Last interglacial-glacial climatic cycle in loess-palaeosol successions of north-western France

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The loess series at St. Pierre-les-Elbeuf and St. Sauflieu are key successions for the western European Quaternary stratigraphy. The present study proposes a detailed record of the last interglacial–glacial climatic cycle at St. Pierre and its integration into the synthetic pedosedimentary record of north-western France using detailed correlations with the type sections of St. Sauflieu and Achenheim. Finally, comparisons with the marine isotope, Greenland GRIP chronologies and dust records are proposed. At St. Pierre, the pedostratigraphic and sedimentological analyses (total iron, organic matter, carbonate, grain size), in association with low field magnetic susceptibility measurements, demonstrate that this loess succession records the major climatic events of the Upper Pleistocene. The basal soil complex at St. Pierre is similar to those from the main successions of North (St. Sauflieu) or Northeast France (Achenheim). It shows a Bt horizon of brown leached soil, a deeply reworked grey forest soil and two isohumic steppe soils separated by a non-calcareous loess layer. This loess level corresponds to the first aeolian event clearly observed in the succession and can be correlated with Marker II of the Central European stratigraphy located around the marine isotope stage (MIS) 5/4 boundary. The main aeolian sedimentation starts after the soil complex and ends with the top soil (brown leached soil). Finally, a good parallel is observed between the strongest peaks of the dust records of the ice cores and the main period of loess deposition in St Pierre-lès-Elbeuf occurring during MIS 2.

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The best known loess successions are the central European and Asian series (Kukla 1977; Heller & Liu 1984; Haesaerts 1985; Liu 1985; Kukla 1987; Kukla *et al*. 1988; Forster & Heller 1994). They are strongly developed and generally record the complete climatic history of the Quaternary. However, elsewhere in the United States of America (Morrison 1991; Rousseau & Kukla 1994), in Western Europe (Sommé *et al*. 1980, 1986; Lautridou 1985; Van Vliet-Lanoë, 1987; Cremaschi 1990; Antoine *et al*. 1994, 1998a, b; Rousseau *et al*. 1998a, b), Argentina (Zarate & Fasano 1989) and in New Zealand (Lowe 1996) loess successions have provided fundamental palaeoclimatic information.

The western margin of the Eurasian loess belt provides detailed pedostratigraphic and climatic records from sections located in the Rhine valley, Belgium, Northern France and Normandy (Fig. 1). These records have been correlated, providing a reliable stratigraphical framework for the Quaternary deposits in this area (Lautridou *et al*. 1983, 1985, 1986; Haesaerts 1985; Sommé *et al*. 1986; Antoine *et al*. 1998a–c). Located at the westward limit of the Eurasian loess belt, the St. Pierre-les-Elbeuf succession (Seine valley/Normandy, Fig. 1) is a key reference section. It shows four superimposed cycles mostly composed of pedocomplexes overlain by loess units (Lautridou 1985; Lautridou *et al*. 1986). They overlie a fluvial terrace, the top of which yields a particular terrestrial malacofauna dated marine isotope stage (MIS) 11 (Rousseau *et al*. 1992).

Although considerable attention has been devoted to the complete loess-palaeosol succession, little interest has been focused on the significance of the Upper Pleistocene until now. For this reason we present here a high-resolution study of the last climatic cycle of St. Pierre-les-Elbeuf.

The results are compared to the reference pedosedimentary successions of St. Sauflieu (Somme basin) and Achenheim (Rhine valley). The former provides detailed sedimentological, palynological, magnetic susceptibility (MS) and TL/IRSL records (Antoine *et al*. 1994, 1998b, c; Engelmann & Frechen, 1998), while the latter document is a continuous MS record with TL dating (Rousseau *et al*. 1994; Rousseau, *et al*. 1998a, b).

Finally, the Upper Pleistocene record of the St. Pierre succession is discussed and compared with the synthetic

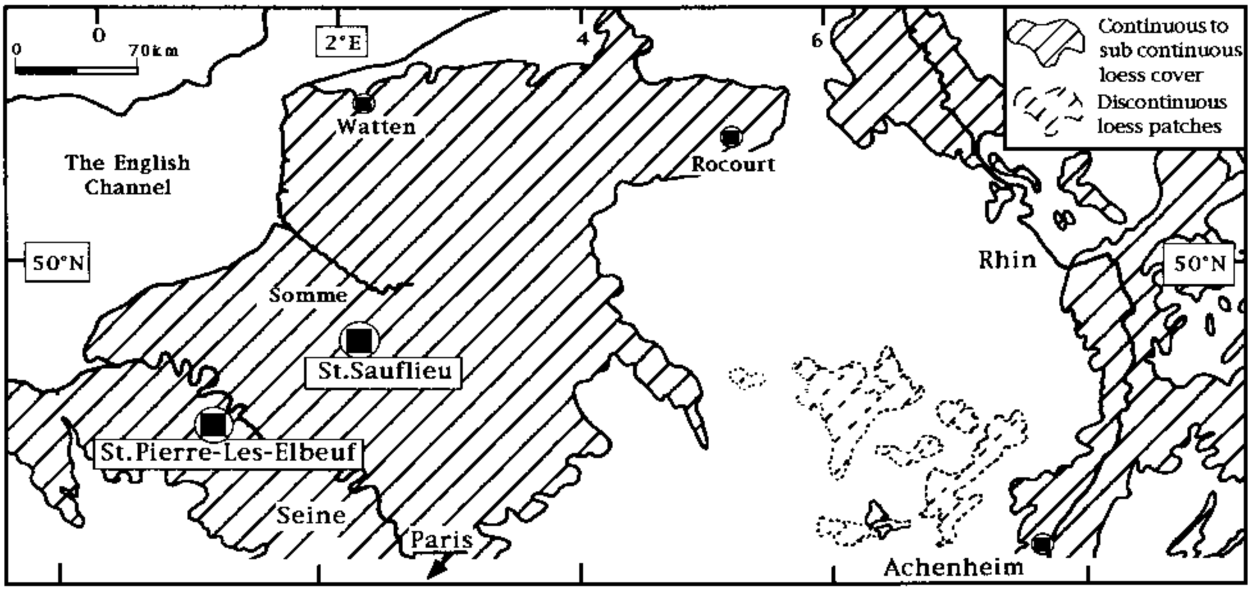

Fig. 1. Location of the sections in the west European loess belt referred to in the text.

pedosedimentary sequence of north-western France, built from the correlation of all the pedosedimentary profiles studied in this area (Antoine 1990, 1991; Antoine *et al*. 1994, 1998a, b).

