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Quantification and regulation of organic and mineral sedimentation in a late-Holocene floodplain as a result of climatic and human impacts (Taligny marsh, Parisian Basin, France)

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Abstract: Quantification in grams per metres squared per year of the sediment accumulation in a flood plain ('marsh') located in the southwestern Parisian basin showed that there is no close relationship between the accumulation of organic matter (OM) and mineral matter (MM) during the late Holocene, and provided an accurate view of the distinct yield and storage conditions of both sediment components. Endogenic OM accumulation in peaty sediments is not related to the climate but to felling of the alder forest and its substitution by Cyperaceae and paludal taxa in the marsh (Iron Age and Middle Ages). MM accumulation expresses mainly the sediment yield on the slopes, determined by landuse. During an initial phase (from the late Neolithic to the early Middle Ages), land-use change from crop cultivation to pastureland, possibly related to climate deterioration, led to a decrease in the sediment yield. During a second phase, since the early Middle Ages, the considerable development of crop cultivation over pasturing, even during periods of climate deterioration (such as the 'Little Ice Age'), led to a sharp increase in sediment yield. However, although sediment yield was high, the hydrodynamics in the fen did not favour particle retention. Thus, since the Neolithic, yield and storage of OM and MM sediment have been marked by human activities, initially with high climatic stress, but since the Middle Ages without significant climatic stress.

Key words: Flood plain, alluvium, peat, quantification of sedimentation, sediment yield, response to climate and land-use change, late Holocene, Parisian basin, France.

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Introduction

Lateglacial and Holocene fluvial sediment piles of the west European valleys are often composed of organic matter- (OM) rich beds whose origin is mainly endogenic (peat *sensu lato.*), alternating with silty-clayey to sandy-gravelly detrital beds, mainly composed of mineral matter (MM) yielded by the catchment (Huault and Lefèvre, 1983; Haeserts, 1984; Starkel, 1991; Bohncke and Vandenberghe, 1991; Burrin and Jones, 1991; Vandenberghe *et al.*, 1994; Visset *et al.*, 1999). OM-rich beds are generally related to periods of low detrital supplies and stability of morpho-sedimentary evolution due to climate improvement or a low level of human activity; detrital beds are mainly related to periods of increasing erosion due to climate deterioration or deforestation for arable farming (Vandenberghe *et al.*, 1994; Pastre *et al.*, 1997; Antoine *et al.*, 2002; Orth *et al.*, 2004).

The identification and interpretation of these sediment sequences are based on the observation of their facies and the analysis of their main mineral and organic components using the standard methods of sedimentary petrography. Analytical results are expressed as a percentage (weight) of the bulk sample, from which it can be inferred that an OM-rich bed (thus MM poor) was deposited during a period unfavourable to detrital sedimentation, and *vice versa*. The sedimentation rate expressed in 10^{-3} m/yr implies that the storage processes and the fabric of organic and mineral components are similar, but this is not in fact the case. We have shown (Macaire *et al.*, 2005) that the specific mass accumulation rates of OM on the one hand and MM on the other must be calculated in order to obtain an accurate view of the relationship between these two sediment components.

The accumulation rate of fluvial sediments depends on several controlling factors: (1) the sediment yielded by the catchment (mainly MM particles) and the retention capacity of this exogenic matter in the sedimentation basin, and (2) the endogenic production of matter (mainly OM) and the ability of the basin to preserve that matter (Berglund, 1991). In a catchment of given lithology and morphology, the factors controlling sedimentation are the vegetation and hydrological conditions related to climate and, during the Holocene, to human activities (Meade *et al.*, 1990). By quantifying the accumulation rates (Ar) of OM and MM separately, it is possible to interpret more accurately the environmental factors controlling the sediment origin.

The aim of this paper is to analyse the impact of climate variations and human activities on the fluvial sedimentation in the downstream stretch of a river in the Parisian basin. The mass accumulation rates of OM (ArOM) and MM (ArMM) were quantified and correlated with some proxies of the palaeoenvironments (vegetation and malacofauna) in order to understand the origin of each of these two sediment components. From petrographic analysis of the sediments, the location of the sediment yield area and the hydrological conditions of the transfer and storage of matter in the basin were defined. Finally, this study gives some information about the interactions between a global variable, the Holocene climate, and a regional variable, namely human activities (Zolitschka *et al.*, 2003), in a sedimentary basin of western Europe.

The Taligny marsh

The Taligny marsh is located in the downstream stretch of the River Négron, a tributary of the Vienne, in the southwestern Parisian Basin, about 60 km southwest of the town of Tours (Figure 1). The Négron catchment covers an area of 162 km^2 with an elevation of 35 to 120 m. The bed-rock is composed of Oxfordian limestones and marls, Cenomanian sands and marls, and Turonian chalks covered with Senonian and Eocene clay, sand and conglomerate with flint (Alcaydé and Joubert, 1987; Alcaydé *et al.*, 1989). Upper Pleistocene loess, with a mean thickness of 1 m, and colluvium, mainly located in cultivation terraces called ‘rideaux’, cover the bedrock locally.

The Taligny marsh, a Mecca of French literature (site of the Picrocholine war in François Rabelais’ *Gargantua*, 1535), is located in a 2.8 km × 300 m (maximum) depression, at a mean elevation of 36 m on Cenomanian deposits, and is surrounded by Turonian chalk hills (Figure 2). It is supplied with water by the River Négron and two of its tributaries, the Chavenay and the Quincampoix. In the southern part of the marsh, the water flows through two perennial, artificial channels: channel A, located upstream at the western edge of the valley and downstream at the eastern edge near former water mills, and channel B located in the axis of the marsh, about 1 m lower than channel A. The mean water discharge of the Négron is 0.42 m^3/s (Oubelkasse, 1998). Today, the marsh is covered with reedbeds, Caricaeae and poplar plantations. It is filled with sandy-gravelly to organic silty-clayey sediments and peat, with a maximum thickness of 5.80 m. The detrital sediments stored in the marsh were evaluated at 4.1×10^6 t, ie, about one-third of the whole fluvial store (12.8×10^6 t) deposited in the Négron catchment (Macaire *et al.*, 2002).

Sampling and methods

The marsh sediments were studied from 33 core drillings carried out with a percussion sampler. Four drillings (T9, T19, T22 and T24) were performed no more than 5 m apart in the middle of the marsh (47°07′812 N; 0°11′494 E) where the sediment infill is representative and is at its thickest (Figures 2 and 3). Sediment samples were collected by increments of 10 to 15 cm (39 samples) in the T19 drilling.

Mollusc shells were separated out prior to sediment analysis. OM (1), silicate and oxy-hydroxide (2) and carbonate (3) contents were determined for each sample (% mass of the bulk without shells):

(1) OM content was calculated by multiplying by two the content in total organic carbon (TOC) determined by Rock-Eval pyrolysis (Duchaufour, 1983). The hydrogen index (HI in mg HC/g TOC) gives information on the quantity of released hydrocarbon indicating the terrestrial or lacustrine origin of the OM, and the cracking temperature ($T_{\max}$ in °C) characterizes the degree of OM maturation (Espitalié *et al.*, 1977);
(2) carbonate content was obtained by calculating the difference between the weight of the bulk (10 to 50 g according to the sample) and the weight of the residue after dissolution of the carbonates in HCl 1N;
(3) silicate and oxy-hydroxide content were calculated as the difference between 100% and the OM and carbonate contents. (2)+(3) is the mineral matter (MM).

After eliminating organic fragments, the grain size of the bulk of the sediment was analysed by wet-sieving for the gravel and sand sizes and by laser microanalysis (Cilas 920) for the silt and clay sizes. The mineralogical composition of the clay fraction (< 2 μm) was determined by XRD. Semi-quantitative

