Revelles-Terres-Sellier, 28) Etricourt-Manancourt HUZ, 29) Gentelles, 30) Cagny Ferme-de-l'Épinette (Cagny-Rocade), Saint-Illiers-N5. [Color figure can be viewed at wileyonlinelibrary.com]

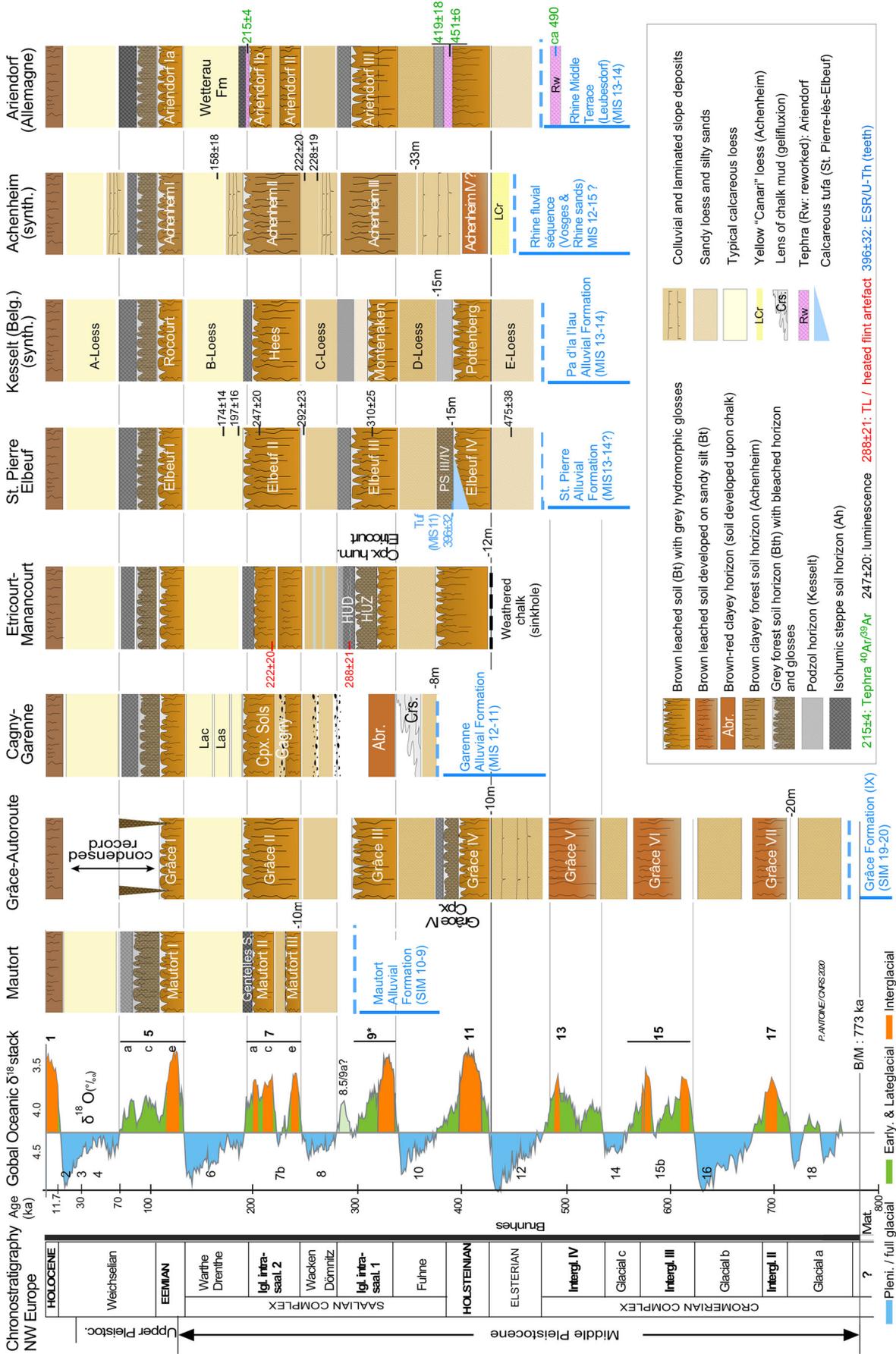


Figure 9. The LPS from northern France: correlation with isotopic stages and reference loess-palaeosol sequences for the Middle Pleistocene of western Europe (According to Antoine *et al.*, 2020, modified). North-western Europe chronostratigraphy according to Cohen and Gibbard, 2020, generalised curve of the oceanic $\delta^{18}O$ variations SPECMAP, according to Lisiecki and Raymo, 2005. Loess-palaeosol sequences: Mautort (Antoine, 1990, 1994), Cagny-la-Garenne (Haesaerts and Dupuis, 1984; Antoine, 1990, 1994), Etricotourt-Manancourt (Coutard *et al.*, 2019). Etricotourt-Manancourt (Coutard *et al.*, 2019); Cliquet *et al.*, 2009). Kesselt (synthesis: Nelissen, Albert Canal West and Op de Schans) (Meijs, 2002, Meijs *et al.*, 2012). Achenheim (Lautridou *et al.*, 1985, Zöller *et al.*, 2004). Ariendorf (Haesaerts *et al.*, 2019). [Color figure can be viewed at wileyonlinelibrary.com]

data, the series of soils Grâce VII, VI and V are therefore allocated to the succession of the MIS 17, 15 and 13 interglacial periods.