Material and methods

The stratigraphy of the Upper Pleistocene loess section at St. Pierre-les-Elbeuf was described by Lautridou (1985) as being composed of two major units. At the base, a pedocomplex contains the interglacial soil (truncated Bt horizon) overlain by a grey loam with a thin bed of flint gravels on top. These are overlain by a black soil, a brown loam showing maculation, a second black soil, and a bioturbated layer (Figs 2 and 3). Overlying the pedocomplex are the loess units, beginning with a brown clayey loess with pseudomycelia at the base. It ends with a marker horizon (Figs 2 and 3, −2 m, between units 3 and 4) which can be correlated with the Nagelbeek tongue horizon (Haesaerts *et al*. 1981; Juvigné *et al*. 1996) distributed widely across western Europe (Sommé *et al*. 1986). Above this periglacial marker lies a calcareous greyish-yellow loess. This loess unit ends with a brown leached soil (Bt horizon) overlain by the humic horizon of the present-day soil (Figs 2 and 3, 0 to −1.05 m).

Ten magnetic susceptibility measurements were taken every 5 cm and averaged using a portable MS2 Bartington meter with the MS2F sensor working at a frequency of 0.58 KHz. Samples were also taken for later laboratory measurements in order to control the field data. Samples of sediment were taken in parallel with the susceptibility readings for the sedimentological study: grain-size analysis, total iron and organic-matter content. The analyses were carried out in order to improve our understanding of the variations in magnetic susceptibility related to the variable origin of the magnetic grains in the sediment (Maher & Taylor 1988; Zhou *et al*. 1990; Heller *et al*. 1991; Verosub *et al*. 1993; Jia *et al*. 1996). Finally, the pedostratigraphic investigations are based on field observations and on detailed studies of soils and loess blocks; they are complemented by earlier micromorphological data (Fédoroff & Goldberg 1982; Van Vliet-Lanoë 1987).

Stratigraphy and sedimentology

The present stratigraphy differs slightly from that reported earlier by Lautridou (1985). In this study, seven main units are identified within the succession (Figs 2 and 3). The pedosedimentary sequence begins with a slightly foliated loam ("limon à doublets") (Lautridou 1985) developed in the Saalian loess. This unit (number 10, Figs 2 and 3) is represented by a compact, clayey and non-calcareous light brown (10YR 5/8) loam with thin irregular grey lineaments (2–5 mm thick).

The first Upper Pleistocene unit is represented by a clayey, dense, brown to orange-brown loam with sparse ferromanganese nodules and thick clay coatings. It is interpreted as the Bt horizon of a brown leached soil that can be subdivided into two sub-units numbered 9a and 9b in Figs 2 and 3. At the base, a lower Bt horizon (sub-unit 9b, 7,5 YR 5/6), showing a platy structure, contains

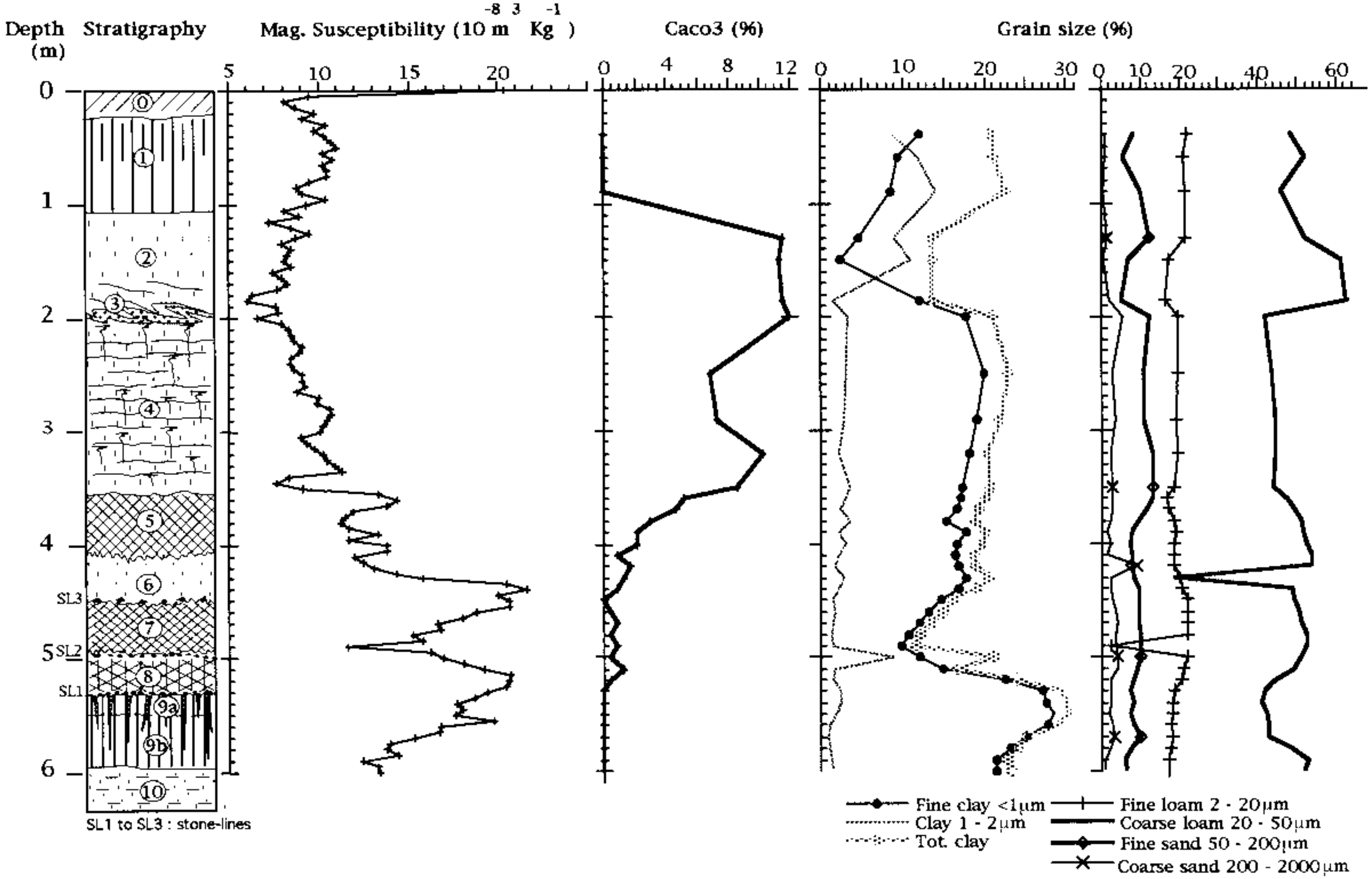

Fig. 2. Stratigraphy, grain-size parameters, carbonate content and low field magnetic susceptibility evolution in the St. Pierre-les-Elbeuf succession (description of the stratigraphical units in the text).