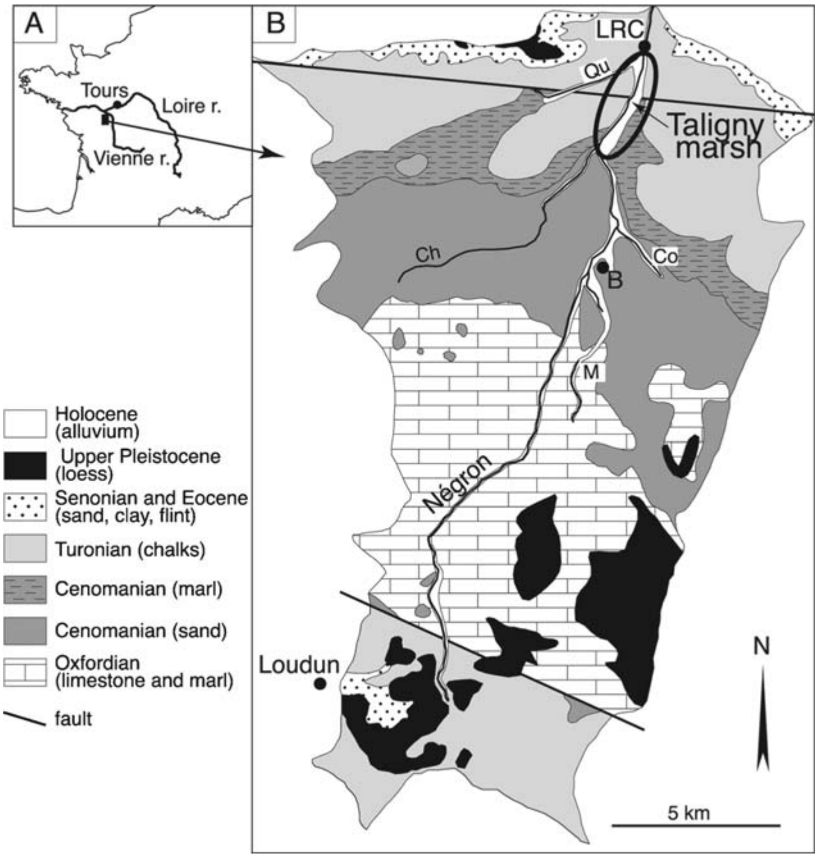

Figure 1 (A) Location and (B) geology of the Négron catchment and Taligny marsh (from Alcaydé and Joubert, 1987 and Alcaydé *et al.*, 1989). LRC, La Roche-Clermault; B, Beuxes; Ch, river Chavenay; Co, river Comprigny; M, river Merdelon; Qu, river Quincampoix

data were obtained by estimating the surface area of the (001) diffraction peaks of the clay minerals on diffractograms.

The apparent volumetric mass of the sediments (dry weight divided by the wet volume, in 10^6 g/m^3) was calculated from the T22 borehole by weighing sediments after given volumes of sediments were dried at 50°C for 48 h.

Pollen analysis was carried out on core T9. Pollen was extracted from the peat where it was generally abundant, using the standard 'NaOH' method (Van Campo, 1950). The MM-rich sediments were treated with 'Thoulet' solution ($d = 2.1$) (Goeury and de Beaulieu, 1979) to concentrate the pollen grains. A minimum of 300 pollen grains were identified and counted in each sample.

Seven ^{14}C datings were carried out on peat and wood fragments at the Laboratory of Isotope Geochemistry, University of Arizona, Tucson (USA), and were calibrated according to Stuiver *et al.* (1998). The sedimentation rates (in 10^{-3} m/yr) or the accumulation rates (in g/m^2 per yr) were calculated using calibrated ages.

Malacological sampling was carried out on core drilling T24 (Figures 2 and 3). No molluscs were observed in the basal units U1. Forty samples were extracted at regular intervals along the core taking account of the lithology. Samples were sieved and shells extracted, identified and counted following the procedure described in Puisségur (1976).

Results

Lithology

All the core drillings cut through sandy-gravelly to silty-peaty sediments overlying the bedrock formed of Cenomanian marls (upstream part of the marsh) and Turonian chalks (downstream part) (Figures 2 and 3). The cross-section (Figure 3) is representative of the marsh sedimentary fill. The T19 drilling, located in the middle of the marsh, shows seven units (Figure 4A):

0–60 cm: blackish brown peaty silt (U7),
60–140 cm: brown silty peat (U6),
140–190 cm: greyish brown peaty silt (U5),
190–270 cm: greenish grey organic silt (U4),
270–325 cm: blackish organic silt (U3),
325–360 cm: greenish silt (U2),
360–510 cm: greenish calcareous gravelly-sandy silt (U1),
over 510 cm: very hard grey sandy marl of the Cenomanian bedrock.

The lithostratigraphy is very similar in T9 and T19 drillings apart from the thickness of U5 and U2 (130–210 cm and up to 360 cm, respectively in T9; Figures 5 and 6); it differs slightly in T24 (Figure 6). All units were identified and sampled for the volumetric-mass determination in the T22 drilling.

U1 does not contain much OM ($<4.7\%$) (Figure 4C); silt dominates (Figure 4D), but sand and gravel are abundant (up to 46.8%), while clay content does not exceed 10.5%. U1 sediments are composed about equally of carbonates (fragments of Oxfordian limestones) on one hand, and silicates (mainly quartz) and oxy-hydroxides on the other. The overlying units (U2 to U7) do not contain carbonates, except for the mollusc shells.

The composition of the U2, U3 and U4 sediments is very similar: OM content, higher than in U1 sediments, is nevertheless low ($<13.1\%$), but increases irregularly from the bottom up. The mineral fraction is mainly silty ($>78.7\%$), quartzous, with little sand (1.6 to 10.8%) and clay (7.8 to 12.9%). These units differ from each other mainly in colour because of the oxydo-reduction processes. U5 is clearly

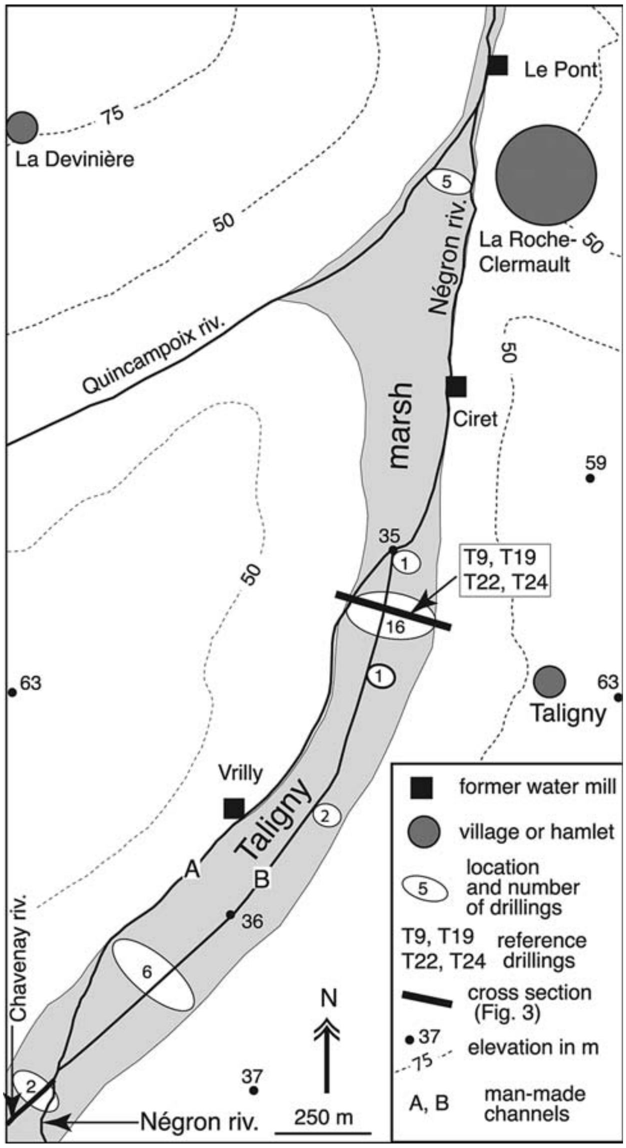

Figure 2 The Taligny marsh. Location map of the main sites and drillings, topography and hydrology

enriched in OM (up to 32.8%), the grain size of its mineral fraction being similar to that of the U2, U3 and U4 sediments, with an abundant silt fraction.

U6 is a peaty unit characterized by high OM content (42.2 to 80.8%). However, the mineral fraction, in which silt always dominates, shows lower clay content ($< 5.5\%$) and higher sand content (up to 50%) than U2 to U5. The OM content and grain size of the U7 sediments are fairly similar to U5 sediments.

The mineralogical composition of the clay size fraction clearly differs in each unit (Figure 4E). For U1, smectite generally dominates, but illite is abundant, while kaolinite and quartz are rare. U2 to U5 contain mostly smectite, with little or no illite, kaolinite and quartz. U5 presents traces of clinoptilolite and CT opal. U6 clearly differs by the presence of smectite, kaolinite and illite in very variable proportions, illite sometimes being absent; it also contains some quartz and CT opal, and especially clinoptilolite which is very abundant in some samples. U7 is marked by the disappearance of illite, increased smectite and CT opal with quartz and clinoptilolite, which is sometimes absent, and particularly the appearance of lepidocrocite.

The apparent volumetric mass of the sediments (Figure 4F) is 1.5×10^6 g/m^3 in U1 and lower and invariable in U2, U3 and U4 *pro parte* (0.6×10^6 g/m^3); it varies at the top of U4 and in U5, U6 and U7 between 0.45 and 0.15×10^6 g/m^3, the lower values being in U6.

Datings and palynology

The seven ^{14}C datings obtained vary from 5555 ± 65 yr BP (4360 cal. yr BC) at a depth of 340 cm (U2), to 775 ± 55 yr BP (AD 1265 cal. yr) at a depth of 55 cm (U7) (Table 1 and Figure 3).

