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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

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ABSTRACT

Continuous high-resolution mass accumulation rates (MAR) and X-ray fluorescence (XRF) measurements from marine sediment records in the Bay of Biscay (NE Atlantic) have allowed the determination of the timing and the amplitude of the 'Fleuve Manche' (Channel River) discharges during glacial stages MIS 10, MIS 8, MIS 6 and MIS 4–2. These results have yielded detailed insight into the Middle and Late Pleistocene glaciations in Europe and the drainage network of the western and central European rivers over the last 350 kyr. This study provides clear evidence that the 'Fleuve Manche' connected the southern North Sea basin with the Bay of Biscay during each glacial period and reveals that 'Fleuve Manche' activity during the glaciations MIS 10 and MIS 8 was significantly less than during MIS 6 and MIS 2. We correlate the significant 'Fleuve Manche' activity, detected during MIS 6 and MIS 2, with the extensive Saalian (Drenthe Substage) and the Weichselian glaciations, respectively, confirming that the major Elsterian glaciation precedes the glacial MIS 10. In detail, massive 'Fleuve Manche' discharges occurred at ca 155 ka (mid-MIS 6) and during Termination I, while no significant discharges are found during Termination II. It is assumed that a substantial retreat of the European ice sheet at ca 155 kyr, followed by the formation of ice-free conditions between the British Isles and Scandinavia until Termination II, allowed meltwater to flow northwards through the North Sea basin during the second part of the MIS 6. We assume that this glacial pattern corresponds to the Warthe Substage glacial maximum, therefore indicating that the data presented here equates to the Drenthe and the Warthe glacial advances at ca 175–160 ka and ca 150–140 ka, respectively. Finally, the correlation of our records with ODP site 980 reveals that massive 'Fleuve Manche' discharges, related to partial or complete melting of the European ice masses, were synchronous with strong decreases in both the rate of deep-water formation and the strength of the Atlantic thermohaline circulation. 'Fleuve Manche' discharges over the last 350 kyr probably participated, with other meltwater sources, in the collapse of the thermohaline circulation by freshening the northern Atlantic surface water.

1. Introduction

The Middle and Late Pleistocene were periods of fluctuating climate accompanied by prominent sea-level lowstands during the glacial intervals, when massive continental ice sheets extended from mountainous to lowland areas as far as about 50°N over Europe (Ehlers, 1990; Ehlers et al., 2004; Ehlers and Gibbard, 2007) (Fig. 1). The retreat of the shoreline on the extensive present-day shallow continental shelves of the southern and eastern parts of the British Isles induced a reorganisation of the European drainage network and the appearance of large rivers, with considerable drainage catchments, after the merging of present-day French and British rivers and German and Dutch rivers on the subaerially exposed English Channel and North Sea basin, respectively

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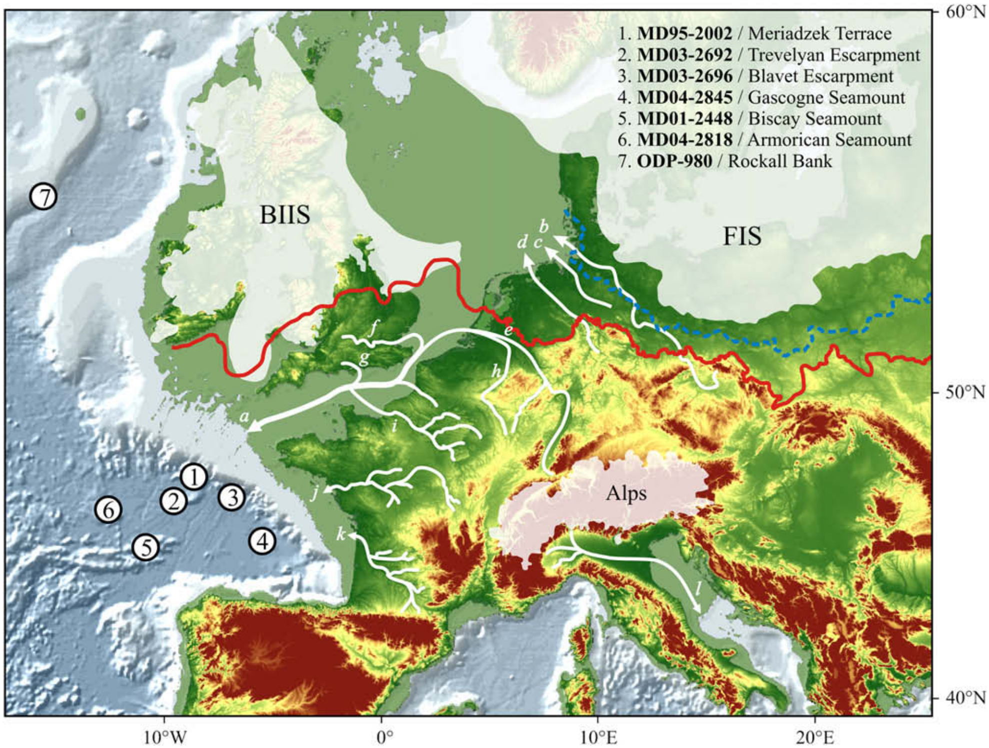

Fig. 1. Map of NW Europe showing the glacial limits of the British-Irish Ice Sheet (BIIS), Fennoscandian Ice Sheet (FIS) and the Alps Glaciers for the Late Weichselian (MIS 2 – white shaded area) and Saalian glaciations (Drenthe advance = continuous red line; Warthe advance = dotted blue line) (Ehlers and Gibbard, 2004). The white arrows and the associated lowercase letters identify the main European rivers: *a*: 'Fleuve Manche', *b*: Elbe, *c*: Wesser, *d*: Ems, *e*: Rhine, *f*: Thames, *g*: Solent, *h*: Meuse, *i*: Seine, *j*: Loire, *k*: Gironde, *l*: Pô. The numbers indicate the core locations (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

(Gibbard, 1988). Complex networks of palaeovalleys highlight that the present-day Somme, Seine, Solent and numerous minor French and British rivers merged into the English Channel during eustatic lowstands to form the 'Fleuve Manche' (Channel River) palaeoriver (Larsonneur et al., 1982; Lericolais, 1997; Antoine et al., 2003; Bourillet et al., 2003) (Fig. 1). Although the chronology and the cause of the opening of the Dover Strait are still a matter of debate (e.g. Gibbard, 1995; Meijer and Preece, 1995; Van Vliet-Lanoë et al., 2000; Gupta et al., 2007; Busschers et al., 2008), it is now generally accepted that the North Sea fluvial systems have been on several occasions diverted southwards into the English Channel since the onset of extensive continental glaciations. The invasions of ice masses in the Northern European Lowlands over the last about 600 kyr (Ehlers et al., 2004; Ehlers and Gibbard, 2007) strongly modified the fluvial directions of the central European rivers, and forced the present-day Elbe, Rhine and Thames rivers to flow southwards during periods of coalescence of the Fennoscandian (FIS) and British-Irish (BIIS) ice sheets in the North Sea basin (Gibbard, 1988; Sejrup et al., 2000). Numerous studies have attempted palaeogeographical reconstructions of drainage directions of the major European rivers (Gibbard, 1988; Bridgland and D'Olier, 1995; Bridgland, 2002; Busschers et al., 2007, 2008) and of invasions of continental ice in the North Sea basin during glacial periods (Zagwijn, 1973; Ehlers, 1990; Sejrup et al., 2000, 2009; Ehlers et al., 2004; Busschers et al., 2008). However, the combined erosional effects of the successive alternating ice advances and sea-level variations have caused scarcity of long-term shallow marine and continental sequences (e.g. Bridgland, 2002), which added to the difficulties of dating precisely the sedimentary records, still make difficult the correlation of continental records with the marine isotopic stratigraphy (e.g. Bowen, 1999; Ehlers and Gibbard, 2004; Gibbard and Van Kolfschoten, 2005), a challenge of central importance in Quaternary stratigraphy. In contrast, deep-sea sediments, because of their continuous record of Earth's climate variability, offer an invaluable alternative to the usually discontinuous continental sequences to reconstruct the freshwater and sediment discharges of lowstand rivers and to detect the imprint of surrounding ice-sheet oscillations and attendant modification of hinterland drainage directions.

The deep-sea sedimentation in the northern Bay of Biscay (Armorican margin – NE Atlantic) has been strongly influenced by the 'Fleuve Manche' palaeoriver discharges throughout the glacial intervals of the Middle and Late Pleistocene (Bourillet et al., 2003, 2006; Mojtahid et al., 2005; Zaragosi et al., 2006; Eynaud et al., 2007; Toucanne et al., 2008). For the last deglaciation, Toucanne et al. (2008) have recently shown downstream from the English Channel huge and extensive sediment accumulation with rates reaching up to 10 m ka^{-1}. This resolved the discussion about the size and strength of the 'Fleuve Manche' (e.g. Bridgland, 2002) and confirmed the Armorican margin as an appropriate site for reconstructing the 'Fleuve Manche' palaeoriver activity and the evolution of the surrounding ice masses throughout the Quaternary.

In this paper, we provide a reconstruction of the 'Fleuve Manche' palaeoriver activity since Marine Isotopic Stage (MIS) 10, based on the study of the seaward transfer of continentally-derived material onto the Armorican margin using mass accumulation rates (MAR) and X-ray fluorescence (XRF) intensities of Ti from six long piston cores retrieved in the Bay of Biscay (Fig. 1). These marine records provide a direct land–sea–ice correlation using the marine climate proxies (planktic foraminifera assemblages and ice-rafted detritus – IRD), continental indicators (terrigenous input) and global ice-volume tracer (benthic foraminiferal oxygen isotopes). Finally, we discuss the interaction and phasing between the European ice sheets and the 'Fleuve Manche' activity, and the reorganisation of the drainage network of the western and central European rivers during MIS 10–2, while refining the chronology of the ice-sheet oscillations in the North Sea basin during the Saalian and Weichselian glaciations. The comparison of our results with the main Pleistocene palaeoceanographic changes at site ODP-980 (Rockall Bank – NE Atlantic, Fig. 1) also provide relevant information about the ice sheet–ocean interactions over the last four glacial intervals.