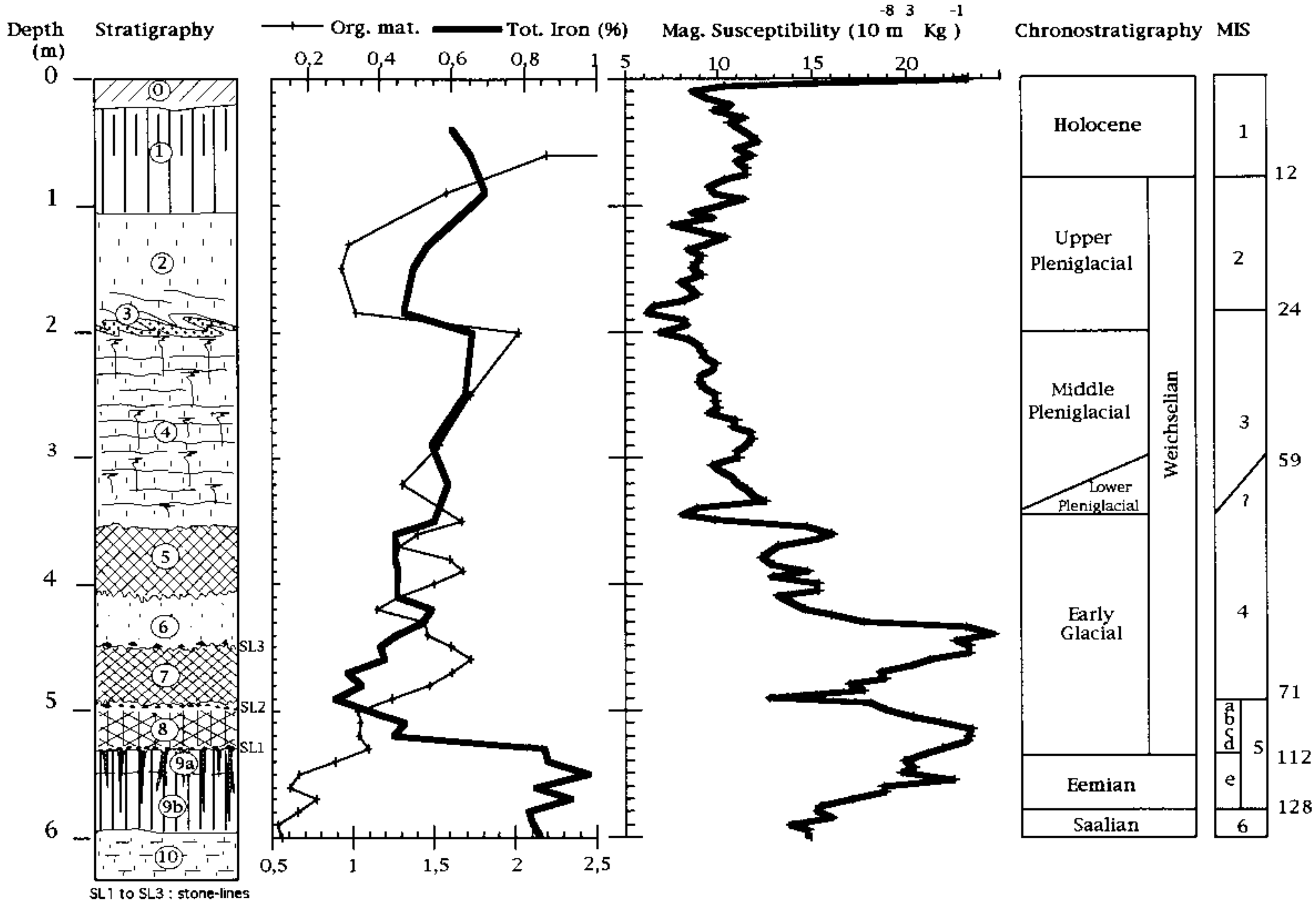

Fig. 3. Stratigraphy, total iron and organic matter, low field magnetic susceptibility and chronostratigraphical interpretation of the last climatic cycle at St. Pierre-les-Elbeuf. MIS: marine isotope stages.

thick yellow-brown argillans (clay coatings), numerous biopores and biogalleries. At the top, the upper sub-unit (9a) is a brown-orange (7,5 Y/R 4/4), more compact, clayey loam with brown spots. This bed has a polyhedral to platy structure, aggregates and numerous ferromanganese nodules. This polyphased and more complex Bt horizon shows strong dark-brown clay-humic argillans and numerous biogalleries due to earthworm activity. These characteristics are underlined by an increase in organic matter content in sub-unit 9a (Fig. 3). These two horizons are characterized by the strongest clay and iron contents in the succession (clay: 25 to 30%, total iron: 2.5%) (Figs 2 and 3). The values are very similar to those obtained from the Bt and the grey forest soil SS1 in the St. Sauflieu soil complex (Antoine *et al*. 1998b, c). Both sub-units 9a and 9b can be correlated with the Rocourt soil described in Belgium (Gullentops 1954) because of their pedological characteristics and their location in the succession. The top of the Bt is marked by erosion (sparse flint gravels: stone line 1, SL1, in Figs 2 and 3) and by the presence of a layer of soil veins (thermal contraction).

The succession then shows a humic soil complex overlaying Bt unit 9a–9b. It consists of three individual soil horizons. The basal horizon, represented by a compact grey-brown (10 YR 5/3) silty-sandy loam (unit 8 in Figs 2 and 3), shows the characteristics of grey forest soils (Van Vliet-Lanoë 1990; Gerasimova *et al*. 1996) or Greyzems (FAO 1974). This soil horizon is developed in clayey loams including numerous brown clayey nodules reworked from the interglacial horizon (colluvium). Nevertheless, at St. Pierre the pedological features of this soil are partly reworked by frost-creep and have been strongly affected by deep seasonal freezing demonstrated by the occurrence of white silt lineaments (skeletan). The development of this grey forest soil is clearly characterized by the penetration of thick dark-brown clay coatings into the underlying Bt, sub-unit 9a. This phase of grey forest-soil development is therefore responsible for the polygenic pattern and for the brown patches observed on top of the Bt in sub-unit 9a (bioturbation fed by humic loam). The reworking phase was followed by a period of deep seasonal freezing which produces a strong polyhedral pattern in unit 8 and in the underlying Bt. The top of unit 8 is also marked by an erosion surface associated with a discontinuous bed of small flint gravel (SL 2 in Figs 2 and 3).

The second soil, which is strongly bioturbated (unit 7 in Figs 2 and 3), is an isohumic steppe soil developed on colluvium (clayey loam with scattered small flints and reworked small soil nodules). This is a dark grey (10 YR 5/3 to 5/4) humified sandy-silty loam, with a weak lamellar structure underlined by thin white silt layers. It is characterized by low values of iron (1%) and an increased organic matter content (0.4–0.6%). The clay content (10–20%) is clearly lower than in typical grey forest soils (about 30%). The contrast with the lower soil (unit 8) is also reinforced by the lack of clay coatings and clayey aggregates.