In the Cagny-Rocade LPS, overlying a more recent alluvial formation of the Somme (Formation VII), the two leached brown soils (units 4 and 6) would be the equivalent of the Grâce IV and V soils in accordance with the ESR age (600 to 550 ka) of the underlying fluvial deposits (Figs. 6 and 9). Further westward, in Normandy, the Grâce VII, VI and V soils are equivalent to the partly rubified interglacial soils of Bosc-Hue VII, Iville VI and Iville V, developed on sandy loess of local origin (Lautridou, 1985). These three soils are indeed directly underlying the Elbeuf IV soil (Lautridou, 1985), well dated from the Holsteinian interglacial (MIS 11) by several geochronological methods (U-series, IRSL, ESR, ESR/U-series) and the malacological content from the directly overlying calcareous tufa (*Lyrodiscus* biome; Cliquet *et al.*, 2009; Limondin-Lozouet *et al.*, 2015).

The importance of the erosive processes associated with the base of sub-sequence 2 at Grâce-Autoroute and the unprecedented volume of laminated silts and sands then deposited at the foot of the slope during this event imply very rigorous climatic conditions and (or) a much longer period of destabilisation than during the deposition of the sandy silts from previous cycles (H, G and F). These harsh climatic conditions undoubtedly correspond to a major glacial period from the Middle Pleistocene. Given the position of unit 6 within the sequence, it is proposed to assign it to MIS 12, which represents in north-western Europe one of the most marked glacial phases of the Middle Pleistocene (Elsterian or Anglian, Cohen and Gibbard, 2020). In Normandy, it would correspond to the sandy loess on which the Elbeuf IV soil was developed during MIS 11.

In the Somme Basin, MIS 11 interglacial sequences were recorded at Grâce-Autoroute and Cagny-Rocade as a typical brown leached soil horizon developed upon sandy silts.

Furthermore, as previously specified, the Grâce IV soil horizon is integrated into a soil complex (Grâce IV Soil Complex) including a Bt horizon of typical interglacial brown leached soil and a degraded grey forest soil horizon (Bth) overlain by an isohumic steppe layer (Ah) (only observed at Grâce). This Grâce IV Soil Complex clearly exhibits the same evolution as the soil complexes recorded during the Eemien/Weichselien Early Glacial period in northern France such as at Saint-Saulfieu (Antoine *et al.*, 1994), Remicourt, Belgium (Haesaerts *et al.*, 2016) or 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 from the underlying fluvial levels (Bahain *et al.*, 2007) allow the allocation of this soil complex to the pedosedimentary budget of the MIS 11 Interglacial (Holsteinian) and the beginning (Early Glacial phase) of MIS 10 (first glacial of the Saalien complex). Evidencing this soil complex in the Somme for the MIS 11 and 10 stages represents a major contribution to the stratigraphy of the loess of the Middle Pleistocene, since it had never been described in the reference profiles of western Europe such as Saint-Pierre-lès-Elbeuf in Normandy (Lautridou, 1985; Cliquet *et al.*, 2009) or Kesselt-Op de Schans, Belgium (Meijs *et al.*, 2012). Only the Ariendorf sequence, on the right bank of the Rhine in Germany (Brunnacker *et al.*, 1975), recently restudied by Haesaerts *et al.* (2019), clearly shows a soil complex comparable to Grâce IV Soil Complex. It includes an interglacial soil (Bt) allocated to MIS 11 (Ariendorf IV soil), fossilised by the Rieden Tephra dated to around 420 ka ago by $^{40}\text{Ar}/^{39}\text{Ar}$ (van den Bogaard and

Schminke, 1990), then covered by two humic horizons allocated to early MIS 10, including one grey forest soil horizon (Bth) (Fig. 9). Further eastward, in the Danube Basin, in Serbia in particular, where the LPS posterior to the Brunhes-Matuyama boundary can reach 50 m thick and include more than eight interglacial palaeosols (Marković *et al.*, 2015), the equivalent of Grâce IV would be the Cambisol soil V-S4.