2. Core materials and methods

This study is based on 'Calypso' long piston cores retrieved from hemipelagic environments of the Bay of Biscay (NE Atlantic) during oceanographic cruises onboard the R/V 'Marion Dufresne' (IPEV). Details about cores and coring sites are given in Fig. 1 and Table 1. These sites are situated far from any turbiditic influences which make them suited for recording continuous sediment input variability from the 'Fleuve Manche' palaeoriver throughout the last few glacial periods (Bourillet et al., 2003, 2006).

Physical properties of the cores were determined onboard by measuring the P-wave velocity and gamma-ray attenuation density every 2 cm using a 'Geotek Multi Sensor Core Logger' (MSCL). All cores were then sampled continuously at 5–10 cm intervals. The stratigraphic frameworks are based on the counts of the planktic polar foraminifera *Neogloboquadrina pachyderma* (s) (%) and ice-rafted debris (IRD, expressed in lithic grains per gram) which were performed on the sand size fraction (>150 μm) in representative sample splits of >300 grains per sample. Radiocarbon ages were performed on monospecific samples from maxima of absolute *Globigerina bulloides* or *Neogloboquadrina pachyderma* (s) abundances. Ages have been corrected for a marine reservoir effect of 400 years and were calibrated to calendar years using CALIB Rev 5.0/Marine04 data set (Stuiver and Reimer, 1993; Hughen et al., 2004; Stuiver et al., 2005) up to 21.78 ^{14}C ka and Bard et al. (2004) thereafter. Additionally, stable isotope analyses on cores MD03-2692 (see Mojtahid et al. (2005) for details) and MD01-2448 (this study) were undertaken using specimens of benthic foraminifera *Uvigerina peregrina* and *Planulina wuellerstorfi* from the size fraction >150 μm. Isotopic analyses of core MD01-2448 were conducted at the Laboratoire des Sciences du Climat et de l'Environnement (LSCE, Gif-sur-Yvette, France) on both a Finnigan MAT251 and Delta + mass-spectrometers equipped with a Kiel-device automated introduction line. External reproducibility for standards on these two mass-spectrometers was 0.05‰ for oxygen during the time of measurements.

Sedimentological investigations were undertaken by various means and at different depth intervals. The sediment colour (lightness L^*, 2 cm intervals) and the bulk carbonate content (% weight, 5 cm intervals) were measured by using a hand-held Minolta CM-508i spectrophotometer and a Bernard calcimeter (precision ±2%), respectively. X-ray radiograph analyses were performed at the University of Bordeaux 1 using the SCOPIX image processing tool (Migeon et al., 1999). Microscopical observations of thin-sections (10 cm long) of impregnated sediments selected from well-preserved and representative sedimentary facies were performed using a fully automated Leica™DM6000B Digital Microscope. Morphological analyses of lithic grains have been performed using a scanning electron microscope (SEM) JEOL JSM 6301-F (SCIAM, Angers, France). SEM images have been obtained by backscattered electrons with an accelerating voltage of 3.0 kV.

Bulk sediment chemistry was measured on core MD03-2692 by means of profiling X-ray fluorescence (XRF), using the 'Avaatech core-scanning XRF' of the University of Bremen (Mojtahid et al., 2005). The measurements were done at intervals of 2 cm and only data for Ti and Ca are reported in this study. It is commonly admitted that Ti element is related to terrigenous-siliciclastic components (clay minerals) while Ca mainly reflects the marine carbonate content (calcite and aragonite) in the sediment (Richter et al., 2006). Therefore the ratio of XRF intensities of Ti and Ca (Ti/Ca) was used to estimate terrigenous inputs from the 'Fleuve Manche' palaeoriver at the MD03-2692 site.

The terrigenous inputs were quantified on all sites by the calculation of the terrigenous flux. The thickness of sedimentary series is an essential parameter in the calculation of sedimentation rates and fluxes and the detailed observation of the sediment using X-ray imagery reveals that stretching prevails in the upper part of the cores, probably as a result of cable rebound causing upward piston acceleration (e.g. Skinner and McCave, 2003; Bourillet et al., 2007). Correlations of impedance contrasts (i.e. velocity times density from 'Geotek MSCL') of cores MD95-2002, MD03-2692, MD03-2696 and MD04-2845 with very high-resolution acoustic data (3.5 kHz) permitted depth corrections, i.e. the reconstruction of sedimentary series, assuming that seismic horizons in the unconsolidated Pleistocene sediments are mainly controlled by impedance variations (i.e. density contrasts). The very low accumulation rates at sites MD01-2448 and MD04-2818 precluded the detection of well-defined seismic horizons and the depth correction in these cores was exclusively estimated from the CINEMA software developed at IFREMER (Woerther and Bourillet, 2005; Le Breton, 2006; Bourillet et al., 2007). This software simulates the amplitude and the duration of the elastic recoil of the aramid cable and the piston displacement throughout the coring phase, in taking account of the length of the cable (∼water depth) and of the total weight of the coring system especially. Due to the relevant comparison between the 'manual' (i.e. using acoustic data) and 'automatic' (i.e. using CINEMA) corrections for cores retrieved in similar water depths (i.e. MD03-2692, MD03-2696 and MD04-2845) (Fig. 2), we assume that CINEMA ensures confident correction of the disturbances detected in cores MD01-2448 and MD04-2818. The water depth, and hence the length of the coring cable, is indeed of primary importance regarding the deformation rate of the 'Calypso' long piston cores (Skinner and McCave, 2003; Bourillet et al., 2007). Once these corrections had been performed, the terrigenous Mass Accumulation Rates (MAR or terrigenous flux, in g cm^{-2} kyr^{-1}) were calculated according to the following formula:

$$\mathrm{MAR} = \mathrm{LSR} \times \mathrm{DBD} \times (1 - \text{carbonate content}),$$

with:

LSR: Linear Sedimentation Rate (cm kyr^{-1}) and, DBD: Dry Bulk Density (g cm^{-3}), which has been calculated assuming a mean grain density of 2.65 g cm^{-3} and an interstitial water density of 1.024 g cm^{-3} (Cremer et al., 1992; Cremer et al., 1993; Auffret et al., 2002) as follows: $\mathrm{DBD} = 2.65 \times (1.024 - D_{\mathrm{wet}})/(1.024 - 2.65)$. Wet bulk densities ($D_{\mathrm{wet}}$) were derived from gamma-ray attenuation density measurements.

Table 1
Position of studied cores.

Core label	Lat., °N	Long., °W	Depth (m)	Cruise
MD95-2002	47°27.12′	8°32.03′	2174	MD105-IMAGE1
MD01-2448	44°46.79′	11°16.47′	3460	MD123-GEOSCIENCES
MD03-2692	46°49.72′	9°30.97′	4064	MD133-SEDICAR
MD03-2696	46°29.51′	6°02.36′	4422	MD133-SEDICAR
MD04-2818	46°21.44′	12°33.6′	3766	MD141-ALIENOR
MD04-2845	45°20.86′	5°13.17′	4175	MD141-ALIENOR

3. Chronology

The chronostratigraphical framework for cores MD03-2696 (this study) and MD04-2845 (Sanchez Goni et al., 2008; Daniau et al.,

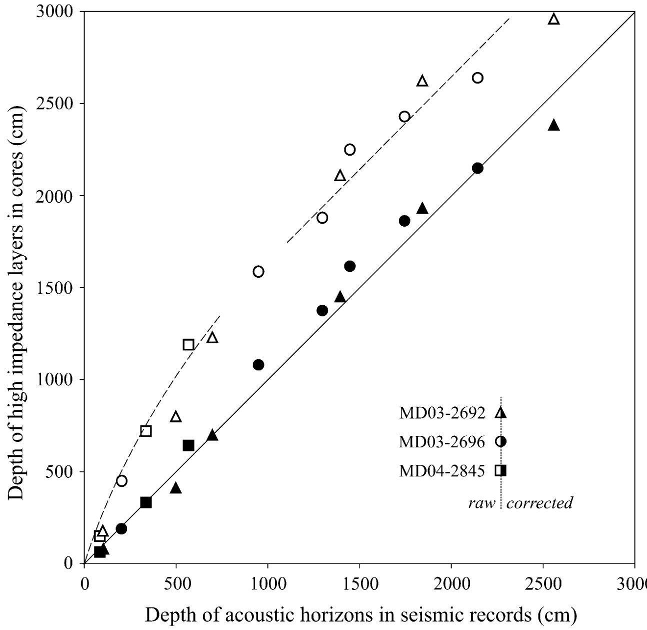

Fig. 2. Relationship between the raw (open symbols) or corrected (filled symbols) depths of high impedance layers of cores MD03-2692 (triangles), MD03-2696 (circles) and MD04-2845 (squares) and the depths of the seismic horizons at sites MD03-2692, MD03-2696 and MD04-2845. The corrected depths are calculated from the raw depths using the CINEMA software (Le Breton, 2006; Bourillet et al., 2007). Note the excellent correlation between the corrected depths of the high impedance layers (filled symbols) and the depth of the acoustic horizons in the high-resolution seismic records (continuous black line). The curvilinear dashed line, which corresponds to the alignment of the raw depths of the high amplitude layers from 0 to 12 m on the *Y*-axis, highlights the elongated zone of the cores as a consequence of the elastic recoil of the cable. The rectilinear dashed line shows the undisturbed part of the cores. Cores MD03-2692, MD03-2696 and MD04-2845 show an equivalent length of their elongated zone because they were retrieved in similar water depths of about 4200 m with the same coring settings, so leading to similar elastic recoil of the cable.

in press) is mainly based on AMS ^{14}C dates complemented by analysis of the relative abundance of *N. pachyderma* (s) and IRD counting (Fig. 3). *N. pachyderma* (s) and IRD in the Bay of Biscay identify abrupt sea-surface changes and glacial-rainout intervals which are stratigraphically contemporaneous with major climatic events (Duprat, 1983; Zaragosi et al., 2001; Auffret et al., 2002; Mojtahid et al., 2005; Peck et al., 2007; Toucanne et al., 2008) (Fig. 3). Age models were constructed by using radiocarbon dates and from additional control points from the reference core MD95-2002, in which age model is based on 20 ^{14}C AMS ages spanning the last 30 ka (Grousset et al., 2000; Zaragosi et al., 2001, 2006; Auffret et al., 2002) (Table 2).