Overlying this isohumic soil is a brown-light yellow loam (10 YR 6/4), slightly calcareous and humic, with pseudomicelia (unit 6 in Figs 2 and 3). This level shows the first occurrence of aeolian sediments in the succession. The relatively high clay content of the deposit is related to its partly local origin, which is also indicated by the occurrence of numerous small grains of soil (papules) originated from reworked older soils.

Finally, the soil complex ends with a second isohumic steppe soil developed on the previous aeolian deposits (unit 5 in Figs 2 and 3). This is a brown-grey (10 YR 5/4), slightly calcareous (2–8%), homogeneous humic loam. Its base is strongly bioturbated and shows numerous patches resulting from degradation of the organic matter. The carbonate content of this unit is mainly linked to secondary precipitation. Nevertheless, the general trend in the carbonate content from the base of unit 6 to the top of unit 5 is a product of the progressive increase in the allochthonous aeolian input.

The main aeolian sedimentation starts on top of the pedocomplex. The first loess is brown with foliated structures and numerous small ferromanganese nodules (unit 4 in Figs 2 and 3). This is a brown-yellow (10 YR 5/6) clayey loess (20–23% $< 2\ \mu m$), heterogeneous, calcareous (8.5–12%), more compact and more sandy than the overlying loess (units 2 and 3). Its granular to finely foliated structure (sorted platy structure) is linked to alternating freeze–thaw cycles and to the development of permafrost (Van Vliet-Lanoë 1987). The increase in carbonate content at the base of this unit is related to the abundance of pseudomicelia and carbonate precipitation on roots tracks (1–2 mm) and biopores. A tongue horizon, weakly greyish, with a stronger organic matter and iron content, marks the upper boundary of this unit. It results from the reworking of a gley horizon developed on top of the clayey loess 4 by weak gelifluxion processes. Above this marker horizon is a weakly bedded calcareous loess unit (unit 3 in Figs 2 and 3), brown-light yellow, with fine grey-brown lineaments. A cap of calcareous (12%) and homogenous, yellow-light grey loess completes the succession, (unit 2 in Figs 2 and 3). Both calcareous loess units 3 and 2 are characterized by a strong increase in coarse loam (20–50 μm) and carbonate content. The contrast with the underlying brown loess 4 is reinforced by a rapid decrease in organic matter, iron and clay content (Figs 2 and 3).

Finally, the upper soil includes a Bt horizon (unit 1), represented by a compact clayey (20% $< 2\ \mu m$) brown loam (7.5 YR 5/6), displaying a prismatic structure, numerous fine biopores and root tracks, and the surface humic horizon (unit 0: brown-grey humic loam with granular structure).

Summarizing the results, the content in organic matter increases from the bottom of the succession until the tongue horizon (Fig. 3). This trend is almost constant, except in the soil complex. The tongue horizon shows a sharp and strong decrease in the values that remain low within unit 2, but increase again in unit 1. The total iron content reflects the identified stratigraphy, indeed the interglacial Bt contains the highest iron content (around 2–2.5%), while the rest of the succession shows values of 1–1.5%, the lowest value being at the base of the first steppe soil (unit 7) (Fig. 2).

Low field magnetic susceptibility (MS)

MS values vary between 6 and 22 SI units. These values are relatively low compared with those of other published loess successions (Heller & Liu 1984; Kukla *et al*. 1988; Forster & Heller 1994; Rousseau *et al*. 1994; Rousseau *et al*. 1998a). The highest values occur in the polyphased Bt (top of sub-unit 9a), the black soils and the humic horizon of the top soil (respectively, 20.5, 21.5 and 20.5 SI units). At the base of the studied section, MS values are low (close to 13 units) and correspond to the top of the Saalian loess (MIS 6, Lautridou 1985). Above this point the susceptibility increases to 20.5 units on top of the Bt horizon (sub-unit 9a). MS decreases progressively in the grey loam (unit 8) and shows very low values at the boundary between unit 7 and 8 (−5.00 m).

MS then increases again towards the top of unit 7 and reaches the highest values near the upper boundary of the first steppe soil (unit 7). Above this black layer, MS decreases almost regularly (from 21.5 to 7) in the three units immediately overlying the black soil 7 (6 to 4). Nevertheless, a short increase in MS values clearly marks the top of the second steppe soil (unit 5 at −4.6 m).

The readings in the first typical loess unit (3) indicate a slight trend towards the lowest values obtained above the tongue horizon in the calcareous bedded loess at approximately −1.8 m. In the last loess unit (2), the values are very low and almost stable. On top of the succession, the Bt horizon of the top soil indicates relatively low values compared with those of the Last Interglacial Bt. Finally, as generally observed, higher values are obtained in the present-day humic horizon near the surface (20.4).

Pedosedimentary evolution, correlations and climatic interpretation

The general pattern of the St. Pierre succession described above shows a relatively condensed pedosedimentary record of the Last Interglacial–Glacial cycle according to the North-European Upper Pleistocene stratigraphy (Paepe & Sommé 1970; Sommé *et al*. 1980, 1986; Lautridou *et al*. 1983, 1985, 1986; Haesaerts 1985; Lautridou 1985; Antoine 1990; Antoine *et al*. 1994, 1998a, b; Rousseau *et al*. 1994, 1998). This interpretation is reinforced by the occurrence, at St. Pierre, of the main pedological and periglacial marker levels of the Upper Pleistocene – the Rocourt Soil, the St. Sauflieu/Warneton humic soil complex and the Nagelbeek tongue horizon.

Basal soil complex (units 9 to 5)

The base of the St. Pierre-les-Elbeuf succession is represented by the non-calcareous foliated loam (unit 10 in Figs 2 and 3). The relatively large susceptibility in this unit is related to the occurrence of clayey layers in the foliated loam resulting from an early clay illuviation prior to the development of the typical Bt, unit 9. This early illuviation has been interpreted as the result of permafrost degradation during the Weichselian Late Glacial (Lautridou 1985; Van Vliet-Lanoë 1987).