The rest of the Middle Pleistocene sequence in northern France is always represented by loessic materials characterised by a strong sandy component (fine sands: 30–40%). These sandy loess accumulations are mainly produced by 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. Indeed, during the more recent part of the Middle Pleistocene, the initial stock of Tertiary sands was strongly reduced and less and less available for reworking by aeolian deflation or hillwash. This trend is also indicated by the progressive reduction in the quantity of reworked small Tertiary flint pebbles (2–3 cm long) in the gravels of alluvial terraces from Alluvial Formation V (MIS 12–11; Fig. 2) to the more recent alluvial formation (Antoine, 1994).

At the regional scale, the next interglacial (MIS 9) is marked by the formation of a typical leached brown soil named at Grâce-Autoroute Grâce III Soil. 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 discovered in this humic soil complex (HUD) confirm the allocation 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 leached brown soil Grâce III would therefore be correlated with brown leached soil at Elbeuf in Normandy (Elbeuf III soil, based on pedostratigraphy and on IRSL dates, Cliquet *et al.*, 2009), at Montenaken, 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 Complex, eastern France (Lautridou *et al.*, 1985).

The following cold stage (MIS 8) is marked by deposits that are a little less rich in sands in the Somme sequences and more clearly loessic at sites located at a greater distance from potential sources of sand (large periglacial rivers) such as Etrécourt-Manancourt. 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 dissolution doline (25 m in diameter) in chalk (Coutard *et al.*, 2019; Lamotte *et al.*, 2019). According to TL dating on heated flints from the Palaeolithic level preserved at the base of this sequence in silty-clayey deposits (average: 271 ± 21 ka ago, 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. A similar situation was observed in Normandy at Le Pucheuil (Fig. 1), where a 50 m wide and 10 m deep doline has trapped two superimposed sequences of Saalien loess associated with several Palaeolithic occupations (Delagnes and Ropars, 1996).

The soil Grâce II, which represents the following interglacial, has pedological characteristics and a stratigraphic position which allow it to be parallelised with the leached brown soils assigned (and/or) dated to MIS 7, like the Soil Complex of Cagny (Haesaerts and Dupuis, 1986), Elbeuf II soil in Normandy, Hees soil in Belgium (Meijs *et al.*, 2012) or the Ariendorf Ib-II complex in Germany (Fig. 9). In some sequences, we observe a clear subdivision of this soil into

two distinct Bt horizons, as in other sequences of the Somme such as Mautort (Mautort III and II soils, Antoine, 1990), Cagny-la-Garenne (Haesaerts and Dupuis, 1986) or Etrécourt-Manancourt (Coutard *et al.*, 2018). The most demonstrative example is represented by the complex formed by the succession of the Mautort III/Mautort II soils at the base of the cover sequence of the fluvial deposits of the Mautort Formation. In 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). It must be noted that the subdivision of MIS 7 soils is also reflected in the fluvial record of the Somme Basin in which one periglacial gravel body (gravels of Alluvial Formation II or Low Terrace) is allocated to the cold stage of MIS 7d, about 230 ka ago (Antoine *et al.*, 2007). In addition, the upper Bt horizon (Mautort II soil) is capped by a homogeneous grey isohumic steppe soil horizon. The same type of humic soil, although more developed, was observed in the sinkhole site of Gentelles (Tuffreau *et al.*, 2017) where the ESR/U-series dates obtained on two horse teeth from the directly overlying loess (199 ± 20 ka ago) is also in favour of 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 this same climatic transition have been recognised at Le Puceuil in Normandy (Delagnes and Ropars, 1996), Villiers-Adam near the Oise Valley (Locht *et al.*, 2003) and Etrécourt-Manancourt (Hérisson *et al.*, 2016). At this last site, this humic soil is overlain by a loess layer dated from 180 to 144 ka by IRSL (Coutard *et al.*, 2018). Finally, at Therdonne, close to the Thérain Valley, 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 ago by thermoluminescence on heated flints (Locht *et al.*, 2010) (Fig. 8). This soil has produced remains of *cf. Citellus superciliosus*, a rodent from the continental steppes, suggesting a cold and dry climate as well as an open environment.

At Gentelles, the humic soil allocated to the MIS 7–6 transition is affected by periglacial structures (sand wedges) of more than one metre in depth as well as by large-scale cryo-injection, both features representing the oldest evidence of permafrost in the area (Coutard *et al.*, 2019). The remnant of a former large ice wedge deformed by hillwash processes has also been described at Mautort within the MIS 6 loess sequence (Antoine, 1994).

In contrast to the facies of the loess deposited before MIS 7, the typical Upper Saalian calcareous loess dated to MIS 6 shows a markedly greater extension within the landscape and is therefore much more often observed and described, especially from rescue archaeology test pits.

The main sequences are Cagny-la-Garenne (LAC), Etrécourt-Manancourt (U6), Gentelles (Balescu, 2013), Sangatte (Antoine, 1989; Coutard *et al.*, 2019), Villiers-Adam (Antoine *et al.*, 2003c) and Saint-Pierre-lès-Elbeuf (Coutard *et al.*, 2019) (Figs. 1 and 9).