The pollen analysis shows the presence of pollen grains from U2 to U7, up to a depth of 340 cm. For further interpretation, pollen data were expressed in percents of humid area taxa (*Alnus*, Cyperaceae, and paludal and aquatic taxa) on one hand, and in percentage of catchment vegetation (trees, Poaceae and other herbs, heath and cultivated taxa) on the other (Figure 5).

Information concerning the marsh vegetation starts during the middle Neolithic, from 5555 yr BP (4360 cal. yr BC) and stops during Modern times. This period can be divided into four main ecological phases (EP 1 to 4) of which only the main characteristics are described here.

Ecological Phase 1

EP1 corresponds to U2 *pro parte*, U3, U4 and U5 *p.p.*, during the sub-Boreal and the beginning of the sub-Atlantic (middle Neolithic to the Bronze Age). During this period, the marsh was essentially covered with alder (*Alnus*) and the surrounding slopes with deciduous forest of oak (*Quercus*), hazel (*Corylus*) and lime (*Tilia*).

At the middle Neolithic–late Neolithic transition (in U3), we observe a decrease in *Quercus* on the slopes and *Alnus* in the marsh where paludal taxa and Cyperaceae increased considerably. Cereal cultivation developed. At the late Neolithic–Bronze Age transition (in U4), the forest developed again, on the marsh and on the catchment slopes.

During the Bronze Age, while cultivation seems to have declined in the area, *Alnus* also decreased, but the increase in aquatics indicates the presence of ponds. The forest decreased on the slopes in favour of grassland.

Ecological Phase 2

EP2 corresponds to the first part of U5 during the lower sub-Atlantic (Iron Age). Deforestation was particularly marked. In the marsh, *Alnus* almost disappeared, and the paludal taxa and the Cyperaceae formed a Magnocaricion in a fen environment. On the surrounding slopes, *Quercus* decreased, and *Corylus* and *Tilia* disappeared; the previously observed grassland developed considerably, while cereal cultivation was sporadic.

Ecological Phase 3

EP3 corresponds to the second part of U5 during the middle sub-Atlantic (Gallo-Roman period). This period, accurately defined by radiocarbon datings, was marked by the return of a forest system both in the marsh (*Alnus*) and on the slopes (mainly *Quercus*).

Ecological Phase 4

EP4 corresponds to U6 and U7 during the upper sub-Atlantic (Middle Ages and Modern times). We observe a marked change in the vegetation. In the marsh, *Alnus* totally disappeared early in the Middle Ages, while the marsh taxa and particularly the Cyperaceae spread over the entire surface. On the slopes, deforestation increased, creating an open environment. Cereal cultivation developed as well as grassland (pasturing). This trend continued throughout the middle Middle Ages with a period marked by the decline of the

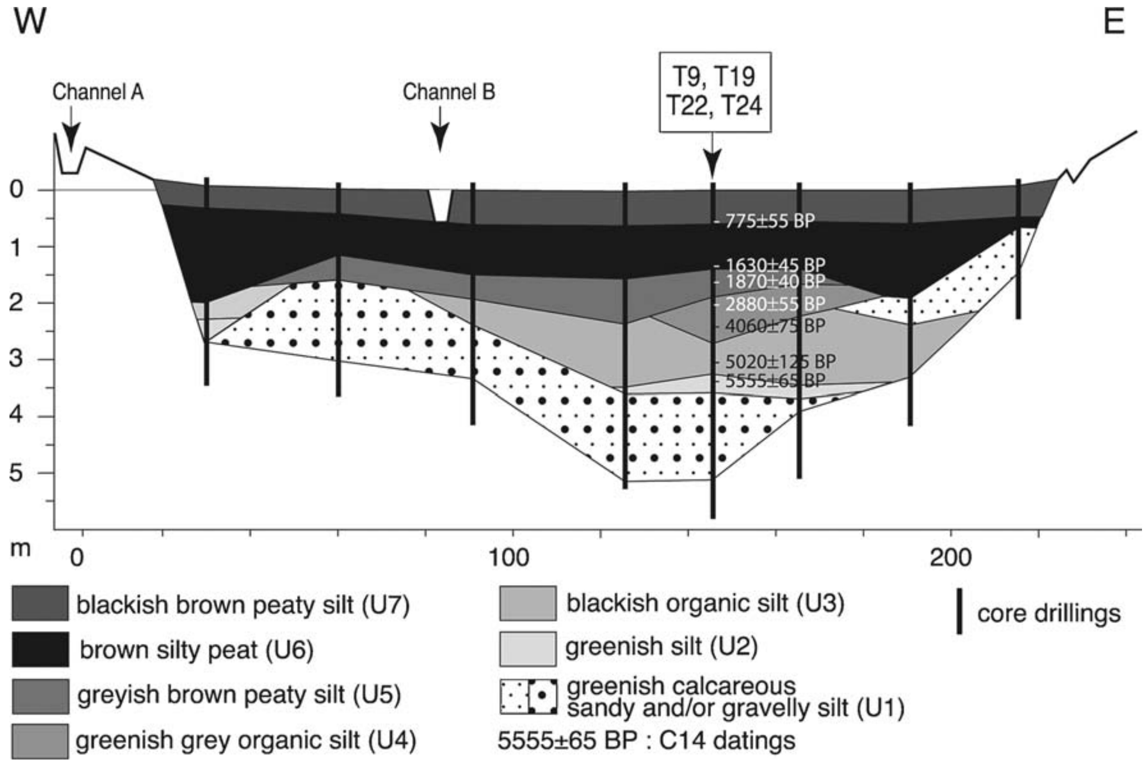

Figure 3 Cross-section through the Holocene sediments in the median part of the Taligny marsh (location: see Figure 2). T9–T24: core drillings

paludicols, which were replaced by aquatics, indicating the formation of open water.

Malacology

Malacological results versus lithology are summarized in Figure 6. Distribution of terrestrial and aquatic molluscs is shown in graph form in Figure 6B. The graph in Figure 6C gives information about diversity, showing the number of terrestrial and aquatic species as well as a curve of species richness calculated for an average sample weight of 330 g.

Three environmental phases may be described from the malacofauna. At the base (samples 40 to 33 = U2), assemblages are dominated by aquatic molluscs with *Valvata cristata* and *Armiger crista* appearing as the most abundant taxa. Both are representative of calm, well-oxygenated water bodies rich in aquatic plants. *A. crista* and several of the existing species (*Acroloxus lacustris*, *Radix balthica*, *Gyraulus laevis*) are not able to withstand seasonal dry periods (Kerney, 1999), implying a permanent aquatic habitat such as channels.

From sample 32 to sample 16 (U3 to U5), terrestrial molluscs become dominant. Exundation of the site is confirmed by presence of earthworm granules (Figure 6A). Within these assemblages, marsh species are particularly well represented, dominated by molluscs such as *Carychium minimum, Zonitoides nitidus* and *Oxyloma elegans*, which are able to survive winter flooding (Kerney *et al*., 1983). Some shade-loving species are also present, indicating the existence of forest biotopes. Among the aquatics, the most widespread species (*Galba truncatula*, *Anisus spirorbis*) are characterized by their ability to survive temporary dry phases, with the exception of *Pisidium nitidum*, which implies the presence of permanent water bodies. The landscape that can be described from these assemblages is thus a marshy environment with patches of forested habitats and limited permanent water bodies, such as a largely exundated floodplain.

After a peaty episode without malacofauna (U6 *pro parte*), the top of the sequence (upper part of U6 and U7) yields assemblages again dominated by aquatic molluscs. Nevertheless, the composition of malacological populations appears to be different from those of the first episode. The most abundant species indicate water bodies rich in plants (*Bithynia tentaculata*, *Viviparus contectus*, *Planorbarius corneus*) and several are common in temporary aquatic biotopes (*G. truncatula*, *Stagnicola palustris*, *Planorbis planorbis*, *Radix labiata*) such as fens. In the top sample, terrestrial molluscs, and particularly forest species, tend to develop. During this last phase, molluscan data indicate the predominance of aquatic habitats in the marsh but with more pronounced seasonal dry periods, and a trend towards the return of terrestrial conditions at the top (floodplain).