The whole unit 9 (9a and 9b) is interpreted as a complex Bt horizon of a brown leached soil. It shows the same characteristics as the Rocourt soil of Northern France and Belgium stratigraphy, and is generally considered to be the pedological equivalent of the Eemian (Gullentops 1954). Nevertheless, it has been shown, using micromorphological analysis, that this soil could be a polygenic Bt corresponding to soil development during MI Substages 5a to 5e (Haesaerts & Van Vliet-Lanoë 1981; Van Vliet-Lanoë, 1987), especially in plateau positions where there is no colluvial sedimentation during MIS 5d to 5a (Antoine *et al*. 1998b, c). At St. Pierre-les-Elbeuf the lower part of the soil complex (units 9 to 8) results from the succession of the following pedosedimentary events:

1. Development of a brown leached soil (unit 9) in the Saalian loess (10).
2. Hydromorphic phase marked by some glosses, grey patches and ferromanganese concretions on top of unit 9 (beginning of the differentiation of sub-unit 9a).
3. Erosion, followed by a first deep freezing phase associated with the opening of soil veins on top of sub-unit 9a.
4. Colluvial sedimentation of sandy clayey loam fed by the erosion of the soils of unit 9 on a slope surface (material for future soil of unit 8).
5. Development of a grey forest soil (unit 8), bioturbation and migration of the clayey-humic coatings in the horizon 9a (end of the pedological differentiation of 9a).
6. First phase of reworking of the grey forest soil (erosion and reworking by frost creep).
7. Major phase of deep seasonal freezing with development of a strong polyhedral to lamellar structure in units 8 to 9b (minimum depth of 1 m).

At the base of the St. Pierre profile the succession of units 9a and 9b is characteristic of polyphased horizons. The polyphased feature clearly occurs in both macro

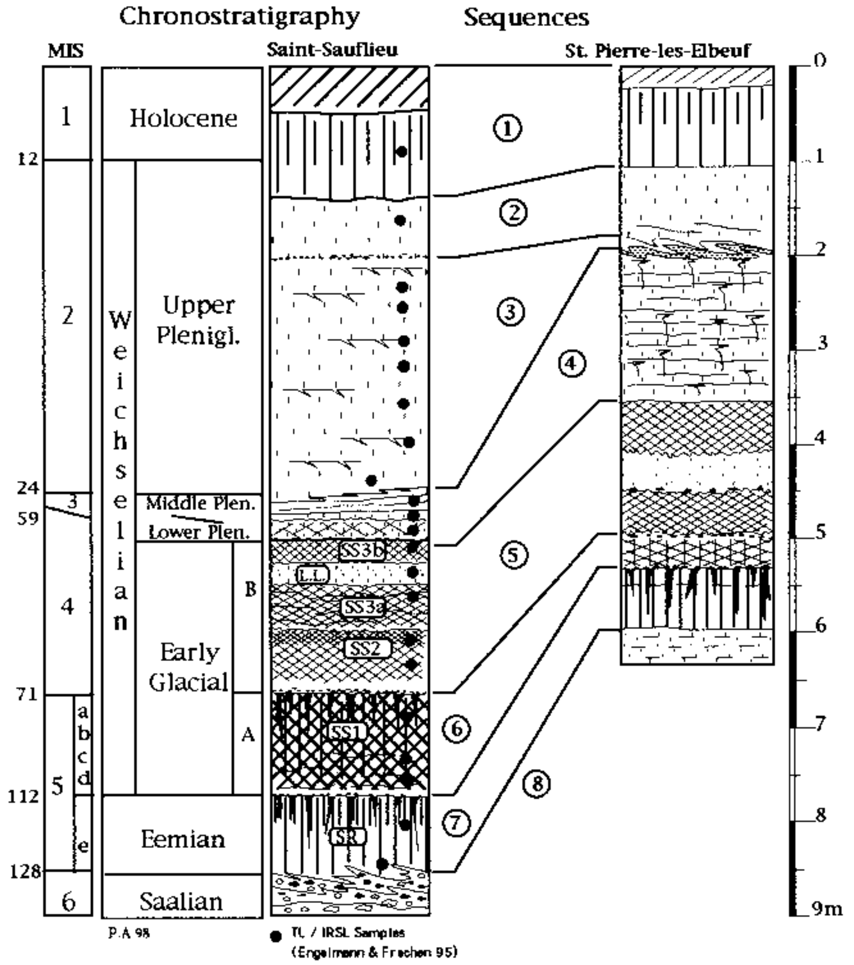

Fig. 4. Stratigraphic correlation between the successions in St. Pierre-les-Elbeuf and St. Sauflieu and general chronostratigraphical interpretation. 1 – top soil (humic horizon and Bt horizon); 2 – homogeneous calcareous loess; 3 – bedded calcareous loess with small frostcracks; 4 – lense of bedded loam with reworked soil nodules (St. Sauflieu), and clayey brown loess (St. Pierre); 5 – isohumic steppe soils (SS2 to SS3b) and aeolian loam (LL); 6 – grey forest soil with stone line and hydromorphic horizon at the top (SS1); 7 – Bt horizon of brown leached soil with soil veins, hydromorphic horizon and fine stone line at the top (Rocourt / Elbeuf 1 soil); 8 – Saalian deposits (loess at St. Pierre, chalky slope deposits at St. Sauflieu).

and microfacies and in the sedimentological data as a consequence of the superimposition of the humic grey forest pedogenesis on the previously truncated Bt. The evolution of the susceptibility in these horizons thus results from the occurrence of a polyphased pedogenesis in the upper part of sub-unit 9a and of the combination between pedogenesis and slope processes in unit 8 (Figs 2 and 3).

The same evolution has been described in the lower part of the St. Sauflieu soil complex, near Amiens (Fig. 1), which is the reference succession for the Weichselian Early Glacial in Northern France (Antoine *et al*. 1994, 1998b). There, the grey forest soil Saint-Sauflieu-1 (Fig. 4, SS1), overlying the Eemian Bt, is related to a continental climate according to the palaeopedology (Antoine 1989, 1990) and to the pollen analysis (Antoine *et al*. 1994; Munaut 1998). This soil is contemporaneous with a boreal forest (AP = 70–80% dominated by *Betula* and *Pinus*). It is interpreted as the Bth horizon of a complex grey forest soil corresponding to the succession of the two Early Glacial forested interstadials (Brörup and Odderade) separated by the Rederstall stadial and is time-equivalent to MIS 5c to 5a (Antoine *et al*. 1994, 1998b). Although the main geomorphological response is observed just after the Eemian during the Herning Stadial (erosion and reworking of all the Eemian deposits) in Northern France (Sommé *et al*. 1994), the Rederstall Stadial did not have a strong impact on the environment. At Watten it is only marked by a lowering in the AP/NAP curve (Sommé *et al*. 1994). This observation could explain why the succession of the Brørup and Odderade interstadials is not clearly recorded as two distinct soils in northwestern France slope environments.

Nevertheless, the equivalent of the SS1 soil in St. Pierre-les-Elbeuf (unit 8) is reworked, as indicated by the degradation of the pedological features, by much lower values in organic matter, total iron and clay content (15–20%), and by the presence of carbonate (1%). Indeed, in St. Sauflieu the typical grey forest soil shows a clay content rising to 32–33% and no carbonates.