The appearance of typical calcareous loess facies (CaCO_3 : ≈ 15 –18%) with an unprecedented extent across 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 France 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 6 to 10 m in thickness (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, 2010, 2016), at Böckingem (Bibus, 2002) or 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 underlined by a significant change in the composition of heavy minerals with high concentrations of green hornblende (Balescu, 1988; Haesaerts *et al.*, 1984; Meijs, 2002; Pirson *et al.*, 2018). This break in both sedimentation rates, carbonate content and heavy mineral compositions is difficult to interpret as the result of a purely climatic forcing since much more intense and longer former glacial periods as MIS 16 or 12 did not give rise to the same intensification of aeolian processes and loess sedimentation. The MIS 6 'loess revolution' thus likely indicates a significant increase in the volume of the detrital sediments available for aeolian deflation processes. The source of these sediments corresponds probably to the braided channels of the Channel River draining the eastern Channel in a configuration where it is connected to the south-west of the North Sea Basin (Antoine *et al.*, 2003b). Indeed, during the lower Pleistocene and at the beginning of the Middle Pleistocene (before 450 ka ago), a chalk land bridge connected France and England and bounded to the south-west the proglacial lake occupying the southern part of the North Sea during glacial stages. During MIS 12 this barrier underwent a catastrophic erosion event causing the first opening of the Pas-de-Calais (Strait of Dover) (Gibbard, 1995, Gupta *et al.*, 2007). A similar process would have occurred later during MIS 6 (Gupta *et al.*, 2007), generating a major reorganisation of the drainage network from north-western Europe towards the Atlantic Ocean (Toucanne *et al.*, 2009).

This interpretation is still debated (Westaway and Bridgland, 2010; White *et al.*, 2017), because, if such catastrophic event was necessary to 'open the way' to a south-westward drift of meltwater and associated sediments from the Scandinavian Ice Sheet, it is not sufficient to fully explain the unprecedented high loess sedimentation rates observed in western Europe during MIS 6, implying an important increase in the production of silt-sized particles by glacial grinding and their subsequent transportation to the deflation area of the southern North Sea and English Channel. Such a process could have been achieved during the severe (full) glacial periods of MIS 12, 6 or 2. However, in northern France, no typical loess was deposited during MIS 12 whereas, at that time, aeolian deposits were derived from the local reworking of sandy material (Antoine *et al.*, 2020), thus highlighting the absence of an extensive deflation source in the Channel during MIS 12.

Besides, according to numerous field observations, very strong similarities have been evidenced between facies succession, loess structures and mineralogy of the loess deposited between MIS 6 (≈ 150 –140 ka) and MIS 2 (≈ 30 –17 ka) on the large area from northern France to western Germany through Belgium (Antoine *et al.*, 2016; and unpublished data). These common features are: (1) the systematic occurrence of a thick body of laminated calcareous loess with micro-crack networks covered by a thinner unit made of homogeneous loess (Hesbayan-Brabantian succession in Belgium; Gullentops, 1954); (2) the development of several tundra gley horizons corresponding to former permafrost active layers; (3) the occurrence of large ice-wedge cast networks, the latter being extremely rare or absent before MIS 6; and (4) high concentrations in green hornblende in heavy

mineral assemblages (Pirson *et al.*, 2018). These observations show that both palaeoclimatic and palaeogeographic conditions were similar during the MIS 6 'loess revolution' (≈ 160 – 140 ka ago) and late MIS 3 and MIS 2 (≈ 30 – 17 ka ago).

According to Toucanne *et al.* (2009) these periods were characterised by the connection of the *Fleuve Manche* to the drainage system of the Fennoscandian Ice Sheet and the rerouting of the Elbe–Weser fluvial network to the south-west 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 (Sejrup *et al.*, 2009; Scourse *et al.*, 2009). This time span corresponds exactly to the period where the highest sedimentation rates are depicted in western European loess sequences (Antoine *et al.*, 2001, 2016; Hae-saerts, *et al.* 2016; Moine *et al.*, 2017, Rousseau *et al.*, 2017). Finally, it is thus very likely that the unprecedented loess volume deposited in northern France during late MIS 6 is the signature of an original palaeogeographic pattern characterised by the coalescence of north European ice sheets in the North Sea basin and inducing a rerouting of the drainage system and associated sediments to the eastern Channel deflation area.