Interpretation and discussion

The Négron River catchment stored the major part (92%) of its sediment yield during the Holocene, with about one-third in the Taligny marsh (Macaire *et al*., 2002). In almost all of the 33 core drillings performed in the marsh, sediments exhibit a similar stratigraphy: gravelly-sandy silt (U1) at the bottom, silt (U2 to U4) in the middle, and peaty silt–silty peat–peaty silt (U5–U6–U7) at the top. The silty sediments (U2 to U4) are thicker in the upstream half of the marsh, while peaty sediments are thicker in the downstream half. Sometimes, especially near the banks of the marsh, silty units (U2 to U5) are lacking (Figure 3). Thus, the sedimentary units extend quite regularly into the marsh, as in lacustrine fillings. Unit distribution and radiocarbon datings show that sediments have been deposited almost continuously, without marked erosion phases, for at least 6500 yr. The sedimentation record of the T9, T19, T22 and T24 drillings located in the middle of the marsh is representative of the sedimentation processes and the environmental evolution in the downstream stretch of the Négron during the middle and upper Holocene.

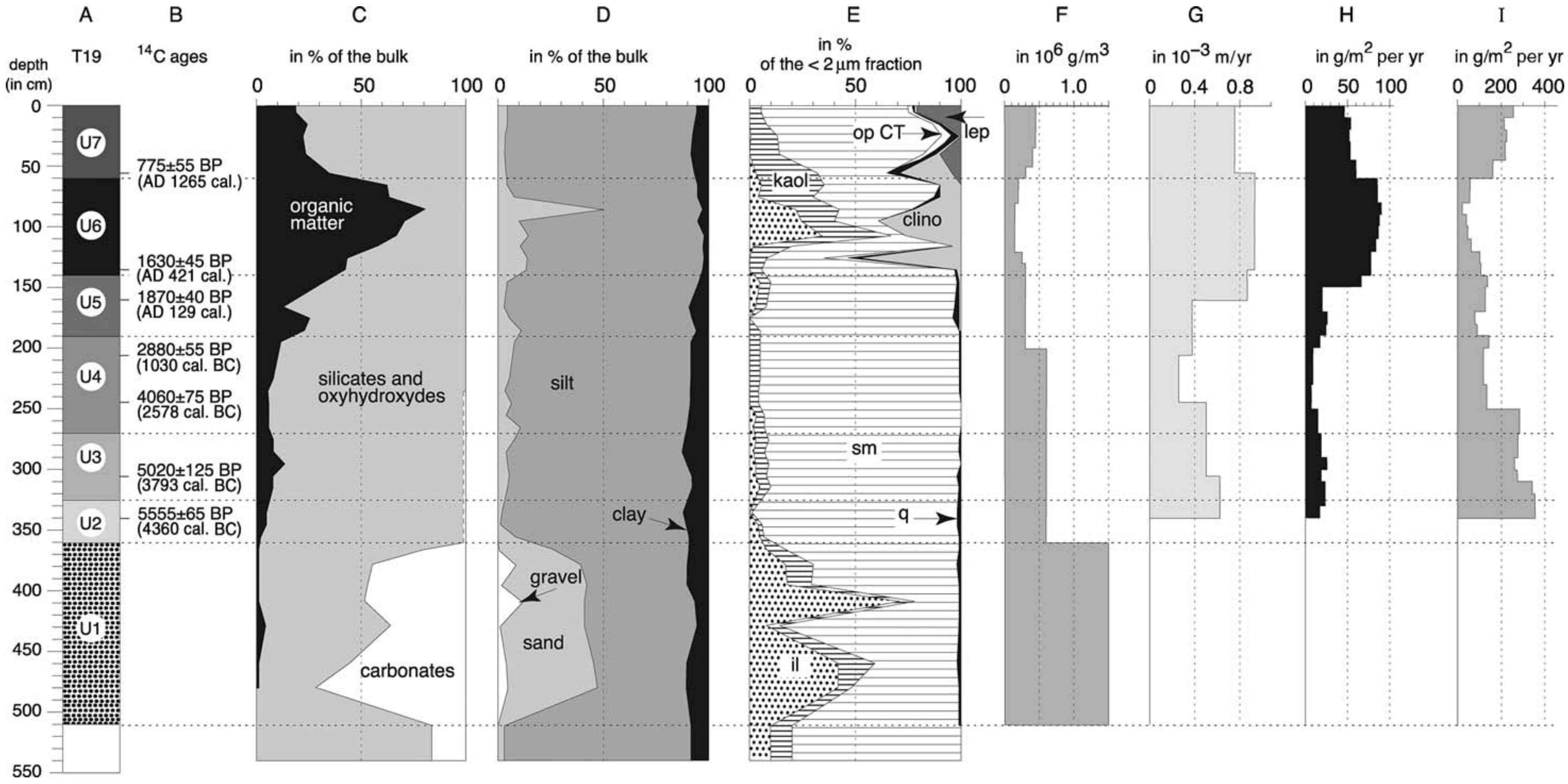

Figure 4 Stratigraphy, lithology and accumulation rates of organic and mineral matter from T9, T19 and T22 cores in the Taligny marsh. (A) Stratigraphic log and units; (B) ^{14}C datings calibrated in yr BC and AD according to Stuiver *et al*. (1998); (C) contents in organic and mineral matter in sediments; (D) grain size of sediments; (E) mineralogical composition of the <2 µm fraction; (F) apparent volumetric mass of sediments; (G) sedimentation rates; (H) accumulation rates of organic matter; (I) accumulation rates of mineral matter

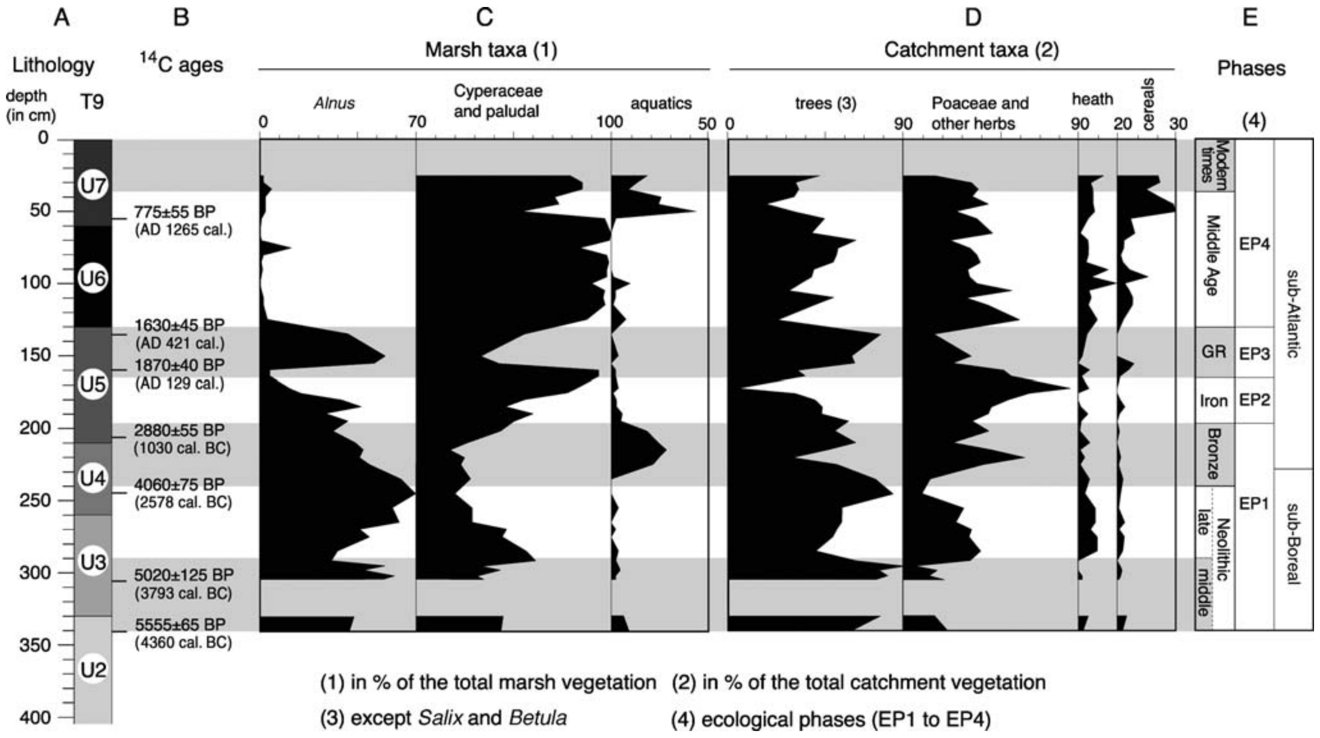

Figure 5 Lithology, pollen diagrams and ages from T9 core in the Taligny marsh

Relationship between organic and mineral sedimentation

The Holocene sediments of the Taligny marsh vary from coarse-grained detrital (U1) to peaty organic (U6) (Figure 4A). The peaty sediments extend across the whole marsh (Figure 3) and were deposited in a rheotrophic fen (Moore, 1986) supplied with water by the Négron River. The patterns of OM and MM contents (Figure 4C) and of the sediment granulometry (Figure 4D) indicate that the U1 unit (middle Holocene), very poor in OM and fairly rich in sand and gravel, was deposited in a fluvial channel. The OM and MM contents in U2, U3 and U4 (sub-Boreal and beginning of the sub-Atlantic) show fairly constant sedimentation conditions more favourable to the storage of MM (always more than 86.9%) than OM. These mainly silty sediments were deposited in an abandoned channel or floodplain. From U5 to U7 (sub-Atlantic), the environmental conditions seem to have been increasingly favourable to the sedimentation of OM in a temporary fen to the detriment of MM. OM sedimentation seems to have increased first irregularly (U5), then more regularly up to optimum conditions in U6, and finally decreased (upper part of U6 and U7) until the present time, marked by an increase in MM storage. In this expression of the sedimentation, there is of course a strong anti-correlation between OM and MM content, from which the authors conclude that OM endogenic sedimentation appears during periods of decline of MM supply or MM storage conditions (Vandenberghe *et al.*, 1994; Pastre *et al.*, 1997; Antoine *et al.*, 2002).