An age model for core MD03-2692 was previously proposed by Mojtahid et al. (2005), then by Eynaud et al. (2007) but the chronostratigraphical framework of the penultimate glaciation remained elusive because of the lack of benthic foraminifera in the mid-MIS 6, precisely between 2380 cm and 2600 cm. In order to circumvent this problem, and to compare the palaeoceanographic proxies of core MD03-2692 with the wider North Atlantic, we have compared the discontinuous benthic isotope record of core MD03-2692 with the continuous isotope record of core ODP-980 (McManus et al., 1999) (Fig. 4). The latter is considered as a key reference core for the North Atlantic. Because of their excellent matching, we synchronised the benthic isotope records of cores MD03-2692 and ODP-980 to the standard LR04-stack chronology of Lisiecki and Raymo (2005) (Fig. 4). The age model reveals that core MD03-2692 extends back to about 350 ka (MIS 10) and that the lack of benthic foraminifera within the mid-MIS 6 corresponds to the 148–155 ka interval (Fig. 4). The chronology of the upper part of cores MD03-2692 and ODP-980 is based on radiocarbon ages and corresponds to the age model previously proposed by Eynaud et al. (2007) and McManus et al. (1999), respectively. The average age of HE 5 (45 ka – Hemming, 2004), the lower and upper boundary of HE 4 and the lower boundary of HE 3 were added, based on the chronology of Elliot et al. (2001), to the age model of core MD03-2692 in order to improve the chronostratigraphic framework of the MIS 3 (Tables 2 and 3).

Benthic δ^{18}O isotopic records, sediment colour measurements (L^*) and $CaCO_3$ content were used to reconstruct the chronostratigraphy of the long-time sedimentary records of cores MD01-2448 and MD04-2818 (Fig. 5). Age models were constructed by synchronizing the benthic oxygen isotope record of core MD01-2448 and the sediment lightness and carbonate content records of core MD04-2818 to the standard LR04-stack chronology. The age model of the upper part of core MD01-2448 was finally refined using AMS ^{14}C dates (Jullien, 2006) (Tables 2 and 3).

4. Results and discussion

4.1. Terrigenous input in the Bay of Biscay through the Last Glacial period

4.1.1. Imprint of the glacially-influenced 'Fleuve Manche' palaeoriver into the deep-sea sedimentation of the northern Bay of Biscay

Our reconstruction of the terrigenous input in the Bay of Biscay during the last glacial period shows that mass accumulation rates (MAR) at sites MD95-2002, MD03-2692, MD03-2696 and MD04-2845 are significantly higher than the average terrigenous flux of 4.7 g cm^{-2} kyr^{-1} recorded since the Last Interglacial in the wider northeast Atlantic by Cremer et al. (1992, 1993) (Fig. 6). MAR show a continuous increase trend through the last glacial period. Core MD03-2692, for instance, shows mean terrigenous flux of 7.5, 9.9 and 23.1 g cm^{-2} kyr^{-1} during the MIS 4, MIS 3 and MIS 2, respectively, while interglacials MIS 5 and MIS 1 show rates lower than 2.5 g cm^{-2} kyr^{-1} in comparison (Figs. 6 and 7). The highest rates occurred between ca 20 and 17 ka and more particularly after ca 18.3 ka, reaching until 155 g cm^{-2} kyr^{-1} at sites MD95-2002 and MD03-2696. This pattern, described in all cores of the study, is corroborated by the Ti/Ca ratio of core MD03-2692 which shows an increased trend until ca 17 ka then a rapid decrease thereafter (Fig. 7), highlighting the close relationship between the MAR and the Ti/Ca ratio.

It is commonly accepted that sea-level fall and lowstand conditions favoured the seaward transfer of sediment. Here, we show that the evolution of the sediment source, superimposed on sea-level variations, acted as the main forcing of terrigenous input to the Armorican margin. Indeed, compilation of MAR from discrete periods indicates that the glacial terrigenous flux declines seaward exponentially with a 'half-distance' of 75 to 100 km from a sediment source located in the Western Approaches (Fig. 6). We assume, therefore, that the 'Fleuve Manche' palaeoriver controlled the glacial terrigenous input variability described from the sites studied (Fig. 7) and was the most important source of sediment of the Bay of Biscay throughout the last glacial period. This pattern finally reflects that the glacial accumulations deposited at the studied sites were mainly fluvially-derived sediment, the part of sediment carried by icebergs (i.e. IRD) can thus be considered as of minor importance.

High-resolution study of the MIS 4/2 interval reveals that the dense XRF measurements allow discrimination of some millennial-scale events, only roughly detected in our estimation of the terrigenous flux because of the lack of stratigraphic markers after 25 ka. Significant increases of terrigenous input suggested by

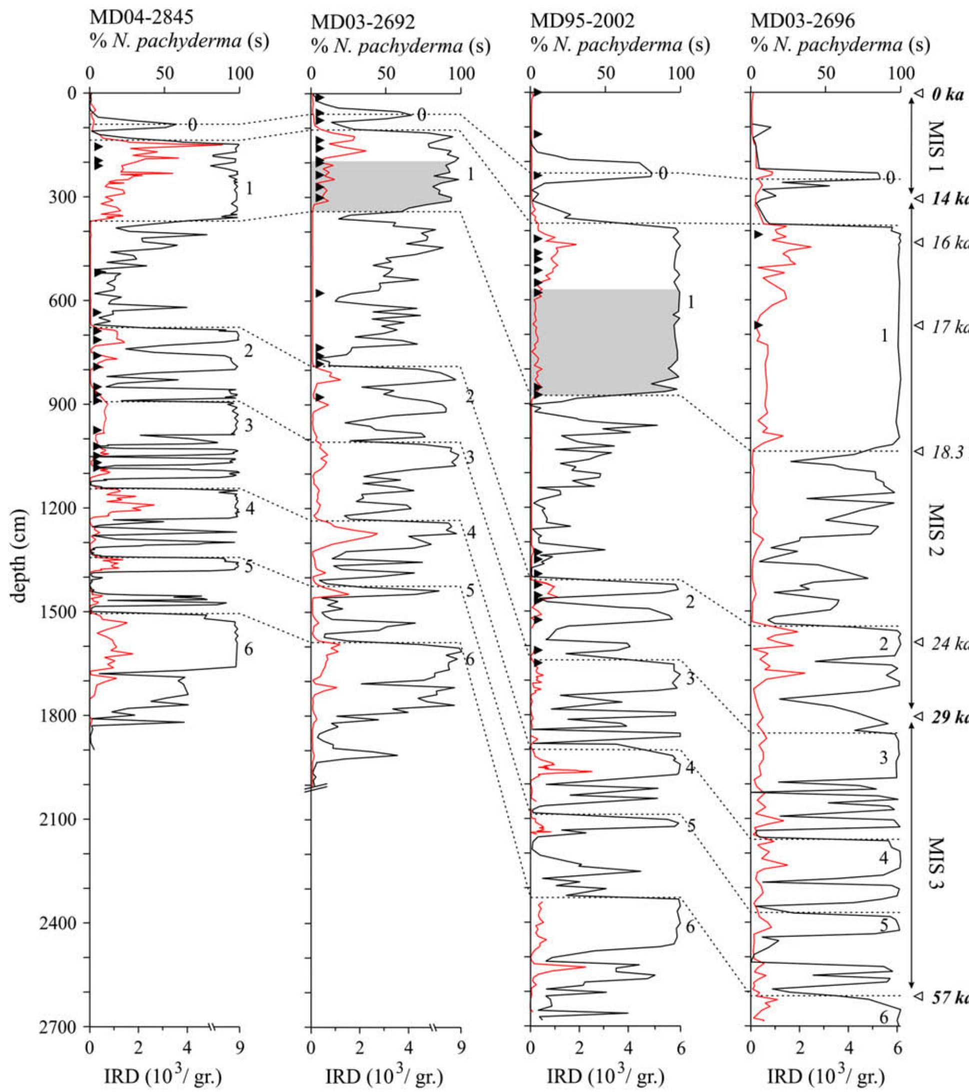

Fig. 3. Abundance of planktic foraminifers *N. pachyderma* (s) (continuous black line – %) and of IRD (red line – 10^3/gr) from sediment cores MD04-2845, MD03-2692, MD95-2002 and MD03-2696. Dashed black lines and associated numbers represent core-to-core correlations using the upper limit of the Heinrich events (HE) 0 (i.e. Younger Dryas), HE 2, HE 3, HE 4, HE 5 and HE 6 and the lower and upper limits of the HE 1. AMS ^{14}C dated samples are marked by black triangles on the depth scale. Bold ages and associated open triangles delimit the Marine Isotope Stages (MIS) boundaries according to the chronology of Lisiecki and Raymo (2005). Intermediate ages and associated open triangles within the MIS 2 make reference to the ages used in Fig. 6. Grey shading corresponds to the laminated facies deposited between ca 18.3 and ca 17 ka at sites MD03-2692 and MD95-2002 (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

increasing MAR and prominent peaks of Ti/Ca ratio occurred between ca 70 and 60 ka (MIS 5/4 transition) and ca 30 ka (MIS 3/2 transition) at site MD03-2692 (Fig. 7). These peaks coincide closely with significant sea-level falls (Lambeck et al., 2002; Waelbroeck et al., 2002), as supported by shifts in benthic δ^{18}O to heavy values in core MD03-2692. Because these sea-level changes caused strong fluvial erosion by the French (Cordier et al., 2006; Antoine et al., 2007), British (Van Huissteden et al., 2001), German (Kasse et al., 2003), Dutch (Busschers et al., 2007) and Belgian (Vandenberghe and De Smedt, 1979) rivers which led to an increase of seaward transfer of continentally-derived material, we assume that deep-sedimentation of the Armorican margin records the response of the 'Fleuve Manche' and its tributary rivers to the significant palaeoenvironmental changes.