Conclusions

Research on Middle Pleistocene LPS from northern France over more than 30 years, especially in connection with rescue archaeology programmes, confirm the great homogeneity of the LPS and their high value as recorders of climatic variations in the continental domain. Here are our main conclusions:

- 1) The Grâce-Autoroute LPS, now proposed as a reference record for western Europe, and other important sequences from northern France, show that, despite evidence of numerous erosion boundaries, LPS represent a sub-continuous record of the Milankovitch glacial–interglacial cycles down to the early Middle Pleistocene at about 750 ka ago (MIS 18).
- 2) Within this sequence, the main part of Middle Pleistocene is marked by local non-calcareous sandy loess incorporating an important fraction of fine sands reworked at short distances by aeolian processes from the former fluvial sediments and (or) by slope hillwash processes from relicts of Tertiary marine sands. Even during very cold and long glacial stages such as MIS 12, typical allochthonous loess has not been deposited in northern France.
- 3) In the whole area, and to a certain extent in Belgium and western Germany, the calcareous *Loess Revolution*, marked by the widespread deposition of typical calcareous loess, is a marker of late MIS 6. It is likely the signature of a major change in both palaeogeography and drainage patterns of the southern North Sea and eastern Channel area considered as the main sources for loess particles.
- 4) At least for the last four interglacial–glacial cycles (MIS 11 to 5e), the same succession of soil facies (Bt, Bth and Ah) can be observed in soil complexes recording the various climatic transition phases between interglacial and glacial periods (early glacial chronoclimatic phases). This is especially impressive for the MIS 9–8 transition observed at Etrécourt-Manancourt where confusion with the Weichselian Early Glacial soil sequence is possible in test pits without taking into account the rest of the LPS. On the other hand, evidence for the MIS 7a–6 transition is less developed with only one humic steppe soil (Gentelles) overlying the interglacial Bt (MIS 7a). This observation is in good

accordance with global climatic records showing a definitely shorter and more abrupt transition at the end of MIS 7a compared with other transitions as MIS 5d–5a or MIS 9c–9a. This last point shows again that LPS are extremely valuable and accurate recorders of Quaternary climatic and environmental changes.

- 5) Sinkhole formation in chalky bedrock areas has occurred systematically during the transition periods between interglacial and glacial (early glacial) under contrasted continental climates and boreal forest environments. These processes are related to both the acidification of precipitation through humic soils developed under coniferous forests and very intense episodes of leaching and soil drainage during spring snowmelt events.
- 6) Finally, even if data are much more scattered and dates less accurate than for the Upper Pleistocene, a marked concentration of Palaeolithic occupations is observed during the early glacial transitional phases of the Middle Pleistocene (MIS 11–10, 9–8 and 7–6 transitions) in forest-steppe contexts under a continental climate. Our studies show that the Palaeolithic settlement of northern France was discontinuous during the Middle Pleistocene as well as during the Last Glacial. We propose that the relationship between the intensity of human occupation and the climatic and environmental context was conditioned by the relative abundance of large mammal fauna, itself linked to vegetation density.

Acknowledgements. This paper is a contribution to ANR research programmes 'PremAcheuSept' and 'NeandRoots' coordinated by Dr M-H Moncel (MNHN, Paris). The authors thank the two anonymous reviewers who helped to significantly improve the first draft of this manuscript.

Data availability Statement

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

Conflict of interest statement—The authors have no conflicts of interest to declare.