Since 5555 yr BP (4360 cal. yr BC), the total sedimentation rates (Figure 4G) are lower in OM-poor units (0.26×10^{-3} to 0.62×10^{-3} m/yr in U2, U3, U4 and U5 *pro parte*) than in OM-rich units (0.76 to 0.93×10^{-3} m/yr in the upper part of U5, U6 and U7). This is mainly the result of the widely differing conditions of MM and OM yield and storage. Sediment-forming MM depends on mechanical erosion processes on the catchment slopes and on fluvial deposition processes in the marsh (Meade *et al.*, 1990), while sediment-forming OM depends on the vegetation in the marsh and on the conditions of OM preservation, controlled by biological, biogeochemical and hydrological processes (Clymo, 1978; Hilbert *et al.*, 2000; Yu *et al.*, 2001). The mineral and organic sedimentary stores have very different fabrics and maturation trends. In particular, peaty material has a high sensitivity to compaction and humification (Aaby, 1986), making it difficult to establish the sediment budget by comparing organic-rich and organic-poor materials on the basis of only their volume or thickness. The accumulation rates of MM and OM in mass per surface unit (in g/m^2) need to be evaluated for an accurate view of sedimentation, as is usual with water-rich and unevenly compacted sediment at the bottom of lakes (Kemp *et al.*, 1978; Vernet *et al.*, 1984).

We have shown (Macaire *et al.*, 2005) that the mass accumulation rates (Ar in g/m^2 per yr) of organic matter (ArOM) and mineral matter (ArMM) can be calculated for each sediment increment with the following equations:

$$\mathrm{ArOM} = \rho\mathrm{OM} \cdot 7 \cdot \%\mathrm{OM} \cdot \mathrm{Sr}/(7 \cdot \%\mathrm{OM} + \%\mathrm{MM}) \qquad (1)$$

and

$$\mathrm{ArMM} = \rho\mathrm{MM} \cdot \%\mathrm{MM} \cdot \mathrm{Sr}/(7 \cdot \%\mathrm{OM} + \%\mathrm{MM}) \qquad (2)$$

where ρOM and ρMM are apparent volumetric mass of the organic and mineral phases of the sediments (0.1×10^6 g/m^3 and 0.7×10^6 g/m^3, respectively); %OM and %MM are % mass of OM and MM in the bulk without shells; Sr is sedimentation rate in m/yr.

We can see (Figure 4H, I) that ArOM and ArMM vary greatly and that, on average, the former are three times lower than the latter (7 to 90 g/m^2 per yr for ArOM versus 21 to 317 g/m^2 per yr for ArMM).

While OM and MM contents, expressed as a percentage of the bulk (Figure 4C), are strongly anti-correlated, there is no significant anticorrelation between ArOM and ArMM for the whole samples ($R^2 = 0.46$; Figure 7). The sediment units can be divided in two groups. The units of the lower group (U2, U3, U4 and U5 *p.p.*) show low ArOM values with little variation (< 50 g/m^2 per yr), while ArMM values are very

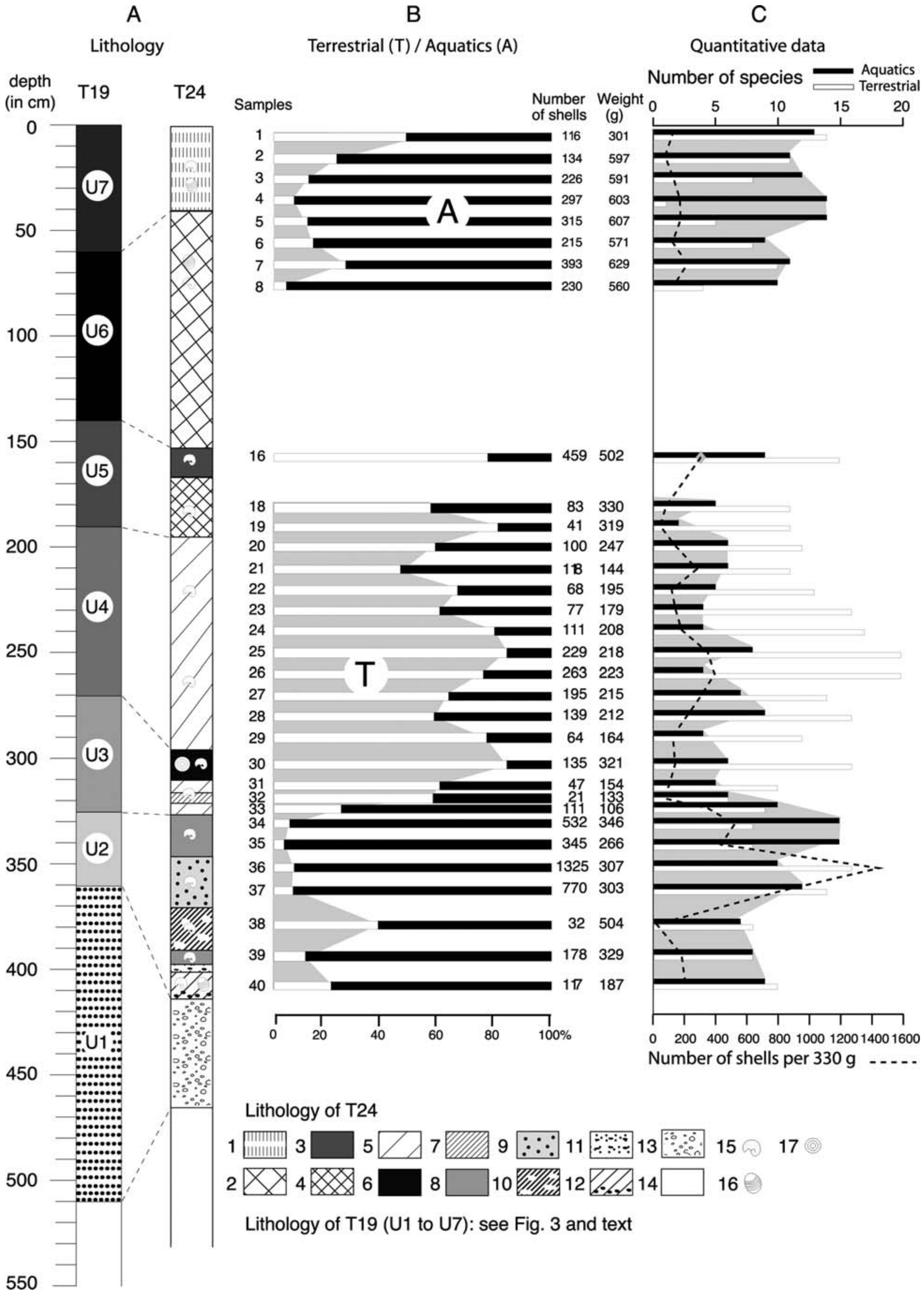

Figure 6 Malacological assemblages versus lithology from cores T24 and T19 in the Taligny marsh. (A) Lithology; (B) percentages of terrestrial and aquatic populations; (C) distribution of terrestrial and aquatic species and curve of richness calculated for an average sample weight of 330 g. Lithology of T24: 1, brown peaty silt; 2, brown peat; 3, dark grey peaty silt; 4, dark brown silty peat; 5, grey organic silt; 6, black silt; 7, greenish silt; 8, grey silt; 9, light grey sandy silt with gravel and plant remains; 10, dark green silt with white gravel; 11, greenish silty sand; 12, greenish silt; 13, calcareous sand and gravel; 14, Cenomanian grey marl; 15, shells; 16, charophyte gyrogonites; 17, earthworm granules

Table 1 ^{14}C data

Reference	Sampling depth (cm)	Material	Unit	^{14}C-age BP	2σ calibrated ^{14}C-age[a]
A 11140	5–55	peaty silts	U7	775 ± 55	cal. AD 1162 (1265) 1299
A 11141	130–135	peat	U6	1630 ± 45	cal. AD 262 (421) 539
A 9375	155–160	peaty silts	U5	1870 ± 140	cal. AD 33 (129) 241
A 9376	200–205	organic silts	U4	2880 ± 55	cal. BC 1258 (1039, 1030, 1023) 903
A 11142	240–245	organic silts	U4	4060 ± 75	cal. BC 2878 (2615, 2578) 2410
A 9377	302–306	organic silts	U3	5020 ± 125	cal. BC 4215(3793) 3537
A 9378	335–340	organic silts	U2	5555 ± 65	cal. BC 4519 (4360) 4254

[a] According to calibration program CALIB rev.4.3 (Stulver *et al.*, 1998).

variable: there is no significant correlation between ArOM and ArMM in these units. Units of the upper group (U5 *p.p.*, U6 and U7) show high ArOM values (>50 g/m^2 per yr) and variable ArMM values. ArMM and ArOM values are significantly negatively correlated ($R^2 = 0.93$). We can see, nevertheless, that both ArOM and ArMM can show high values (up to 200 g/m^2 per yr for the latter).