The 'Fleuve Manche' discharges significantly increased from ca 20 ka, i.e. at the onset of the last glacial/interglacial transition (Termination I), then reached a maximum between ca 18.3 and 17 ka (Figs. 6 and 7). Previous studies in this region detected a strong increase of *Pediastrum* sp. concentration (freshwater alga) (Zaragosi et al., 2001; Eynaud et al., 2007) and of the BIT (Branched and Isoprenoid Tetraether)-index (Ménot et al., 2006), supporting the introduction of large volumes of fluvial terrestrial organic material to the Armorican margin contemporaneous with the high values of both XRF ratios and MAR. MAR of 155 g cm^{-2} kyr^{-1} estimated between ca 18.3 and 17 ka (Fig. 6) are exceptional regarding the open-ocean environment of the hemipelagic sites MD95-2002 and MD03-2696 (Cremer et al., 1992; Andrews and Syvitski, 1994). This indicates the operation of strong efficient erosional processes within the upstream catchment of the 'Fleuve Manche' and high riverine discharges. This assumption is supported by the large extension of the turbid plumes which induced high terrigenous input as far as sites MD04-2818, MD01-2448 and MD04-2845, and by the huge input of turbiditic material into the Armorican turbidite system within the ca 20–17 ka interval (Toucanne et al., 2008). In agreement with Toucanne et al. (2008), we assume that the strengthening of the 'Fleuve Manche' palaeoriver discharges from ca 20 ka mainly resulted from the retreat of the mid-latitudinal European ice sheets and glaciers, as reported from Britain (McCabe

Table 2
Radiocarbon ages of cores MD95-2002, MD01-2448, MD03-2692, MD03-2696 and MD04-2845.

Core label	Depth (cm)	Material	Laboratory number	Corrected ^{14}C, age (yr BP)	Calendar age, (cal yr BP)	Data origin
MD95-2002	0	*G. bulloides*	LSCE-99360	1660 ± 70	1624	Zaragosi et al., 2001
MD95-2002	140	*G. bulloides*	LSCE-99361	9080 ± 90	10329	Zaragosi et al., 2001
MD95-2002	240	*N. pachyderma* s.	LSCE-99362	10790 ± 100	12809	Zaragosi et al., 2001
MD95-2002	420	*N. pachyderma* s.	LSCE-99363	13330 ± 130	15798	Zaragosi et al., 2001
MD95-2002	454	*N. pachyderma* s.	LSCE-99364	13800 ± 110	16426	Zaragosi et al., 2001
MD95-2002	463	*N. pachyderma* s.	LSCE-99365	14020 ± 120	16709	Zaragosi et al., 2001
MD95-2002	510	*N. pachyderma* s.	LSCE-99366	14170 ± 130	16897	Zaragosi et al., 2001
MD95-2002	550	*N. pachyderma* s.	SacA-003242	14430 ± 70	17327	Zaragosi et al., 2006
MD95-2002	580	*N. pachyderma* s.	Beta-141702	14410 ± 200	17332	Zaragosi et al., 2001
MD95-2002	869	*N. pachyderma* s.	SacA-003243	14900 ± 70	18241	Zaragosi et al., 2006
MD95-2002	875	*N. pachyderma* s.	SacA-003244	14880 ± 160	18224	Zaragosi et al., 2006
MD95-2002	1320	*G. bulloides*	SacA-003245	18450 ± 90	22062	Zaragosi et al., 2006
MD95-2002	1340	*G. bulloides*	SacA-003246	19030 ± 100	22514	Zaragosi et al., 2006
MD95-2002	1390	*G. bulloides*	SacA-003247	20220 ± 80	24690	Zaragosi et al., 2006
MD95-2002	1424	*N. pachyderma* s.	Beta-123696	19840 ± 60	23777	Grousset et al., 2000
MD95-2002	1453	*N. pachyderma* s.	Beta-123698	20030 ± 80	23984	Grousset et al., 2000
MD95-2002	1464	*N. pachyderma* s.	Beta-123699	20200 ± 80	24174	Grousset et al., 2000
MD95-2002	1534	*N. pachyderma* s.	Beta-123697	21850 ± 70	25810	Grousset et al., 2000
MD95-2002	1610	*N. pachyderma* s.	Beta-99367	24010 ± 250	28173	Auffret et al., 2002
MD95-2002	1664	*N. pachyderma* s.	Beta-99368	25420 ± 230	29684	Auffret et al., 2002
MD01-2448	127	*N. pachyderma* s.		20380 ± 90	23930	Jullien, 2006
MD01-2448	143	*N. pachyderma* s.		23670 ± 200	27832	Jullien, 2006
MD01-2448	193	*N. pachyderma* s.		31980 ± 400	36380	Jullien, 2006
MD01-2448	206	*N. pachyderma* s.		32670 ± 400	37000	Jullien, 2006
MD03-2692	10	*G. bulloides*	SacA-001895	7830 ± 60	8747	Eynaud et al., 2007
MD03-2692	60	*N. pachyderma* s.	SacA-001896	10700 ± 60	12764	Eynaud et al., 2007
MD03-2692	80	*G. bulloides*	SacA-001897	11420 ± 60	13272	Eynaud et al., 2007
MD03-2692	120	*N. pachyderma* s.	SacA-001898	13360 ± 70	15843	Eynaud et al., 2007
MD03-2692	160	*N. pachyderma* s.	SacA-001899	14150 ± 70	16874	Eynaud et al., 2007
MD03-2692	190	*N. pachyderma* s.	SacA-001900	14240 ± 70	16998	Eynaud et al., 2007
MD03-2692	200	*N. pachyderma* s.	SacA-001901	14300 ± 70	17108	Eynaud et al., 2007
MD03-2692	230	*N. pachyderma* s.	SacA-001902	14700 ± 80	17828	Eynaud et al., 2007
MD03-2692	260	*N. pachyderma* s.	SacA-001903	14760 ± 80	17883	Eynaud et al., 2007
MD03-2692	300	*N. pachyderma* s.	SacA-001904	14820 ± 80	17976	Eynaud et al., 2007
MD03-2692	580	*G. bulloides*	SacA-001905	16890 ± 90	20010	Eynaud et al., 2007
MD03-2692	740	*G. bulloides*	SacA-001906	19920 ± 130	23871	Eynaud et al., 2007
MD03-2692	760	*G. bulloides*	SacA-001907	20130 ± 130	24095	Eynaud et al., 2007
MD03-2692	780	*N. pachyderma* s.	SacA-001908	20320 ± 140	24308	Eynaud et al., 2007
MD03-2692	880	*N. pachyderma* s.	SacA-001909	22060 ± 160	26042	Eynaud et al., 2007
MD03-2696	420	*N. pachyderma* s.	SacA-009011	13655 ± 45	15703	this paper
MD03-2696	669	*N. pachyderma* s.	SacA-009012	14770 ± 50	17205	this paper
MD04-2845	150	*N. pachyderma* s.	SacA-002955	13490 ± 100	15754	this paper
MD04-2845	191	*N. pachyderma* s.	SacA-002957	13840 ± 110	16482	this paper
MD04-2845	210	*N. pachyderma* s.	SacA-002958	14050 ± 110	16743	this paper
MD04-2845	520	*G. bulloides*	SacA-002960	16890 ± 150	20027	Daniau et al., in press
MD04-2845	690	*N. pachyderma* s.	SacA-002961	20420 ± 80	24441	Daniau et al., in press
MD04-2845	710	*N. pachyderma* s.	SacA-002962	20710 ± 80	24881	Daniau et al., in press
MD04-2845	770	*N. pachyderma* s.	SacA-002963	21860 ± 160	25821	Daniau et al., in press
MD04-2845	790	*N. pachyderma* s.	SacA-002964	22150 ± 170	26141	Daniau et al., in press
MD04-2845	850	*G. bulloides*	SacA-002965	24050 ± 210	28216	Daniau et al., in press
MD04-2845	860	*N. pachyderma* s.	SacA-002966	24680 ± 230	28894	Daniau et al., in press
MD04-2845	890	*G. bulloides*	SacA-002968	25230 ± 240	29482	Daniau et al., in press
MD04-2845	980	*N. pachyderma* s.	SacA-002970	26780 ± 290	31118	Sanchez Goni et al., 2008
MD04-2845	1020	*G. bulloides*	SacA-002971	28680 ± 350	33083	Sanchez Goni et al., 2008
MD04-2845	1048	*G. bulloides*	SacA-002974	29470 ± 390	33886	Sanchez Goni et al., 2008
MD04-2845	1060	*N. pachyderma* s.	SacA-002975	30290 ± 420	34712	Sanchez Goni et al., 2008
MD04-2845	1078	*G. bulloides*	SacA-002976	30950 ± 460	35370	Sanchez Goni et al., 2008

and Clark, 1998; Bowen et al., 2002; McCabe et al., 2005; O'Cofaigh and Evans, 2007), Scandinavia (Dahlgren and Vorren, 2003; Rinterknecht et al., 2006), Poland (Marks, 2002) and the Alps (Hinderer, 2001; Ivy-Ochs et al., 2004), in response to the increase of the Northern Hemisphere summer insolation. The strong increase of the 'Fleuve Manche' activity from ca 18.3 ka occurred at time of important environmental changes in the north and north-western British ice margin (Knutz et al., 2002a,b; Wilson et al., 2002; Hall et al., 2006), contemporaneous with the maximum decay of the FIS (Svendsen et al., 1996; Kleiber et al., 2000; Vorren and Plassen, 2002; Dahlgren and Vorren, 2003; Nygard et al., 2004; Lekens et al., 2005; Knies et al., 2007; Rinterknetch et al., 2007; Goehring et al., 2008), reinforcing the idea that the 'Fleuve Manche' activity was strongly dependent on the surrounding ice-sheet runoff. As a result, the 'Fleuve Manche' was a glacially-fed river and the Bay of Biscay was a depocentre for the European ice-sheets' erosional products, whose accumulations are still widely visible all along the southern margins of the past FIS (Eissmann, 2002; Houmark-Nielsen and Kjær, 2003; Ehlers et al., 2004) and BIIS (Eyles and McCabe, 1989; Bowen et al., 2002; Evans and O'Cofaigh,

Table 3
Control points used to tune benthic $\delta^{18}O$, $CaCO_3$ (%) and lightness (L^*) records of cores MD01-2448, MD04-2818, MD03-2692 and ODP-980 to the benthic stack of Lisiecki and Raymo (2005).