References

- Antoine P. 1989. Stratigraphie des formations pléistocènes de Sangatte (Pas-de-Calais) d'après les premiers travaux du Tunnel sous la Manche. *Bulletin de l'Association française pour l'étude du Quaternaire* 1: 5–17.
- Antoine P. 1990. Chronostratigraphie et environnement du Paléolithique du bassin de la Somme. *Publication du Centre de Recherches et d'Études Préhistoriques de Lille* 2: 231.
- 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. 2002. Contexte stratigraphique et paléopédologique; interprétation chronostratigraphique et environnementale. In *Le gisement de Bettencourt-Saint-Ouen (Somme, France): cinq occupations du Paléolithique moyen au début de la dernière glaciation*. Documents d'Archéologie Française, 90. J.-L. Locht (ed.). Maison des Sciences de l'Homme: Paris, 16–39.
- Antoine P. 2012. Thermokarst processes and features from west-European loess series: new evidences for rapid climatic warming events during the Last Glacial. *Quaternary International* 21: 279–280.
- 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(3): 257–270.
- Antoine P, Munaut AV, 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, Lautridou JP, 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, Rousseau DD, Degeai JP *et al.* 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 DD, Zöller L *et al.* 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.
- Antoine P, Coutard JP, Gibbard P *et al.* 2003a. The Pleistocene rivers of the Channel Region. *Journal of Quaternary Science* **18**: 227–243.
- Antoine P, Catt J, Lautridou JP *et al.* 2003b. The loess and coversands of northern France and southern England. *Journal of Quaternary Science* **18**: 309–318.
- Antoine P, Bahain JJ, Debenham N *et al.* 2003c. 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, Limondin-Lozouet N, Chaussé C *et al.* 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, Goval E, Jamet G *et al.* 2014. Les séquences loessiques pléistocène supérieur d'Havrincourt (Pas-de-Calais, France): stratigraphie, paléoenvironnement, géochronologie et occupations paléolithiques. *Quaternaire* **25**(4): 321–368.
- Antoine P, Coutard S, Guérin G *et al.* 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, Bahain JJ, Chaussé C *et al.* 2018. Quaternaire et géoarchéologie pléistocène de la France. Quoi de neuf depuis 1976? In *La Préhistoire de la France*, Djindjian F (ed.). Édition Hermann: Paris; 38–84.
- Antoine P, Moncel MH, Locht J-L *et al.* 2019. The earliest record of Acheulean Human occupation from northern Europe and the rediscovery of the Moulin Quignon site. *Scientific Reports* **9**: 13091.
- Antoine P, Bahain JJ, Coutard S *et al.* 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**(3): 205–230.
- Bahain JJ, Falguères C, Laurent M *et al.* 2007. ESR chronology of the Somme River Terraces system and of the first human settlements of northern France. *Quaternary Geochronology* **2**: 356–362.
- Bahain JJ, Falguères C, Dolo JM *et al.* 2010. ESR/U-series dating of teeth recovered from well-stratigraphically age-controlled sequences from northern France. *Quaternary Geochronology* **5**: 371–375.
- Bahain JJ, 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. In *Actes du XXVIII Congrès Préhistorique de France, Amiens 30 mai-4 juin 2016*. Société préhistorique de France: Paris; 41–54.
- Balescu S. 1988. *Apports de la thermoluminescence à la stratigraphie et à la sédimentologie des loess du Nord-Ouest de l'Europe*. Thèse Doctorat Sciences, Université de Bruxelles; 144.
- Balescu S. 2013. Chronologie des loess du Pléistocène moyen de Normandie. *Quaternaire* **24**(3): 237–245.
- Bibus E. 2002. Zum Quartär im mittleren Neckarraum: Reliefentwicklung, Löss/Paläobodensequenzen, Paläoklima. *Tübinger Geowissenschaftliche Arbeiten*. Reihe D, *Geökologie und Quartärforschung* **S. D08**: 1–276.
- Biquand D. 1974. Position chronologique de la très haute nappe alluviale de Grâce (vallée de la Somme) par rapport à la limite paléomagnétique Brunhes-Matuyama. *Bulletin de l'Association française pour l'étude du Quaternaire* **11**(3–4): 157–159.