After a period of strong erosion marked by the stone line SL2 (Figs 2 and 3), the upper part of the soil complex (units 7 to 5) at St. Pierre is characterized by steppe soils and by the occurrence of aeolian sedimentation in a similar stratigraphic location than in the reference section of St. Sauflieu. Indeed, at St. Sauflieu the grey forest soil SS1 (Fig. 4, unit 6) is overlain by three isohumic steppe soils labelled SS2, SS3a and SS3b (Fig. 4). This part of the soil complex is interpreted as the steppe phase of the Weichselian Early Glacial (Antoine *et al*. 1994, 1998b). The comparison between the two successions then allows a more precise interpretation of the St. Pierre succession where TL data are not yet available.

The pedological and sedimentological characteristics of unit 7 indicate an isohumic steppe soil developed on sandy-loamy colluvium fed by the erosion of the underlying horizons. This soil is characterized by low values of clay content (10–17%), values 50% lower than those recorded from the grey-forest horizons. This soil subsequently underwent a stage of seasonal freezing less developed than the one occurring on top of unit 8. According to its characteristics and its stratigraphical position, unit 7 can be correlated with the SS2 soil of the St. Sauflieu complex in the Somme valley (Antoine 1989, 1990; Antoine *et al*. 1994). This soil is characterized by high organic matter and a relatively low iron and clay content (Figs 2 and 3). In contrast, the Bt of the brown leached soil 9b is characterized by some elevated values of total iron and clay (mainly fine clay <1 μm).

On top of the soil of unit 7, a non-calcareous homogeneous brown clear yellow deposit shows a loess texture. It strongly differs from the underlying heterogeneous colluvium. This first loess deposit is marked by a progressive decrease in both susceptibility and organic matter, and by an increase in the carbonate content. Such trends characterize the progressive arrival of aeolian material, which is less rich in elements removed from the underlying soils. The high MS values observed in the first centimetres of this deposit (Fig. 3, -4.4 to -4.5 m) could result from the reworking of the magnetic minerals of the top of soil 7 by aeolian activity.

A new increase in the susceptibility occurs from the bioturbated boundary between units 6/5 reaching a maximum within the isohumic soil 5. This unit yields the facies of a second isohumic steppe soil which could be correlated with the SS3b soil at St. Sauflieu (Fig. 4). The mean values of the magnetic susceptibility are considerably lower than in the previous soil (unit 7). The progressive increase in carbonate content from the base to the top of unit 5 (2–8.5%) is interpreted to be the result of the increasing aeolian input.

Soils 7 and 5 are interpreted as corresponding to the steppe phase of the Early Glacial (Early Glacial B, Fig. 4). This succession, characterized by the occurrence of slightly calcareous autochthonous loess (unit 5), then by some isohumic steppe soils, corresponds to dry climatic continental oscillations at the end of the Weichselian Early Glacial. This steppe-soil succession is assumed to occur at the transition between MIS 5a and MIS4, based on pollen and palaeopedological data (Antoine *et al*. 1994,) but also recent TL and IRSL dates (Engelmann & Frechen 1998). Despite the lack of accuracy of TL dates, new results from Achenheim (Rousseau *et al*. 1998a, b) and from St. Sauflieu (Antoine *et al*. 1998b) support this interpretation. According to the high resolution climate records from the Greenland ice cores these short climatic oscillations could be the continental response to interstadials 19 and 20 dated around 68 and 72 Ka BP (Dansgaard *et al*. 1993; GRIP 1993). Consequently, the succession of the soil complex at St. Pierre-les-Elbeuf (units 9b to 5) represents a complete record of the whole MIS 5 and early MIS 4 in the particular geomorphological context of slope environment. Generally, the present study shows that the humic soil complex at St. Pierre-les-Elbeuf is typical of the pedosedimentary succession in Northern France (Figs 4 and 5).

The Loess succession

The loess succession begins with a brown to yellow-brown clayey loess facies with a finely laminated structure (unit 4, -3.5 to -2 m). This first loess unit is clearly distinguished from the above calcareous loess, units 2 and 3, by its highest clay content. The iron and organic contents are also much higher and show similar values to those from the upper part of the soil complex. These values tend to increase similarly and progressively toward the top of the unit.

In contrast, the magnetic susceptibility shows a general decreasing trend intersected by three poorly marked peaks. The susceptibility reaches very low values on top of unit 4, near the boundary with the loess unit 3. This loess can be correlated with the brown heterogeneous loess of the Somme basin, which is interpreted to represent the pedosedimentary budget of the Middle Weichselian Pleniglacial (MIS 3). In fact this unit corresponds to the accumulation of several phases of loess deposition separated by weak episodes of pedogenesis associated with the different relative climatic improvements which occurred during MIS 3 (boreal to arctic brown soils, numbered 8b and 8a in Fig. 5). At St. Pierre-les-Elbeuf, no distinct soil horizon is visible on top of this brown loess as it is observed in the Somme (Soil of St. Acheul, Antoine 1990) or in the Oise basins (soil complex of St. Acheul/Villiers-Adam, Bahain *et al*. 1996, Antoine *et al*. 1998a, b), in Germany (Löhner Boden, Bibus *et al*. 1989) or in Hungary (Mende F1 and F2 soils, Pecsi 1990).

The top of unit 4 is marked by a soliflucted gley horizon which is a major stratigraphic marker horizon. This level is punctuated by a network of ice wedges marking the beginning of the Upper Pleniglacial in the Weichselian loess successions in Northern France (Fig. 5) (Antoine 1990, 1991, 1998a). This horizon occurs in other Norman sections and notably at Glos (Lautridou