Core label	Depth (cm)	Age – LR04 stack	Core label	Depth (cm)	Age – LR04 stack
MD03-2692	1735	71	ODP-980	1137	71
MD03-2692	1830	82	ODP-980	1207	82
MD03-2692	1930	96	ODP-980	1337	96
MD03-2692	2070	125	ODP-980	1418	109
MD03-2692	2160	135	ODP-980	1714	125
MD03-2692	2250	142	ODP-980	1881	135
MD03-2692	2600	156	ODP-980	1946	142
MD03-2692	2670	167	ODP-980	2170	156
MD03-2692	2749	174	ODP-980	2220	167
MD03-2692	2840	183	ODP-980	2275	174
MD03-2692	2960	200	ODP-980	2320	183
MD03-2692	3044	224	ODP-980	2527	200
MD03-2692	3118	240	ODP-980	2802	224
MD03-2692	3298	262	ODP-980	3022	240
MD03-2692	3550	283	ODP-980	3263	262
MD03-2692	3730	324	ODP-980	3720	283
MD03-2692	3810	339	ODP-980	3848	295
			ODP-980	4068	317
			ODP-980	4281	324
			ODP-980	4435	339
MD04-2818	560	71	MD01-2448	300	71
MD04-2818	620	82	MD01-2448	340	82
MD04-2818	650	87	MD01-2448	390	96
MD04-2818	680	96	MD01-2448	460	109
MD04-2818	760	109	MD01-2448	490	125
MD04-2818	830	125	MD01-2448	555	139
MD04-2818	935	139	MD01-2448	675	154
MD04-2818	1130	154	MD01-2448	705	174
MD04-2818	1160	174	MD01-2448	787	191
MD04-2818	1265	191	MD01-2448	880	224
MD04-2818	1370	224	MD01-2448	905	240
MD04-2818	1425	240	MD01-2448	995	265
MD04-2818	1535	265	MD01-2448	1066	278
MD04-2818	1600	278	MD01-2448	1125	303
MD04-2818	1680	303	MD01-2448	1175	329
MD04-2818	1740	329	MD01-2448	1190	336
MD04-2818	1755	336	MD01-2448	1220	350
MD04-2818	1810	350	MD01-2448	1325	389
			MD01-2448	1400	405
			MD01-2448	1470	436

2003). Because Late Weichselian ice sheets never reached the English Channel area (Ehlers and Gibbard, 2004), we conclude that the Rhine–Thames drainage, which was a conduit for sediment-laden meltwater from the BIIS, FIS and the Alpine glaciers, flowed via the Dover Strait into the Bay of Biscay at the end of the last glacial period, confirming previous proposals by Gibbard (1988) and Busschers et al. (2007).

Coalescence of the BIIS and FIS in the North Sea basin is proposed for the last glacial period (Sejrup et al., 1994, 2000, 2009; Carr et al., 2006; Graham et al., 2007; Bradwell et al., 2008) and we assume that the southwards-directed drainage pattern described originates from this glacial configuration. The significant increase of terrigenous flux detected at ca 30 ka (Fig. 7), interpreted as enhanced 'Fleuve Manche' discharges, could reflect the southwards diversion of the North Sea fluvial systems expected from the coalescence of the ice sheets in the North Sea ca 30 ka ago, according to Sejrup et al. (1994, 2000, 2009). A glacial lake probably formed in the southern North Sea at this time but our data do not provide details of its presence and characteristics as such a lake has been repeatedly hypothesised previously, for example by Valentin (1957), Nilsson (1983) and Cohen et al. (2005). Moreover, the southern limit of the ice sheet in the North Sea during this period is poorly documented (e.g. Sejrup et al., 2009) and we consider that the strong increase in the 'Fleuve Manche' runoff from ca 20 ka may indicate, among other things, the retreat of this part of the ice sheet. This pattern, combined with the retreat of the ice sheet in the northern North Sea from ca 25 ka (Sejrup et al., 2000, 2009; Bradwell et al., 2008), supports the hypothesis of Bradwell et al. (2008) concerning the decoupling of the BIIS and FIS from the north, and interpreted by the authors as a result of rising sea level. In the light of our results, and in agreement with the chronology proposed by Carr et al. (2006), we propose, therefore, that the BIIS and FIS were confluent in the central North Sea up to ca 20 ka. This assumption must be tested, however the southwards flow of the FIS meltwater through the Dover Strait until ca 18 ka provides an important constraint on the glacial scenarios in the North Sea region during the last glacial period.

MAR and Ti/Ca ratio sharply decreased after ca 17 ka (Fig. 7), indicating a substantial reduction of seaward transfer of continentally-derived sediment onto the Armorican margin. This trend explains the rapid shutdown of the turbiditic activity (Toucanne et al., 2008) and the strong decrease of both *Pediastrum* sp. concentration and BIT-index in core MD95-2002 at ca 17 ka (Zaragosi et al., 2001; Ménot et al., 2006). The decrease of the 'Fleuve Manche' activity was contemporaneous with the onset of the Canadian-derived IRD input (very low Ti/Ca ratio, i.e. dolomitic-rich sediment) in the Bay of Biscay (Grousset et al., 2000; Zaragosi et al., 2001; Ménot et al., 2006) and with a significant re-advance of the BIIS (McCabe et al., 2007; Bateman et al., 2008), FIS (Nygard et al., 2004; Knies et al., 2007) and central European glaciers (Buoncristiani and Campy, 2004; Ivy-Ochs et al., 2006) suggesting that subglacial material transfer from the European ice masses to the Bay of Biscay was markedly reduced during re-advance episodes. Cold and dry conditions over Europe, described as polar desert conditions at around 16 ka according to Kasse et al. (2007), may also have favoured reduced fluvial transfer of sediment to the Bay of Biscay. Moreover, the Armorican margin was affected by a rapid and sustained rise of the global sea level from 16 to 12.5 ka (Lambeck et al., 2002) which probably induced a decreasing influence of the 'Fleuve Manche' palaeoriver and favoured the trapping of sediments in the 'Fleuve Manche' palaeoriver valleys and on the continental shelf. The extremely low terrigenous flux detected after ca 7 ka closely coincides with the disappearance of the 'Fleuve Manche' palaeoriver and the development of marine conditions in the English Channel, then through the Dover Strait (Lambeck, 1997; Lericolais, 1997; Bourillet et al., 2003). Our reconstruction of seaward sediment transfer to the Armorican margin therefore demonstrates a close relationship between global climate variability, palaeoenvironmental changes and 'Fleuve Manche' activity.

4.1.2. *Genetic interpretation of laminated sediments and palaeoenvironmental implications*

Detailed X-ray observation of the sediment deposited between ca 18.3 and 17 ka revealed laminations in cores MD95-2002 and MD03-2692 (Fig. 8), firstly evidenced by Zaragosi et al. (2001) and Mojtahid et al. (2005), respectively. Laminated sediments have been identified from many localities on the NW European margin during MIS 2 (e.g. Dahlgren and Vorren, 2003; Lekens et al., 2005), but those described from the Armoricain margin appear markedly different, even unique in the context of open-ocean environments (see O'Cofaigh and Dowdeswell (2001) for a thorough review). The facies studied mainly consists of millimetre to centimetre-scale layers of ungraded mud layers alternating with millimetre-scale layers of IRD-rich mud (Zaragosi et al., 2001), the repeated alternation of massive mud and IRD-rich layers imparting the laminated appearance (Fig. 8). The IRD-rich units, among 190 and 91 in cores MD95-2002 and MD03-2692 respectively, show admixture of scattered detrital grains, which are very predominantly quartz from 10 to 400 μm. SEM analyses reveal that the grains show

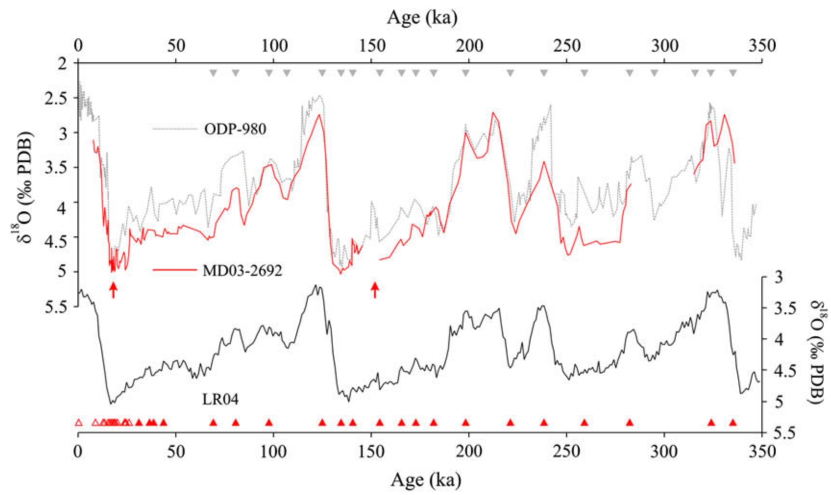

Fig. 4. Basis of the age models for cores MD03-2692 and ODP-980. Age control was established by alignment of the benthic foraminifera oxygen isotope records (δ^{18}O (‰), continuous red line: MD03-2692 and dotted grey line: ODP-980 (McManus et al., 1999)) with the LR04 benthic oxygen isotope stack of Lisiecki and Raymo (2005). Filled red and grey triangles indicate positions of the tie points for cores MD03-2692 and ODP-980, respectively. Open red triangles indicate the position of the AMS ^{14}C datings for core MD03-2692. Red arrows indicate the position of the laminated facies in core MD03-2692 (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

mechanically rounded edges and contains irregular breakages and V-shaped patterns, indicating that grains have been subjected to subaqueous mechanical action (i.e. fluvial origin) according to Krinsley and Doornkamp (1973) (Fig. 8). Although the mud fraction composing the IRD-rich units is ungraded, the IRD fraction is occasionally characterised by coarser grains at the base of the unit than at its top, thus forming peculiar normally-sorted IRD deposits supported by ungraded muds (Fig. 8). Dispersal of the outsized grains, despite their frequent grading, throughout the ungraded muds clearly indicates that such layers are not the result of turbiditic processes. This confirms the IRD origin of the outsized grains and strongly suggests that the mud deposition lasted at least as long as the ice-drift season (e.g. Hesse and Khodabakhsh, 2006).