- Bourdier F, Chalaine J, Munaut AV *et al.* 1974. La très haute nappe alluviale de la Somme. *Bulletin de l'Association française pour l'étude du Quaternaire* **11**: 137–143.
- Brunnacker K, Lohr H, Boenick W *et al.* 1975. Quartär-Aufschlüsse bei Ariendorf am Unteren Mittelrhein. *Mainzer Naturwissenschaftliches Archiv* **14**: 93–141.
- Brunnacker K, Löscher M, Tillmans W *et al.* 1982. Correlation of the Quaternary terrace sequence in the Lower Rhine Valley and northern Alpine foothills of central Europe. *Quaternary Research* **18**: 152–173.
- Cliquet D, Lautridou JP, Antoine P *et al.* 2009. La séquence loessique de Saint-Pierre-lès-Elbeuf (Normandie, France): nouvelles données archéologiques, géochronologiques et paléontologiques. *Quaternaire* **20**(3): 321–343.
- Cohen KM, Gibbard PL. 2020. Global chronostratigraphical correlation table for the last 2.7 million years v2020 Mendeley Data (data.mendeley.com). <https://doi.org/10.17632/dtsn3xn3n6.3> (Open Access).
- Commont V. 1909. Saint-Acheul et Montières. Notes de Géologie, de Paléontologie et de Préhistoire. *Mémoire de la Société géologique du Nord*, VI(mém. III): 68.
- Coutard S, Antoine P, Hérison D *et al.* 2018. La séquence loessique pléistocène moyen à supérieur d'Éricourt-Manancourt (Picardie, France): un enregistrement pédo-sédimentaire de référence pour les derniers 350 ka. *Quaternaire* **29**(4): 311–346.
- Coutard S, Antoine P, Deschodt L *et al.* 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. In *Actes du XXVIII Congrès Préhistorique de France, Amiens, 2016*. Société préhistorique de France: Paris; 63–90.
- Delagnes A, Ropars A (eds). 1996. *Paléolithique moyen en Pays De Caux (Haute-Normandie)* Documents d'Archéologie Française, Maison des Sciences de l'Homme: **56**: 242.
- Dodonov AE, Zhou LP, Markova AK *et al.* 2006. Middle-Upper Pleistocene bio-climatic and magnetic records of the northern Black Sea coastal area. *Quaternary International* **149**: 44–54.
- 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 *et al.* 2013. Loess-paleosol sequence at Korshiv (Ukraine): chronology based on complementary and parallel dating (TL, OSL), and litho-pedosedimentary analyses. *Quaternary international* **296**: 117–130.
- Fitzsimmons K, Hambach U, Veres D *et al.* 2013. The Campanian Ignimbrite eruption: new data on volcanic ash dispersal and its potential impact on human evolution. *PLoS One* **8**: e65839.
- Frechen M, Dodonov AE. 1998. Loess chronology of the Middle and Upper Pleistocene in Tadjikistan. *Geologische Rundschau* **87**: 2–20.
- Gibbard PL. 1995. Formation of the Strait of Dover. In *Island Britain: a Quaternary Perspective*, Preece RC (ed). Geological Society Special Publication: London; 15–26.
- Gullentops F. 1954. Contribution à la chronologie du Pléistocène et des formes de relief en Belgique. *Mémoire de l'Institut de Géologie. Université de Louvain* **18**: 125–252.
- Gupta S, Collier JS, Palmer-Felgate A *et al.* 2007. Catastrophic flooding origin of shelf valley systems in the English Channel. *Nature Letters* **448**: 342–345.
- Haase D, Fink J, Haase G *et al.* 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, Dupuis C, Balescu S *et al.* 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. In *Chronostratigraphie et faciès culturels du Paléolithique inférieur et moyen dans l'Europe du Nord-Ouest. Supplément Bulletin de l'Association française pour l'étude du Quaternaire* **26**: 171–186.
- Haesaerts P, Damblon F, Gerasimenko N *et al.* 2016. The Late Pleistocene Loess-Palaeosol sequence of middle Belgium. *Quaternary International* **411**: 25–43.
- Haesaerts P, Dupuis C, Spagna P *et al.* 2019. Révision du cadre chronostratigraphique des assemblages Levallois issus des nappes alluviales du Pléistocène moyen dans le bassin de la Haine (Belgique). In *Actes du XXVIII Congrès Préhistorique de France. Amiens 2016. Société préhistorique de France: Paris* 179–199.