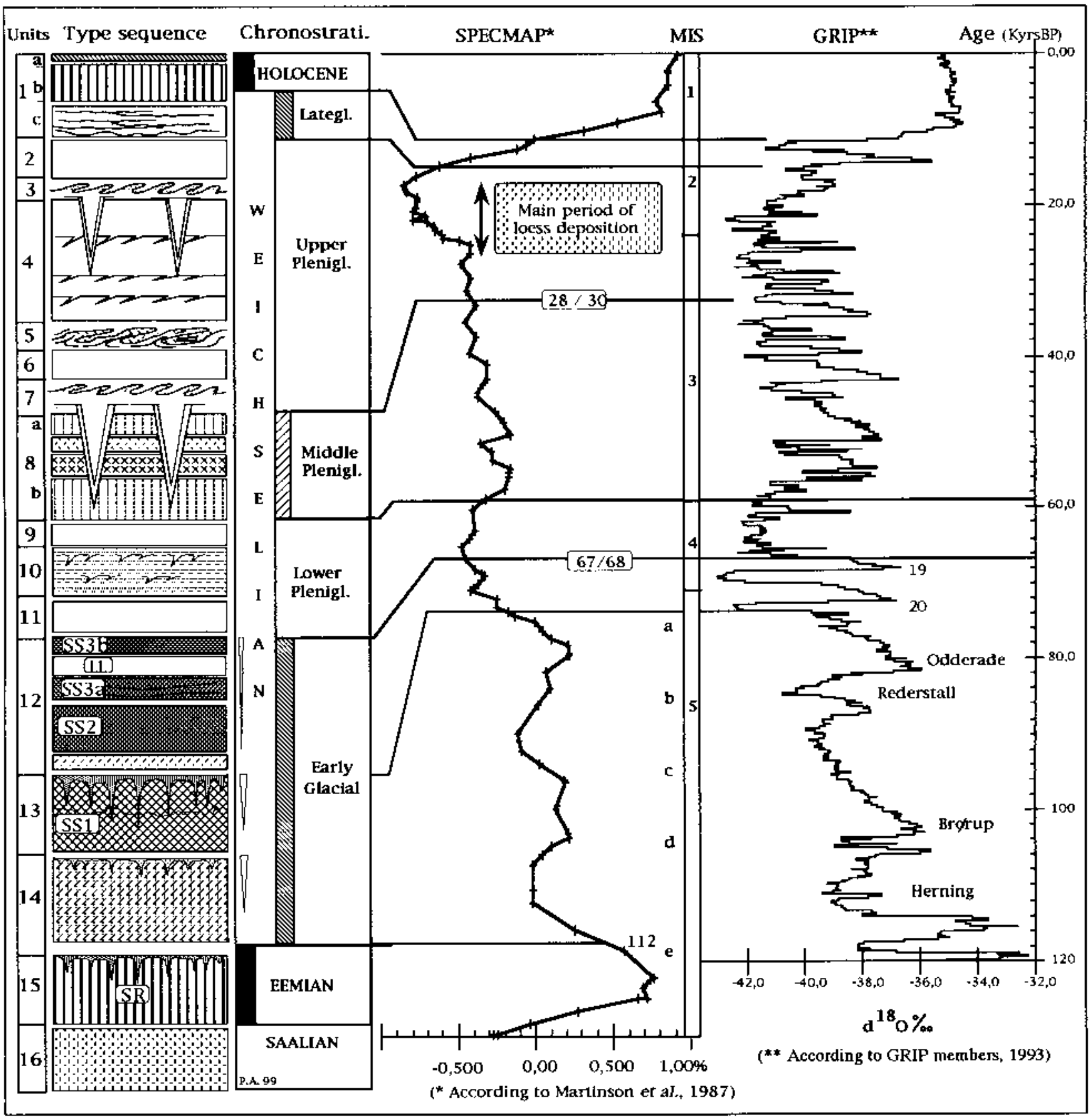

Fig. 5. Correlation between the synthesized pedosedimentary record of the last climatic cycle in northwestern France and the marine and glacial $d^{18}O$ records. 1 – Surface soil (a: Hz L; b: Hz Bt; c: Banded Bt hz "doublets"); 2 – calcareous loess 3 – Nagelbeek tongue horizon; 4 – bedded calcareous loess; 5 – cryoturbated tundra gley; 6 – calcareous loess; 7 – tongue horizon / ice wedges; 8 – Saint-Acheul / Villiers Adam soil complex (a – arctic brown soil; b – boreal brown soil); 9 – calcareous loess; 10 – bedded colluvium with frost wedges; 11 – brownish loess; 12 – Steppe-soils (SS2 to SS3b) with interstratified local non-calcareous loess (LL); 13 – grey forest soil (SS1); 14 – clayey colluvium; 15 – Bt horizon of brown leached soil (Rocourt / Elbeuf 1 soil); 16 – Saalian loess.

1985) and in Belgium on top of a boreal soil (Haesaerts 1985).

A further reference level, characterized by weakly organic periglacial features ("tongue horizon"), is described in North Western European successions in the upper part of the Weichselian calcareous loess, and especially in Belgium where it has been named Nagelbeek Horizon (Haesaerts *et al.* 1981). This horizon has also been observed in the Achenheim succession, where it has been dated by TL (24.0 ± 7 Ka BP, Rousseau *et al.* 1998a). It was first dated at about 21 00–22 000 BP by C^{14} (Haesaerts *et al.* 1981) and is now interpreted as the MIS 3/2 boundary (Juvigné *et al*. 1996). However, in St. Pierre-les-Elbeuf, the tongue horizon that underlines the base of the calcareous loess is probably polyphased because of the weak thickness of units 2 and 3, which represent only the youngest part of the Upper Pleniglacial loess in Fig. 5 (no. 2). This tongue horizon could therefore represent both the first reference level (soliflucted gley) and the Nagelbeek horizon (Fig. 5, nos 7 and 3).

The occurrence of typical calcareous loess (unit 3) is marked by a clear decrease in the susceptibility, organic matter and iron, and a strong increase in the carbonate content. These features correspond to the input of allochthonous unweathered material, characteristic of the calcareous loess of the Upper Pleniglacial (Haesaerts 1985; Lautridou, 1985; Antoine 1990). However, at St. Pierre-les-Elbeuf, the rapid increase in susceptibility, iron and organic matter contents, observed from the mid-section of the calcareous loess, is due to the contamination of its upper part by percolation of iron and of organic matter from the surface. This downward migration is facilitated by numerous root tracks between 0 and -1.5 m and deep cracks induced by the strong prismatic structure of the present Bt horizon. It is interesting to note that the lowest values of the magnetic susceptibility for the last climatic cycle are obtained from the MIS 2 loess deposits as noticed in the Achenheim (Rousseau *et al*. 1998) and St. Sauflieu loess successions. This again is a strong argument for a reliable correlation with the Greenland ice cores which record the highest dust content during MIS 2 (Dansgaard *et al*. 1993).

The succession ends with the Bt horizon of the surface soil (unit 1). It is characterized by a progressive increase in the values of the susceptibility, which reach a maximum in the middle part of the Bt, followed by a relatively less marked decrease on top. In parallel, the organic matter content increases quickly near the surface. These characteristics are due to the enrichment by organic accumulation from the humiferous unit 0, which shows very high susceptibility values characteristic of the superficial organic horizons (Rousseau *et al*. 1994).

Although more condensed, the stratigraphic succession of the loess deposits at St. Pierre-les-Elbeuf shows very strong similarities with the corresponding newly described Upper Pleistocene stratigraphy at Achenheim (Rousseau *et al*. 1998a, b). Both successions start with a pedocomplex, including an interglacial Bt horizon overlain by a grey forest soil (units 9 and 8 at St. Pierre-les-Elbeuf). At St. Pierre-les-Elbeuf, as at St. Sauflieu, a loess loam (unit 6 in Figs 2 and 3, LL in Figs 4 and 5) is located below the last steppe soil (unit 5). This loess loam is in a similar stratigraphic position to a fine silt layer located at the top of the soil complex at Achenheim and identified as a dust layer (Rousseau *et al*. 1998b). A TL date of 64.9 ± 6.9 Ka BP from that deposit allows this dust layer to be correlated with the Marker II (Kukla 1977) at about the MIS 5/4 boundary of the Central European loess stratigraphy.