Intense activity of the 'Fleuve Manche' palaeoriver occurred during the deposition of the laminated facies at sites MD95-2002 and MD03-2692, in response to the substantial retreat of the European ice sheets and glaciers (Zaragosi et al., 2001; Eynaud et al., 2007; Toucanne et al., 2008). As a result, the repeated alternation of massive muds and IRD-rich layers deposited at sites MD95-2002 and MD03-2692 between ca 18.3 and 17 ka is interpreted as having formed by rainout through a combination of continuous suspension settling of turbid hypopycnal surface plumes from the 'Fleuve Manche', which originate from the significant density difference between glacial meltwater and cold seawater (e.g. Mulder and Syvitski, 1995), and episodic IRD input. Though the source of the muds is unambiguously attributed to the 'Fleuve Manche', the source of the IRD nevertheless remains unclear. IRD input from iceberg rafting of sediments is an important feature of the mid-latitude belt of the North Atlantic between ca 18.3 and 16 ka, i.e. during HE 1 (Elliot et al., 2001) and previous studies suggested that the described succession of IRD-rich units was likely the result of the seasonal calving of the BIIS into the Celtic Sea (Mojtahid et al., 2005; Zaragosi et al., 2006; Eynaud et al., 2007). The BIIS origin of the IRD forming the IRD-rich units is questioned here.

Firstly, the seasonal pattern of IRD inputs from iceberg calving is only described in fjords through a complex sedimentation pattern related to the interactions between glaciers and sea–ice (Dowdeswell et al., 2000; O'Cofaigh and Dowdeswell, 2001). Secondly, although winter sea-ice formation was expected in the eastern North Atlantic as far south as $\sim$40°N during HE 1 (de Vernal et al., 2000), IRD-rich sediment described close to the BIIS margin within the ca 18-17 ka interval does not exhibit such a succession of IRD-rich units (e.g. Knutz et al., 2007; Peck et al., 2007). The quasi-monogenic composition (quartz) of the outsized grains at sites MD95-2002 and MD03-2692 also strongly differs from the polygenic 'BIIS-assemblage' (chalk, black limestone, schist clasts, etc.) recognised onto the Celtic and Porcupine areas (Scourse et al., 2000; Peck et al., 2007). Moreover, the BIIS, whose connection with the sea in the present-day Celtic Sea is still much debated (Scourse and Furze, 2001), had already considerably retreated at 18 ka (McCabe et al., 2007; Toucanne et al., 2008). Finally, if the combination of continuous huge fluvial sediment input and episodic iceberg arrivals downstream the 'Fleuve Manche' could have produced the alternation of massive muds and IRD-rich layers at sites MD95-2002 and MD03-2692, it cannot explain the seaward decrease of the number of laminae and of IRD flux observed between sites MD95-2002 and MD03-2692. Average IRD flux of 4650 and 2750 grains cm^{-2} kyr^{-1} interval were calculated within the ca 18.3–17 ka at sites MD95-2002 and MD03-2692 respectively, only 100 km away from each other (Toucanne, 2008). This significant difference of IRD flux between these nearby sites not supports the ubiquitous nature, at least at basin-scales, of the deposits from icebergs discharges (Ruddiman, 1977; Andrews, 2000). As a result, we conclude that the IRD-rich units observed in cores MD95-2002 and MD03-2692 within the ca 18.3–17 ka interval could not originate from BIIS icebergs and from tidewater glaciers more generally.

We propose that periodic expulsion by 'Fleuve Manche' discharges of anchor-ice, i.e. ice attached to the bed of rivers and including bed material (Reimnitz and Kempama, 1987; Kempama et al., 2001), and of sediment-rich frazil ice (Reimnitz and Kempama, 1987) could explain the episodic rainout of IRD described at sites MD95-2002 and MD03-2692. As reported in present periglacial and glacial environments (e.g. Benson and Osterkamp, 1974; Hill et al., 2001; Kempama et al., 2001), the formation of anchor-ice and frazil ice were able to occur in the 'Fleuve Manche' at around 17.5 ka due to the polar conditions prevailing over the NW Europe (Zaragosi et al., 2001; Kasse et al., 2007; Knutz et al., 2007; Peck et al., 2007). Such an alternative explanation to the BIIS origin of the outsized grains explains at the same time the weak extension of the IRD-rich units downstream from the 'Fleuve Manche', the decreasing number of laminae and the seaward decrease of the IRD

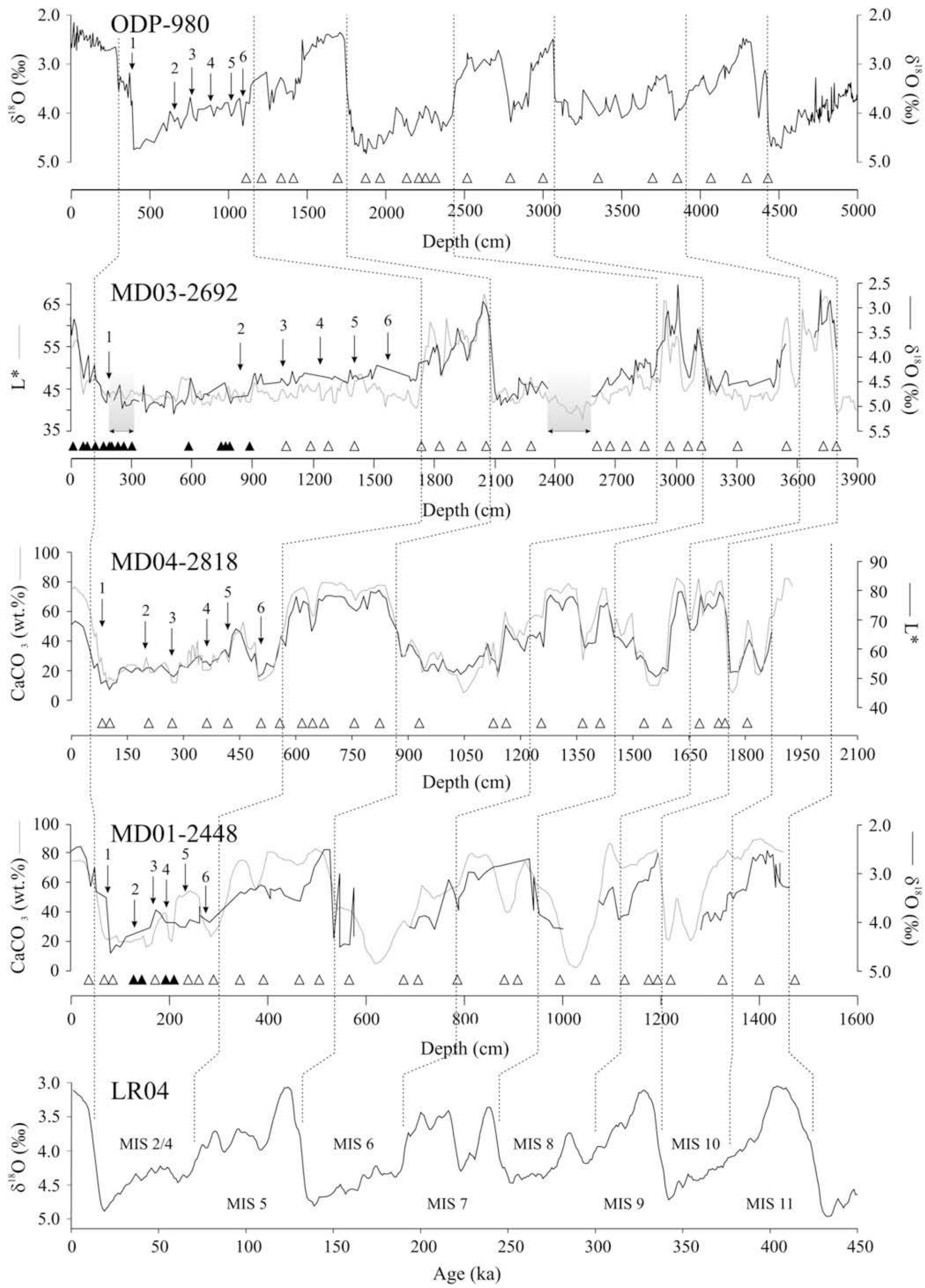

Fig. 5. Downcore records of benthic oxygen isotope values ($\delta^{18}O$), $CaCO_3$ content (weight percentage) and lightness (L^*) from cores MD01-2448, MD04-2818, MD03-2692 and ODP-980 (McManus et al., 2001). Vertical dashed lines show boundaries of the Marine Isotope Stage (MIS). Vertical arrows indicate the position of the Heinrich events 1–6. Black triangles indicate the position of the AMS ^{14}C dates while open triangles indicate the position of the major tie points between the LR04 chronology and the data of sites MD01-2448, MD04-2818, MD03-2692 and ODP-980. Shaded areas in core MD03-2692 indicate the position of the laminated facies.

flux between cores MD95-2002 and MD03-2692. The petrographic (quartz) and morphologic properties (related to their fluvial origin) of the detrital grains forming the IRD-rich units also corroborate our assumption. We assume, therefore, that the most substantial 'Fleuve Manche' discharges were probably able to transport seaward sediment-rich ice from the 'Fleuve Manche' area as far as sites MD95-2002 and MD03-2692. The sorting of the IRD within some of IRD-rich units and the individualisation of these units between massive muds (Fig. 8) could indicate that the IRD were sorted throughout their settling to the water column and that the presence of sediment-rich ice over sites MD95-2002 and MD03-2692 was relativity brief, unlike that of turbid meltwater plumes. We propose that high spring discharge of the 'Fleuve Manche' palaeoriver in response to the increased runoff of the surrounding ice sheets and glaciers could produce the IRD-rich laminae at sites MD95-2002 and MD03-2692, while the massive mud deposited above could materialize the following summer 'Fleuve Manche' activity.