- Hérisson D, Coutard S, Goval É *et al.* 2016. A new key-site for the end of Lower Palaeolithic and the onset of Middle Palaeolithic at Étricourt-Manancourt (Somme, France). *Quaternary International* **409**: 73–91.
- Horvath E. 2001. Marker horizons in the loesses of the Carpathian Basin. *Quaternary International* **76–77**: 157–163.
- Jensen BJL, Evans ME, Froese DJ *et al.* 2016. 150,000 years of loess accumulation in central Alaska. *Quaternary Science Reviews* **135**: 1–23.
- Jipa DC. 2014. The loess-like deposits in the Lower Danube Basin. Genetic significance. *Geo-Eco-Marina* **20**: 7–18.
- Juvigné E, Tallier E, Haesaerts P *et al.* 2008. Un nouveau stratotype du Tephra de Rocourt dans la carrière de Romont (Eben/Bassenge, Belgique). *Quaternaire* **19**: 133–139.
- Kukla G. 1977. Pleistocene land-sea correlations. 1: Europe. *Earth-Science Reviews* **13**: 307–374.
- Lamotte A, Deschodt L, Antoine P *et al.* 2019. Le gisement acheuléen en contexte de doline de Revelles (Somme, France) et ses caractéristiques communes à l'Acheuléen méridional. *L'Anthropologie* **123**(4–5): 695–723.
- Laurent M, Falguères C, Bahain JJ *et al.* 1994. Géochronologie du système de terrasses fluviales quaternaires du bassin de la Somme par datation RPE sur quartz, déséquilibres des familles de l'uranium et magnétostratigraphie. *Comptes rendus de l'Académie des Sciences, Paris* **318**: 521–526.
- Lautridou JP. 1985. *Le cycle périglaciaire pléistocène en Europe du Nord-Ouest et plus particulièrement en Normandie*. Thèse de doctorat d'État, Université de Caen. Centre de Géomorphologie du CNRS: Caen; 908.
- Lautridou JP, Somme J, Heim J *et al.* 1985. La stratigraphie des loess et formations fluviales 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**(2–3): 125–132.
- Lautridou JP, Auffret JP, Baltzer A *et al.* 1999. Le fleuve Seine, le fleuve Manche. *Bulletin de la Société géologique de France* **170**(4): 545–558.
- Lehmkuhl F, Zens J, Krauß L *et al.* 2016. Loess-paleosol sequences at the northern European loess belt in Germany: Distribution, geomorphology and stratigraphy. *Quaternary Science Reviews* **153**: 11–30.
- Limondin-Lozouet N, Antoine P, Bahain JJ *et al.* 2015. Northwest European MIS 11 malacological successions: a key for the timing of Acheulean settlements. *Journal of Quaternary Science* **30**(7): 702–712.
- Lindner L, Bogutsky A, Gozhik P *et al.* 2002. Correlation of main climatic glacial-interglacial and loess-paleosol cycles in the Pleistocene of Poland and Ukraine. *Acta geologica Polonica* **52**: 459–469.
- Lisiecki LE, Raymo ME. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. *Paleoceanography* **20**: PA1003.
- Locht J-L, Antoine P, Bahain JJ *et al.* 2003. Le gisement paléolithique moyen et les séquences pléistocènes de Villiers-Adam (Val-d'Oise): chronostratigraphie, environnement et implantations humaines. *Gallia Préhistoire – Archéologie de la France préhistorique. CNRS Éditions* **45**: 1–111.
- Locht J-L, Antoine P, Hérisson D *et al.* 2010. Une occupation de la phase ancienne du Paléolithique moyen à Therdonne (Oise): chronostratigraphie, production de pointes Levallois et réduction des nucléus. *Gallia Préhistoire – Préhistoire de la France dans son contexte européen. CNRS Éditions* **52**: 1–32.
- Lomax J, Fuchs M, Antoine P *et al.* 2019. Luminescence chronology of the Harletz loess sequence, Bulgaria. *Boreas* **48**: 179–194.
- Marković SB, Stevens T, Kukla G *et al.* 2015. Danube loess stratigraphy - Towards a pan-European loess stratigraphic model. *Earth Science Reviews* **148**: 228–258.
- Meijs EPM. 2002. Loess stratigraphy in Dutch and Belgian Limburg. *Eiszeitalter und Gegenwart* **51**: 114–130.
- Meijs EPM, Van Peer P, De Warrimont JP. 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 *et al.* 2017. The impact of Last Glacial climate variability in west-European loess revealed by radiocarbon dating of fossil earthworm granules. *Proceedings of the National Academy of Sciences of the USA. Earth, Atmospheric, and Planetary Sciences*, May 2017, 10.1073/pnas.1614751114
- Pécsi M. 1990. Loess is not just the accumulation of dust. *Quaternary International* **7/8**: 1–21.
- Pirson S, Baele J-M, Balescu S *et al.* 2018. Green amphibole distribution as a stratigraphic tool in loess sequences from Belgium: A review. *Quaternary International* **485**: 183–198.
- Railsback LB, Gibbard PL, Head MJ *et al.* 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.
- Rousseau D-D, Boers N, Sima A *et al.* 2017. (MIS 3 & 2) millennial oscillations in Greenland dust and Eurasian aeolian records - a paleosol perspective. *Quaternary Science Reviews* **169**: 99–113.
- Schirmer W. 2010. Interglacial complex and solcomplex. *Central European Journal of Geosciences* **2**(1): 32–40.
- Schirmer W. 2016. Late Pleistocene loess of the Lower Rhine. *Quaternary International* **411**: 44–61.
- Sejrup HP, Nygård A, Hall AM *et al.* 2009. Middle and Late Weichselian (Devensian) glaciation history of south-western Norway, North Sea and eastern UK. *Quaternary Science Reviews* **28**: 370–380.
- Sommé J. 1977. *Les plaines du Nord de la France et leur bordure. Étude géomorphologique*. Thèse de doctorat d'état, Université Paris I (1975): Lille, Paris.
- Toucanne S, Zaragosi S, Bourillet JF *et al.* 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, Lamotte A, Antoine P *et al.* 1997. Le gisement acheuléen de la Ferme de l'Épinette (Somme, France). *Archäologisches Korrespondenzblatt* **27**: 513–530.
- Tuffreau A, Auguste P, Balescu S *et al.* 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**(5): 394–427.
- Van Den Bogaard P, Schmincke HU. 1990. Die Entwicklungsgeschichte des Mittelrheinraums und die Eruptionsgeschichte des Ost-Eifel-Vulkanfeldes. In *Rheingeschichte zwischen Mosel und Maas*, Schirmer W (ed.), Deuqua Führer *Deutsche Quartärvereinigung* **1**: 166–190.
- Van Vliet-Lanoë B. 1987. 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**(3): 113–132.
- Westaway R, Bridgland DR. 2010. Causes, consequences and chronology of large-magnitude palaeoflows in Middle and Late Pleistocene river systems of northwest Europe. *Earth Surface Processes and Landforms* **35**: 1071–1094.
- White TS, Bridgland DR, Westaway R *et al.* 2017. Evidence for Late Middle Pleistocene glaciation of the British margin of the southern North Sea. *Journal of Quaternary Science* **32**: 261–275.
- Zöllner L, Rousseau DD, Jäger KD, Kukla G. 2004. Last interglacial, Lower and Middle Weichselian - a comparative study from the Upper Rhine and Thuringian loess areas. *Zeitschrift für Geomorphologie N.F.* **48**(1): 1–24.