Furthermore, it appears that periods of high OM accumulation are not always periods of low MM accumulation, and that OM and MM stores are essentially formed in distinct ways. A low MM supply, as suggested among other factors by Bournerias (1984), does not seem to be necessary for the formation of a fen. Nevertheless, the significant anti-correlation between ArOM and ArMM for high OM values suggests a link between the conditions of accumulation of both sediment fractions, as discussed below.

Origin and accumulation factors of OM

The organic matter in sediments may be the result of either the supply from the catchment rocks or soils, or the endogenic yield in the sedimentation basin (Huc, 1988). In the units of the lower group where ArOM is low, the absence of correlation between ArOM and ArMM, which is exogenic, shows that the OM is of endogenic origin, even if a small part may be due to soil and rock erosion (Di-Giovanni *et al.*, 1999). The rather low values of HI (67 to 258 mg HC/g TOC) and $T_{\max}$ (421°C to 436°C) indicate that OM has a terrestrial origin and is yielded by the watershed soils (Espitalié *et al.*, 1977).

In the upper group units, the abundance of OM and the peaty facies indicate that the OM is mainly of endogenic origin. This is confirmed by the higher values of HI (214 to 281 mg HC/g TOC) and lower values of $T_{\max}$ (326°C to 434°C), such values having previously been observed for typically well-preserved peaty OM (Sebag, 2002; Di-Giovanni *et al.*, 1998). OM yield and preservation in a mire depend on climate- and human activity-related vegetation and hydrology (Duchaufour, 1983).

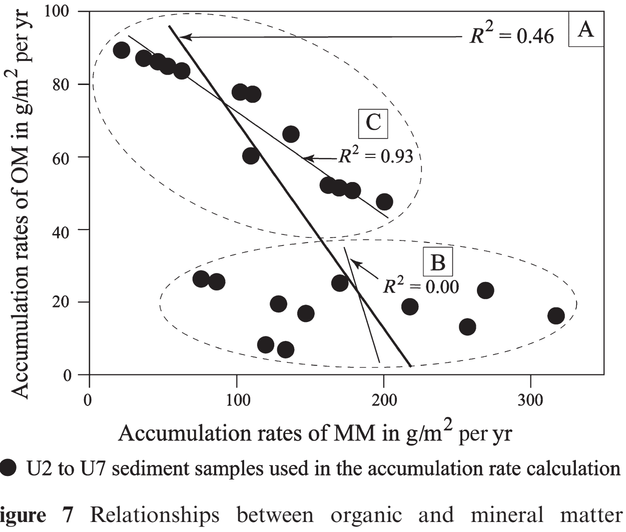

Figure 7 Relationships between organic and mineral matter accumulation rates (U2 to U7 units). (A) Correlation for the whole samples; (B) correlation for the samples showing low OM accumulation rates (<50 g/m^2 per yr); (C) correlation for samples showing high OM accumulation rates (>50 g/m^2 per yr)

ArOM versus vegetation

The vegetation supplying the sediment OM is mostly marsh vegetation: *Alnus*, Cyperaceae, paludal taxa and aquatics (Figure 5C). Except for three samples located close to the U5–U6 limit (130 to 170 cm), which differs slightly in the T9 and T19 cores, we observed a significant positive correlation between the abundance of marsh taxa and Cyperaceae and ArOM ($R^2 = 0.94$) on the one hand, and a negative correlation between the abundance of *Alnus* and ArOM ($R^2 = 0.90$) on the other (Figure 8A and B). Aquatics, which are scarce, do not seem to be correlated with ArOM. Thus there is an accumulation of OM when marsh taxa and Cyperaceae replace *Alnus*. The *Alnus* leaves supply the soil with 5 to 10 t/ha per yr OM versus 20 t/ha per yr supplied by the marsh taxa and Cyperaceae (Ramade, 2003). Moreover, *Alnus*, marsh taxa and Cyperaceae are low C/N ratio taxa (<25) with OM that transforms rapidly into humus (Duchaufour, 1983). The low OM humification observed may be due to the strong humidity and anoxic conditions of the palustrine environment.

ArOM versus palaeohydrology of the marsh

The water-table level in the marsh can be reconstructed from the malacofauna (see Figure 10E). The distribution of terrestrial and aquatic taxa (Figure 6B) indicates a significant correlation between aquatic taxa and ArOM in the silty to peaty units (U3 to U7) (Figure 9: $R^2 = 0.72$). This proves the relationship between OM accumulation and the rise of the water-table in the marsh, resulting from either an increasing supply of water from the catchment or from modification of the marsh drainage. The Négron is mainly fed from springs located in Oxfordian limestones (Lebideau, 1996), whose discharge could have varied according to the climate or the vegetation of the catchment. A climate change (cooler and more humid) beginning about 4000 yr BP (about 2500 cal. yr BC) (Johnsen *et al.*, 2001) and becoming cooler after 2700 yr BP (800 cal. yr BC) (van Geel *et al.*, 1998) has been observed in many places in north-west Europe. However, in the Taligny marsh, this did not result in a high water-table, and the ‘Little Ice Age’ (Aaby, 1976) corresponds to a low water-table stage (U7) (Figure 10E, H and I). The flooding of the marsh cannot have an eustatic origin, although this has been suggested by Visset *et al.* (1999) for a nearby site, because the ocean shoreline is too far away (250 km). The rise of the water-table and formation of the fen in the early Middle Ages (U6) could have been caused by the poor permeability of the mainly silty

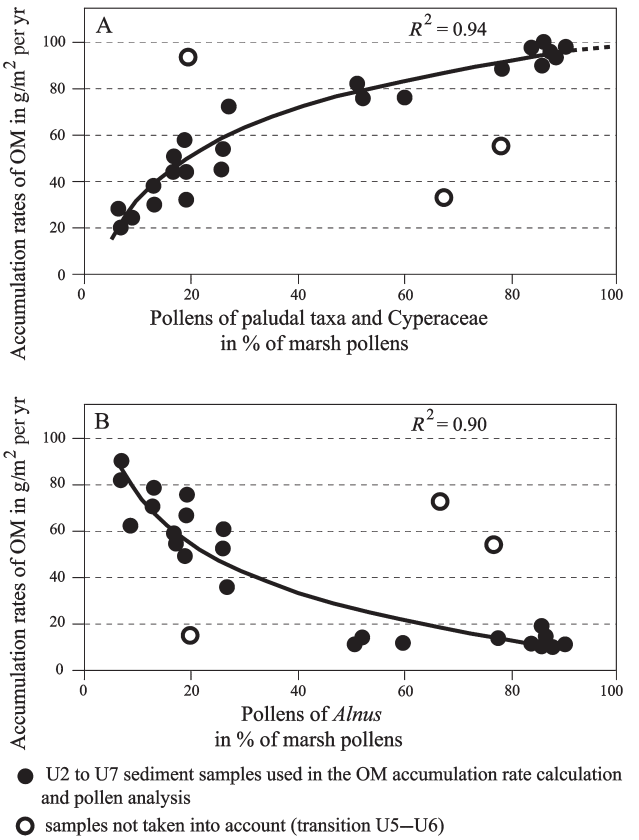

Figure 8 Relationship between organic matter accumulation rates and the marsh vegetation. ArMO versus paludal taxa and Cyperaceae pollen (A) and ArMO versus *Alnus* pollen (B)

U2 to U7 sediments. However, we observed that the peaty U6 unit is the richest in sand (Figure 4D). Moreover, there is no archaeological evidence of a dam downstream of the marsh.

The water-table variations seem to be related to variations in vegetation, as observed elsewhere by Smith and Charman (1988) and Chapman and Rose (1991). The rise of the water-table with the decline of *Alnus* during the sub-Boreal and the sub-Atlantic could be the result of a decrease in evapotranspiration, annual evapotranspiration by an *Alnus* forest being about 1200 to 1500 mm compared with 1000 mm by a reedbed (Pautou and Manneville, 1995).