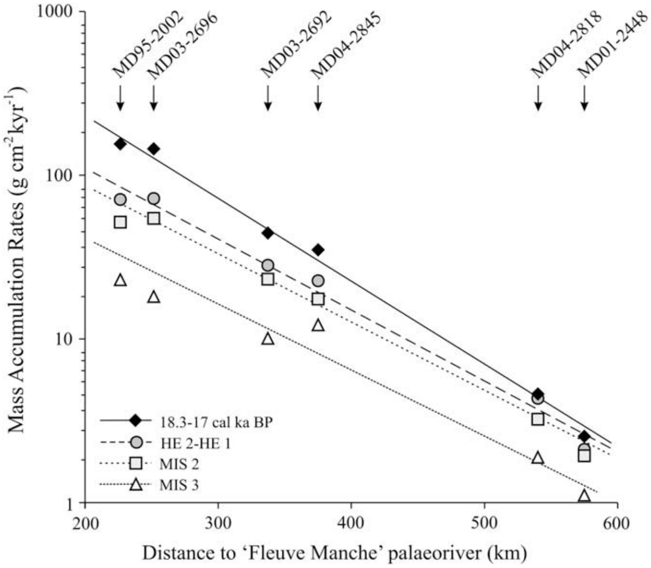

Fig. 6. Mass accumulation rates (MAR) at sites MD95-2002, MD03-2696, MD03-2692, MD04-2845, MD04-2818 and MD01-2448 during the MIS 3 (i.e. ca 57–29 ka), MIS 2 (i.e. ca 29–14 ka), HE 2-HE 1 (i.e. ca 24–16 ka) and ca 18.3–17 ka intervals according to their distance to the palaeo-mouth of the 'Fleuve Manche' palaeoriver (about 49°N / 7°W, in accordance to Bourillet et al. (2003)). Note that the MAR gradually increased throughout the last glacial period and declines seaward exponentially with a "half-distance" of 75 to 100 km from the 'Fleuve Manche' palaeoriver.

A polygenic assemblage of unorganised outsized mud-supported IRD (quartz, feldspar, dolomitic carbonate grains and volcanic debris up to 2000 μm) replace the laminated facies at sites MD95-2002 and MD03-2692 from ca 17 to 16 ka (Fig. 8). SEM analyses reveal that grains are irregular with sharp edges and conchoidal breakage forms characteristic of glacial environments (Fig. 8). This centimetre-scale IRD-rich layer appears in whole cores from the Bay of Biscay and we interpret this deposit as the sedimentary imprint of massive arrival of icebergs from the Laurentide ice sheet (LIS) in the NE Atlantic (Bard et al., 2000; Grousset et al., 2000; Zaragosi et al., 2001). Because cold conditions prevailed in the wider North Atlantic region until ca 16 ka, we suggest that the disappearance of the laminated facies exclusively resulted from the attendant strong decrease of the 'Fleuve Manche' discharges at ca 17 ka, considering that fluvial discharges were not important enough any more to transport the fluvial sediment-rich ice as far as sites MD95-2002 and MD03-2692. As a result, the described laminated facies resulted from the particular combination of cold conditions together with substantial sediment-laden discharges from the 'Fleuve Manche' palaeoriver. Our data show that such conditions, within the last glacial period, prevailed only between ca 18.3 and 17 ka.

4.2. *'Fleuve Manche' activity from MIS 10 to 6: insights into the European ice sheet and glaciers drainage network*

Reconstruction of the terrigenous input onto the Armorican margin between MIS 10 and MIS 2 reveals that the glacials MIS 10, MIS 8 and MIS 6 show significantly higher MAR and Ti/Ca ratio than interglacials MIS 9, MIS 7 and MIS 5 (Fig. 7), highlighting favoured seaward sediment transfer and the presence of the 'Fleuve Manche' palaeoriver during lowstand (glacial) conditions. Nevertheless our data show high Ti/Ca ratio during the interglacial MIS 7d at ca 225 ka. Although the sea level significantly fell (about 60 m according to Waelbroeck et al., 2002) during this period favouring the merging of the Somme, Seine or Solent rivers in the English Channel, our data indicate that the 'Fleuve Manche' activity was weak at this time. MAR was low at site MD03-2692 and we conclude, therefore, that the Ti/Ca ratio maximum resulted from the prominent decrease of the $CaCO_3$ content in core MD03-2692 rather than from substantial seaward transfer of terrigenous elements from the 'Fleuve Manche'. The decrease of the $CaCO_3$ content, which was also detected in cores MD04-2818 and MD01-2448 (Fig. 5), coincides with a prominent increase of the abundance of *N. pachyderma* (s), indicating the development of sub-polar water conditions in the Bay of Biscay which were unfavourable to biogenic carbonate production. Our results show therefore that 'Fleuve Manche' activity was low and confirm that MIS 7d was an extremely cold stadial event, as previously suggested by numerous marine records in the North Atlantic (McManus et al., 1999; Desprat et al., 2006; Roucoux et al., 2006).

4.2.1. *Marine Isotope Stage 10*

As reported from Termination I, Termination IV shows significant terrigenous input in the Bay of Biscay, as suggested by the high Ti/Ca ratio (Fig. 7). The detailed structure of the later part of the MIS 10 shows a complex pattern regarding the XRF measurements and only the peak of Ti/Ca ratio dating from ca 340 ka is considered as evidence of an increase seaward transfer of sediment from the 'Fleuve Manche' palaeoriver. The previous event, detected at ca 350 kyr closely parallels the abundance of outsized lithic grains, interpreted as IRD, and XRF measurements must reflect their chemical composition. Substantial IRD inputs have been detected in many records north of the Bay of Biscay at ca 350 ka (McManus et al., 1999; Hiscott et al., 2001; Helmke and Bauch, 2003) and the high abundance of IRD in core MD03-2692 reinforces the idea that a massive iceberg discharge from the Northern Hemisphere ice sheets occurred during this interval.

Glacigenic marine deposits in the northern North Sea and along the Norwegian margin reveal the presence of an extensive FIS, with an offshore extension considered similar to that in MIS 2, during the glacial MIS 10 (Sejrup et al., 2000, 2005; Dahlgren et al., 2002; Nygard et al., 2005; Rise et al., 2005). This indicates that ice over Europe contributed to the global glaciation and to the attendant significant low sea level which occurred during this interval (e.g. Waelbroeck et al., 2002). The synchronicity between the Termination IV and the increase of terrigenous input onto the Armorican margin suggests a close relationship between the 'Fleuve Manche' and the European ice masses. We suggest that the enhanced activity of the 'Fleuve Manche' results from the increased runoff of the ice sheets in response to the orbital forcing, implying that at least one tributary river of the 'Fleuve Manche' was connected to disintegrating ice during the Termination IV. MAR in cores MD03-2692, MD04-2818 and MD01-2448 are low in comparison to Termination I, indicating that the 'Fleuve Manche' activity was of lesser importance during Termination IV and that both the ice sheet and fluvial pattern in NW Europe during MIS 10 were different from those during MIS 2.

The southerly extension of the European ice sheets during MIS 10 is still a matter of debate, particularly because of the much debated correlation of the Holsteinian (-Hoxnian) temperate Stage with the MIS 11 interglacials (de Beaulieu and Reille, 1995; Vandenberghe, 2000; de Beaulieu et al., 2001; Schreve et al., 2002; Ehlers et al., 2004; Gibbard and Van Kolfschoten, 2005; Nitychoruk et al., 2006; Gibbard and Cohen, 2008) or MIS 9 (Scourse et al., 1999; Auguste et al., 2003; Geyh and Müller, 2005, 2007; Scourse, 2006; Litt, 2007). Correlation between the marine oxygen isotope stratigraphy and the Holsteinian Stage is crucial because this interval followed the extensive Elsterian (-Anglian) glaciation, dating from MIS 12 or MIS 10 depending on the correlation of the Holsteinian with MIS 11 or MIS 9, respectively. Continental ice