Compared with the main loess accumulation of the Pleniglacial, these first aeolian loams (LL in Figs 4 are 5) are only trapped in lower slope positions and include several autochthonous sediments. These first aeolian deposits (unit 6 at St. Pierre, LL in Figs 4 and 5) are then covered by the last steppe soil (SS3b), followed by the first Pleniglacial loess (11 in Fig. 5), and finally covered by bedded colluvial sediments (10 in Fig. 5). A similar unit of colluvial sediments is observed in Alsace, where it yields steppe molluscs (Rousseau 1987; Rousseau & Puisségur 1990).

Both successions indicate that the main phase of loess deposition started during mid-MIS 4 and not at its beginning. In that case, according to the GRIP dust record (Dansgaard 1993; GRIP 1993), the start of the loess deposition in both continental loess successions corresponds to the major dust peaks dated around 65 Ka BP in Greenland (Rousseau *et al*. 1998a, b).

Magnetic susceptibility variations and pedological processes

The relationship between the MS variations and the pedosedimentary processes in the Eemian/Early Weichselian soil complexes and in the Weichselian loess is documented by the data from St. Pierre, Achenheim, St. Sauflieu and some additional profiles (Antoine 1998b). The comparison of the different identified Bt horizons indicates that the highly eroded Bt horizons are characterized by the lowest MS values. The MS values in the Bt are thus related to their degree of erosion and with their geomorphological setting. The strongly eroded Bt as at St. Sauflieu shows the lowest MS values, whereas the plateau Bt indicates higher values. Generally, the intensity of MS reaches a maximum in the upper part of the Bt horizons (0.2 to 0.4 m), and especially when this part shows superimposed humic-clay coatings (grey forest soil), as at St. Pierre in subunit 9a. In addition, the highest values of MS are recorded in the upper part of the grey forest soils, where the clay, total iron and total organic carbon values are at a maximum, as observed in the upper part of the SS1 soil at St. Sauflieu (Antoine *et al*. 1998c). At St. Pierre the relatively low MS values on top of grey forest soil 8 are linked to the destruction of the magnetic minerals by hydromorphy and freeze–thaw processes. Finally, very high MS values are also observed in the humic horizon of the top soil at St. Pierre as in all the other studied profiles.

These observations show that the MS signal recorded in the basal soil complexes of Upper Pleistocene successions from north-western France has a pedological origin and can be linked to the production of magnetic minerals by biological activity, as has been demonstrated from China's palaeosols (Maher & Taylor 1988; Maher & Thompson 1992). This interpretation has been proposed for the magnetic record of pedocomplex Achenheim 1 from the Upper Pleistocene succession in Achenheim (Rousseau *et al*. 1998a). The relationship is clear in the St. Sauflieu soil complex, where the maximum MS values correlate with the maximum organic carbon values in the grey forest soil and not in the interglacial Bt horizon (Antoine *et al*. 1998b). Despite differences in environment, relatively high values are also obtained in the steppe soils as in unit 7 at St. Pierre. Therefore, it is not possible to use the susceptibility measurements of Northern France Eemian/Early Weichselian bottom soil complexes as a direct record of the climate, as was done in the Chinese loess series. The intensity of the MS signal is thus linked to the amount of organic carbon, which shows two main types: organic matter linked to clay in the grey forest soils (humic-clay coatings) or organic microaggregates scattered in all the horizon in the isohumic steppe soils. In the studied soil complexes the highest MS values are therefore not related to full interglacial conditions but to the already cooler Weichselian Early Glacial interstadials. Indeed in North-western Europe brown leached interglacial soils the magnetic minerals seem to be produced in the humic horizon, and only a small percentage is leached into the underlying Bt.

In contrast, during the Weichselian Pleniglacial the relationship between MS and climate appears more direct. Indeed, the lowest values of MS are systematically linked to cold periods in the typical calcareous loess during stage 2, as seen in unit 2 at St. Pierre in which no weathering nor pedogenesis has been recognized. Very low MS values are also observed in the hydromorphic horizons, which record cold phases on top of the Bt or of the grey forest soil, or in the tundra gleys. In these horizons the low MS values results from the destruction of the magnetic minerals by hydromorphic processes.

Conclusions

This study of both the magnetic susceptibility and sedimentological parameters in the loess succession at St. Pierre-les-Elbeuf indicates a weakly dilated but detailed pedosedimentary record of the last climatic cycle.

The pedosedimentary record at the base of the succession is similar to the reference soil succession of St. Sauflieu in northern France, where the Early Glacial interval is especially well recorded (Antoine *et al*. 1994, 1998b, c). This succession is also in agreement with the interpretation of the pedocomplex at the base of the loess succession at Achenheim, where TL dates (Rousseau *et al*. 1998a, b) indicate that the corresponding interval lasted from the last interglacial to the mid-marine isotope stage 4, i.e., 129–69 Ka BP. Furthermore, the occurrence of a widely recognized marker level within the Pleniglacial loess deposits constrains the St. Pierre-les-Elbeuf succession and allows comparison with global signals.

Considering the magnetic susceptibility related to aeolian input, the lowest values are recorded in the calcareous loess dated to about 20–24 Ka BP and are coeval with the highest dust content in the atmosphere over Greenland characterizing MIS 2. On the other hand the weakly developed and weathered lower loess unit (number 4 in Figs 2 and 3), interpreted as corresponding to MIS 3, shows variation in the susceptibility, indicating a succession of at least three oscillations of decreasing magnitude. These oscillations could possibly correspond to the $\delta^{18}O$ record for MIS 3 by SPECMAP (Martinson *et al*. 1987), but TL dates are needed to confirm this interpretation.

In addition, the variations in magnetic susceptibility, together with pedological and sedimentological data, at St. Pierre-les-Elbeuf and St. Sauflieu, suggests a succession of rapid climatic oscillations at the end of the Early Glacial. These variations are correlated with those identified in the reference succession in St. Sauflieu (soils SS2, SS3a and SS3b in Fig. 5). The characterization of these oscillations shows that slope environments recorded palaeoclimatic variations with similar complexity to that observed in the GRIP Greenland ice cores.

The MS signal from north-western France Eemian/Early Weichselian soil successions appears to be complex and thus difficult to use as a direct proxy of past climates. Indeed, strong peaks are, for example, observed in early stage 4 and not just in stage 5, as in the Chinese loess. The signal is more easily interpreted during the Pleniglacial, where the coldest phases, characterized by typical loess deposition, are clearly attested by the lowest MS values. Finally, this detailed study of the St. Pierre-les-Elbeuf provides new data which allow the synthetic pedosedimentary succession of north-western France to be reinforced.

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