Climate or anthropogenic impact on ArOM?

The OM accumulation increase in the marsh seems to be mainly due to human activities. The increase in Cyperaceae and paludal taxa, related to high ArOM, occurred during periods of both climate deterioration (end of the Iron Age) and climate improvement (Middle Ages) (Figure 10D). Moreover, the low climate variations at that time, especially regarding humidity, cannot explain the marked change in marsh vegetation from an *Alnus* forest to a reedbed. Thus, there seems to be no link between ArOM and climate. Tree-felling and reedbed development, probably for timber and thatch production and/or pasture development (Carcaud *et al.*, 2002), could have resulted in a greater amount of OM in the marsh and better preservation conditions (high water-table resulting from decreased evapotranspiration). The lowering of the water-table and decrease of ArOM during the late Middle Ages and Modern times (U7), while *Alnus* did not increase, is the result of draining the marsh for supplying water mills (Guichané, 2002) and controlling the river channel (Visset *et al.*, 1999).

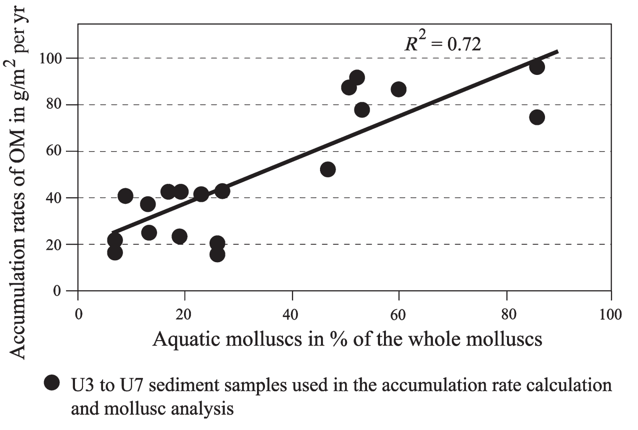

Figure 9 Relationship between organic matter accumulation rates and abundance of aquatic molluscs in U3 to U7 units

Origin and accumulation factors of MM

The sediment-forming MM in the Taligny marsh is mainly of detrital origin: we did not observe endogenic carbonate precipitation, except for the mollusc shells. The average sediment yield calculated from the whole stores (alluvium and colluvium) during the Holocene in the Négron catchment was 12.7 t/km^2 per yr prior to AD 1000 yr and 74.6 t/km^2 per yr after that time (Macaire *et al.*, 2002). The wide ArMM variations in the marsh during the Holocene (Figure 4I) depended on the sediment yield of the catchment and the particle-retention capacity of the marsh, determined by the climate and human activities.

Particle-retention capacity of the marsh

The capacity of a wetland to store particles depends on the dynamics of the water (especially flood pattern) and on the channel and floodplain morphology (Walling and Nicholas, 1996).

The U1 unit, coarse grained and containing mainly aquatic molluscs (Figure 6), was deposited by a high-energy flow in a channel (Figure 3); we do not know its accumulation rate because of the lack of dating. In U2, aquatic molluscs, and the greenish colour of the sediment resulting from the reducing conditions, show sediment deposition in a permanently inundated depression resembling an oxbow lake. The high ArMM value (317 g/m^2 per yr) indicates abundant suspended matter supplied by frequent floods: oxbow lakes are preferential sites of fluvial sedimentation (Allen, 1965).

U3 to U5 sediments, containing mainly terrestrial molluscs, were deposited in similar hydrodynamic conditions to a floodplain (Figure 3). Owing to these almost continuous sedimentary dynamics, the wide variations in ArMM (270 g/m^2 per yr in U3 to 76 g/m^2 per yr in U5) indicate variations in sediment yield.

U6 has the lowest ArMM values (<21 g/m^2 per yr). The permanent flooding of the marsh, enabling accumulation of OM, was not favourable to the retention of suspended matter mainly discharged downstream. Nevertheless, the increase in sand sedimentation, due to bedload retention by the dense vegetal network of Cyperaceae and paludicols and by the peaty soil (McCarthy *et al.*, 1992; Thornton *et al.*, 1997), shows that particle supply and water discharge were probably high at that time, as at about AD 1000–1100 cal. yr in western Europe (Macklin, 1999).

In U7, ArMM increased up to 201 g/m^2 per yr, while at the same time ArOM values were high. This was partly the consequence of draining the marsh to supply mills with water (Guichané, 2002): the resulting evolution of the fen into a floodplain favoured sediment storage.

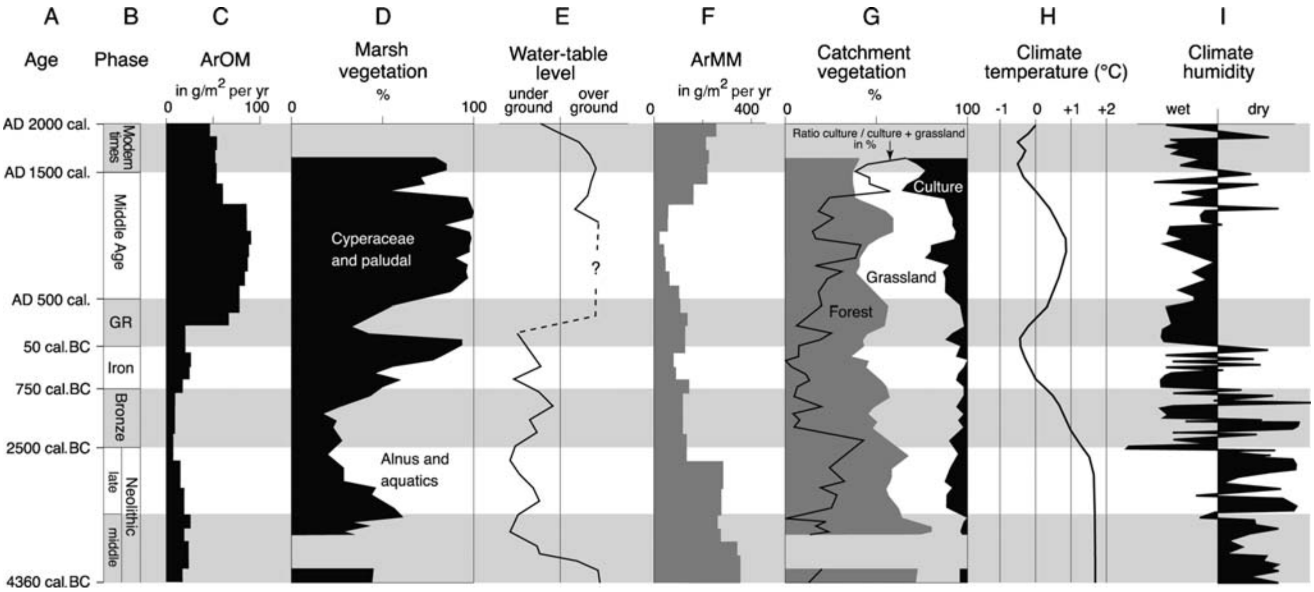

Figure 10 Comparison of OM and MM accumulation rates, vegetation, hydrology, climate and society. (A) and (B) Age and archaeological phase from T9 core pollen analysis and ^{14}C datings; (C) accumulation rates of organic matter from T19 and T22 cores; (D) marsh vegetation from T9 core pollen analysis; (E) water-table level deduced from T24 core malacofauna analysis; (F) accumulation rates of mineral matter from T19 and T22 cores; (G) catchment vegetation from T9 core pollen analysis (forest = all trees except *Alnus*); (H) climate temperature from Johnsen *et al.* (2001); (I) climate humidity from Barber *et al.* (1994) and Macklin (1999)

Sediment sources in the catchment

Quartzous silt, which dominates in all fluvial sediments (Figure 4D), is most abundant in the Pleistocene loess which is now rare in the catchment. As other bedrocks contain very little silt, over one-third of the Holocene sediment stored in the Négron catchment comes from Pleistocene loess erosion (Macaire *et al.*, 2002). Nevertheless, U1 contains quartzous and calcareous sand and gravel and abundant illite (Figure 4E), and was predominantly supplied from periglacial deposits ('grèzes') composed of Oxfordian limestone fragments and Cenomanian glauconitic sand that crops out at the lower part of the slopes and at the bottom of the valley filling (Bellemlih, 1999). Smectites, which strongly dominate in the clays in U2 to U5 sediments, show increasing supplies from Cenomanian marls (Alcaydé *et al.*, 1989). Clinoptilolite and CT opal characterize the clayey fraction of U6 and U7. These minerals, present in Turonian chalks, withstand weathering and occur in alluvium (Leclaire *et al.*, 1973; Macaire *et al.*, 1977). Like the high 10 Å peak in clay mineral, probably also due to glauconite, they indicate an increasing supply from the chalk forming the hills surrounding the marsh. In U6 and U7, this is confirmed by the increase of kaolinite yielded by the Senonian and Eocene clayey-siliceous formations outcropping at the hilltop (Rasplus, 1982).

During the whole sedimentation period, besides the dominant supply from the loess cover, we can also observe an evolution over time of the main type of bedrock supply: Jurassic limestones followed by Cenomanian sand and marl from the middle Neolithic to the Gallo-Roman period, and Turonian chalks during the Middle Ages up to the present time. It seems that up to the Middle Ages, bedrock erosion developed mainly into low-lying Jurassic and Cenomanian formations outcropping upstream of the Taligny marsh: erosion thus developed mainly on the river banks while the slopes seem to have been relatively protected by forest- and grassland-dominated vegetation. Since the beginning of the Middle Ages (after about AD 420 cal. yr), the increasing sediment yield from the Turonian chalk hills confirms the marked development of arable farming on the slopes surrounding the marsh, as shown by the increase of cereal pollen, which is not widely dispersed.

Relationships between ArMM, climate and human activities

Comparison of ArMM values with temperature and humidity curves for the Upper Holocene (Figure 10F, H and I) does not show a clear relationship between sediment yield and climate, although this has been observed by some authors (Macklin and Lewin, 1993; Knox, 1995; Starkel, 1995). In particular, the change to a cooler climate from 4000 yr BP (2500 yr cal. BC; Johnsen *et al.*, 2001), increasing at about 2700 yr BP (800 cal. yr BC; van Geel *et al.*, 1998), did not bring about an ArMM increase, but did conversely result in a decrease in U4 and U5. However, the slight temperature rise during the Middle Ages was marked by low ArMM values, and the cooler 'Little Ice Age' (Modern times) by a strong ArMM increase.

Vegetation is an essential factor of sediment-yield regulation (Meade *et al.*, 1990). Though deforestation for agriculture is a classic factor of sediment yield increase, no correlation appears between the percentage of tree taxa, dominant in the pollen diagrams, and ArMM for units U2 to U7 (Figure 11). Thus, periods of higher ArMM values (Neolithic, late Middle Ages and Modern times) seem to be related to the development of cereals, and heaths, which are abandoned arable areas and also highly erodable (Ursic and Dendy, 1965; Bork, 1989) (Figure 10F and G). The development of pasture over arable land in deforested areas is mainly related to a decrease in ArMM (Bronze, Iron and Gallo-Roman times).

We can highlight two successive phases of the relationship between ArMM and the environmental parameters in the Taligny marsh.

The first phase extended from the Neolithic to the early Middle Ages, and is marked by ArMM decrease. In U3 to U5, units deposited in similar conditions (floodplain), high ArMM values during the Neolithic (especially the final Neolithic) may be explained by the marked development of crop cultivation in favourable climatic conditions (Figure 10G, H and I). During the Bronze and Iron Ages, despite a cooler and more humid climate, ArMM and thus sediment yield decreased, although a number of authors have observed increased detrital sedimenta-

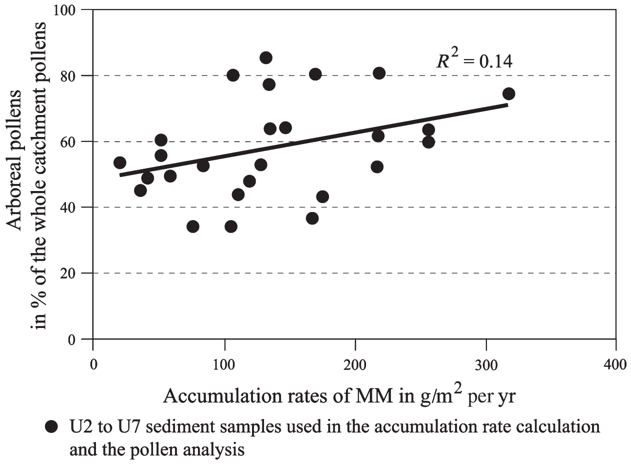

Figure 11 Relationship between mineral matter accumulation rates and abundance of tree pollen in U2 to U7 units

tion in western Europe (Bohncke and Vandenberghe, 1991; Pastre *et al.*, 1997; Macklin, 1999; Orth *et al.*, 2004). This sediment yield decrease has been observed during phases of crop-cultivation decline and aforestation, and may be due to societal decline (Zolitschka *et al.*, 2003) related to climate deterioration at about 2500 and 800 cal. yr BC, at the Neolithic–Bronze and Bronze–Iron transition. Low sediment yield continued when deforestation started again during the Bronze and Iron ages, probably because pastureland expanded more than arable fields. Thus, climate deterioration, leading either to aforestation or to the expansion of grasslands, reducing run-off, resulted in a decrease in sediment yield. During the Gallo-Roman period, while temperature improved, ArMM increased very little, possibly because of the persistence of a small cultivated area relative to that maintained as grassland.

During that initial phase, climate seems to have influenced soil erosion more through its impact on human activities than through its direct natural effects: erosion developed in a context of 'nature-dominated environment – human adaptation' (Messerli *et al.*, 2000). Increasing grassland for animal production rather than cultivation during the post-Neolithic period of climate deterioration reduced the sediment yield and thus the fluvial sedimentation, showing the need to discriminate these two land uses (Berglund, 2003). The lower ArMM values (<21 g/m^2 per yr) correspond to the peaty phase (U6) during the middle Middle Ages. They do not reflect the increasing cultivation related to temperature improvement with continuing humidity. The sediment yield was probably high at that time, while the retention rate of suspended particles flowing through the marsh was low, as explained above.

The second phase developed during the late Middle Ages and Modern times. The strong ArMM increase concomitant with high ArOM values (U6 *pro parte* and U7, Figure 4) is synchronous with a change to a cooler and more humid climate ('Little Ice Age'), and also with marked development of crop cultivation on chalky hills and a reduction of grasslands (Figure 10). It also corresponds to better conditions for particle retention because of the lowering of the water-table in the marsh. We also know that a large part (88%) of the sediment yield in about the last 1000 yr was stored in lynchets on the chalky slopes (Macaire *et al.*, 2002). The second phase is therefore marked by a high increase in sediment yield related to increased cultivation in a variable climatic context. Humans became progressively less dependent on environmental stress (change to a 'human-dominated' environment: Messerli *et al.*, 2000) from the early Middle Ages, and developed arable farming even during periods of climate deterioration, which certainly increased erosion (Macklin, 1999) limited by the formation of lynchets (Zadora-Rio, 1991).

Conclusion

The quantification of fluvial sediment accumulation in the Taligny marsh shows that there is no systematic relationship between OM and MM accumulation. Periods of high OM accumulation are not always periods of low MM accumulation.

Comparison of mass accumulation rates of OM and MM with palaeoenvironmental data for the late Holocene highlighted that:

(1) OM is mainly of endogenic origin. Its accumulation is not related to the climate but is closely related to the decline of the alder marsh forest in favour of marsh taxa and Cyperaceae, particularly during the Iron Age and since the beginning of the Middle Ages. Peat formation is thus essentially due to human activity: *Alnus* felling, which reduced evapotranspiration, favoured the rise of the water-table, the development of aquatic malacofauna and the accumulation of marsh taxa and Cyperaceae OM. The lowering of the water-table and the decrease of OM accumulation during the late Middle Ages and Modern times are due to the draining of the marsh by man.

(2) MM is due to mechanical erosion in the catchment. Since the middle Neolithic, MM storage has been continuous and fluvial dynamics have varied little (floodplain) except during the period of fen development (Middle Ages). Thus, except during the Middle Ages, MM accumulation rates indicate variations of sediment yield on the slopes.

(3) Since the Neolithic, sediment yield variations cannot be explained either by climate variations, nor by deforestation related to societal development. From the Middle Neolithic to the Gallo-Roman periods, the stress resulting from climate deterioration resulted in the expansion of pastureland over arable land during deforestation periods: the antagonistic, but related, effects of changes in climate (temperature and/or humidity) and vegetation (resulting from human activity) resulted in a decrease of the sediment yield at the end of the Neolithic, and then maintained it at low values with little variation. Since the end of the early Middle Ages, climate variations have not greatly influenced sediment yield because human activities have no longer been determined by climatic stress.

(4) The small quantity of MM contained in the peat (Middle Ages) is not always linked to low sediment yield because of the poor retention capacity of suspended matter in the continuously flooded fen. The large storage of matter in the lynchets, the expansion of agriculture and the mineralogy of the MM all show a great increase of the sediment yield in the chalky hills during the middle Middle Ages. The drainage of the marsh favoured the increasing detrital sedimentation during the last centuries.

Acknowledgements

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