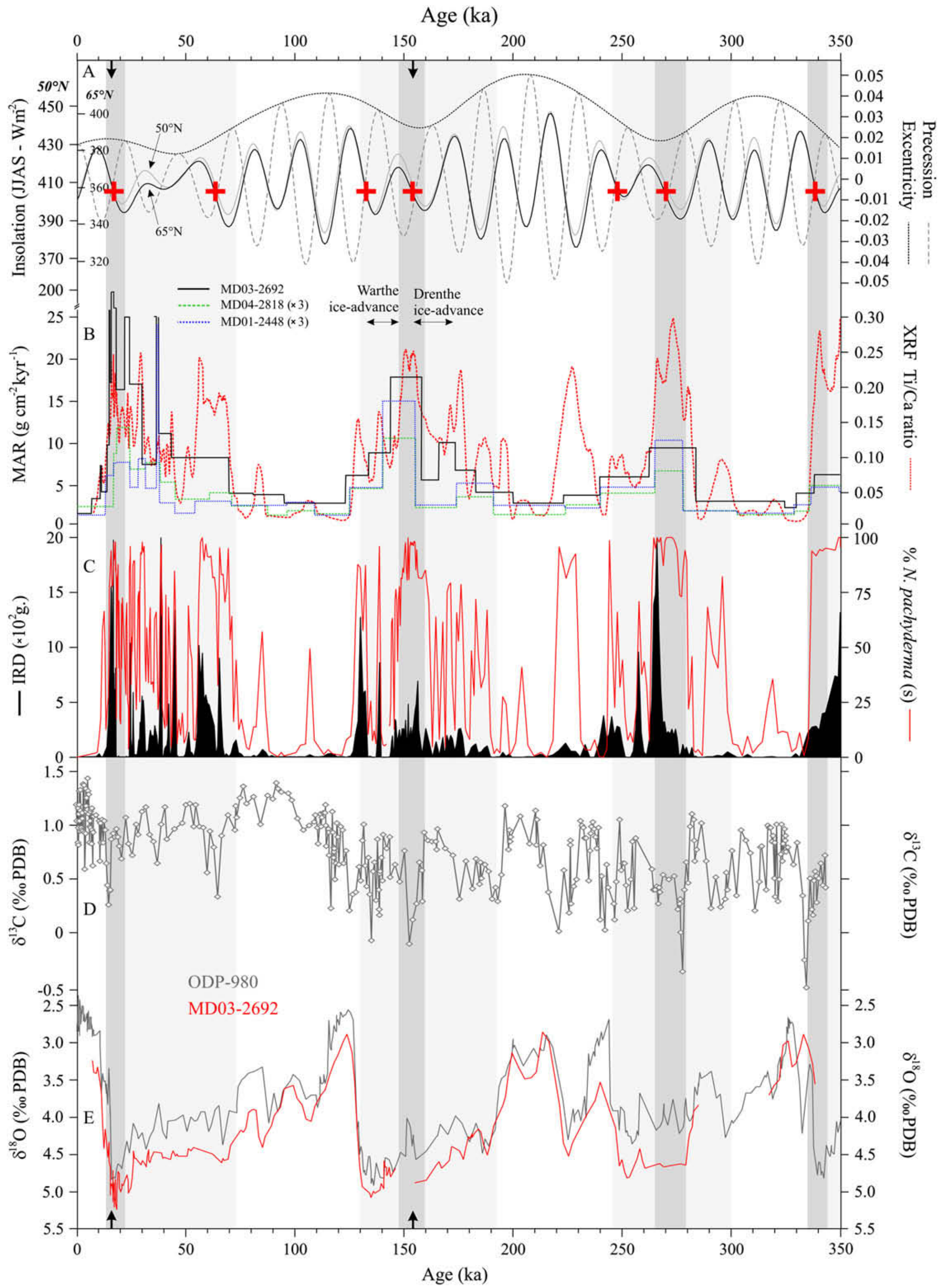

Fig. 7. Comparison of palaeoclimatic records. (A) Eccentricity (dotted black line), precession (dashed grey line) and summer (june to september) insolation curves for 65°N (continuous black line) and 50°N (continuous grey line) (Laskar et al., 2004). (B) Mass Accumulation Rates (MAR) for cores MD03-2692 (continuous black line), MD04-2818 (dashed green line) and MD01-2448 (dotted blue line); XRF Ti/Ca ratio (dashed red line) for core MD03-2692. (C) IRD content (black area) and abundance of the polar planktic foraminifera *N. pachyderma* (s) (continuous red line) for core MD03-2692. (D) ODP-980 benthic $\delta^{13}C$ (McManus et al., 1999). (E) Benthic $\delta^{18}O$ for cores MD03-2692 (red line) and ODP-980 (grey line). Light grey bands indicate glacial periods while dark grey bands highlight periods of increased 'Fleuve Manche' discharges. Black arrows indicate the position of the laminated facies in core MD03-2692. Red crosses positioned on the insolation curves (A) highlight the timing of the strong diminution of the $\delta^{13}C$ in core ODP-980 (D). Note that all strong depletions of the $\delta^{13}C$ during glacial periods occurred at time of increasing Northern Hemisphere summer insolation (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

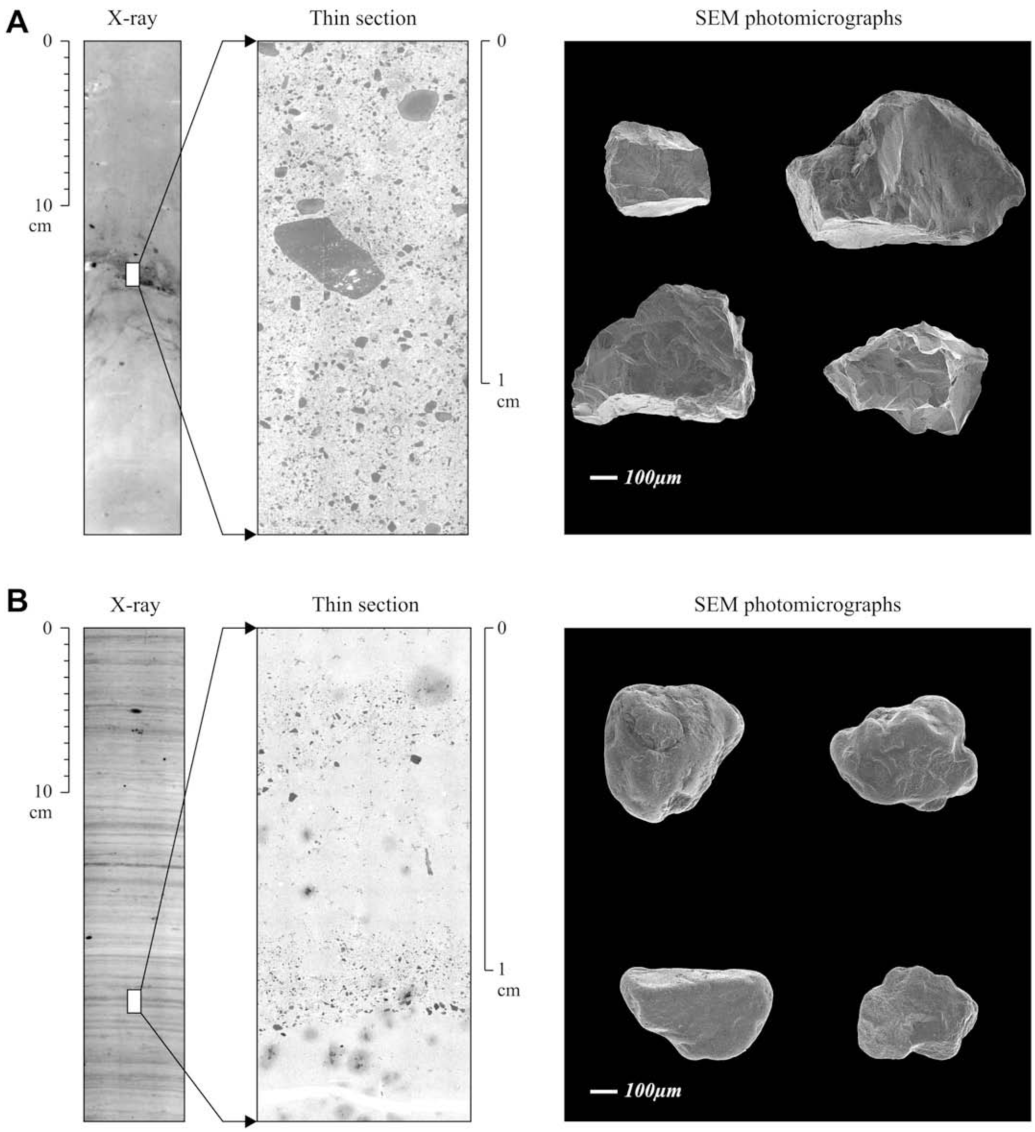

Fig. 8. X-ray imagery and thin section of impregnated sediment of the (A) unorganised hemipelagic sediment rich in outsized IRD and (B) laminated facies showing repeated alternation of massive mud and IRD-rich units of core MD03-2692. Facies A and B were described during the ca 17–16 ka and the ca 18.3–17 ka (MIS 2), respectively. Facies B is also described at ca 155 ka (MIS 6). Note that IRD from facies B are normally-graded. SEM (Scanning Electron Micrographs) photomicrographs reveal that quartz crystals show angular edges in Facies A while grains are well polished and sub-rounded in Facies B.

during the Elsterian glaciation advanced across the North Sea basin from southern Scandinavia, covering Poland, northern Germany and northern Dutch provinces (Ehlers et al., 2004), and then forcing rivers flowing northward (the Elbe and Rhine rivers especially) to be redirected, together with a large volume of meltwater, to a westerly course parallel to the ice margin before flowing through the Dover Strait (Gibbard, 1988). Our data show a low strengthening of the 'Fleuve Manche' discharges during Termination IV, incompatible with the fluvial pattern expected during the Elsterian period and the retreat of such an ice sheet. In the light of current discussions concerning the correlation of the Elsterian glaciation, the evidence from the present study implies that it did not occur during MIS 10, and if correct this questions the correlation of the immediately following Holsteinian temperate Stage with MIS 9.

To explain the synchronous activity of the 'Fleuve Manche' discharges with the retreat of the ice masses in Europe, and because Quaternary ice sheets never reached the English Channel area (Ehlers and Gibbard, 2004), we suggest that all or part of the meltwater from the southern North Sea basin drained through the Dover Strait during Termination IV. However, the relatively low MAR recorded downstream the 'Fleuve Manche' suggests that meltwater volume flowing to the Bay of Biscay was small, unlike during MIS 2. We assume that either the connection between the Channel area and the North Sea basin was reduced or that the 'Fleuve Manche' only collected meltwater from the Alpine glaciers via the Rhine during MIS 10. The expected relatively high-energy fluvial regime of the Rhine, in response to the disintegrating Alpine glaciers, may explain the deposition of the coarse-grained sediments described by Busschers et al. (2008) in the central Netherlands, the latter comprising major channel belts shaped by the river Rhine between MIS 10 and MIS 7. Throughout this period the North Sea basin was probably ice-free, allowing substantial meltwater from the FIS to flow northwards. As a result, we conclude that continental ice in the North Sea basin extended within the limits of the Weichselian glaciation (i.e. MIS 2) during MIS 10.

4.2.2. Marine Isotope Stages 6 and 8

Substantial ice advances occurred in Europe after the glacial MIS 10 and before the last glacial period, i.e. in the latter part of the Saalian Stage (Ehlers and Gibbard, 2004, 2007; Busschers et al., 2008). The Saalian, defined as the period between the Holsteinian (MIS 11, see discussion above) and the Eemian (MIS 5e) (i.e. Vandenberghe, 2000; Gibbard and Van Kolfschoten, 2005), ends with an interval of extensive glaciation considered as the second most important of the Quaternary, after the Elsterian glaciation. The extensive Saalian glaciation is traditionally subdivided into a primary advance phase, named the Drenthe glaciation in the Netherlands (Zagwijn, 1973; Laban and Van den Meer, 2004; Busschers et al., 2008) followed by a second ice re-advance, the Warthe, which generated sedimentary and morphological products well within the limits of the Drenthe glaciation ice sheet (Ehlers et al., 2004) (Fig. 1). During the Drenthe phase, continental ice advanced from centres in northern Russia, Scandinavia, as well as from the northern British Isles (Ehlers, 1990; Clark et al., 2004; Ehlers et al., 2004; Mangerud, 2004; Svendsen et al., 2004) to cover the North Sea basin including Poland, northern Germany and the Dutch area, as well as part of the eastern England (Ehlers, 1990; Laban, 1995; Ehlers et al., 2004; Laban and Van den Meer, 2004). It is commonly accepted that the extensive Saalian glaciation of the North Sea basin occurred during MIS 6 (Laban, 1995; Ehlers and Gibbard, 2004; Busschers et al., 2008) and that the NW European drainage passed through the Dover Strait during this interval, adopting a fluvial network similar to that expected during the Elsterian glaciation (Gibbard, 1988; Busschers et al., 2008).

Cores MD03-2692, MD04-2818 and MD01-2448 record both high MAR and Ti/Ca ratio during the glacial MIS 6, showing that substantial seaward transfer of continentally-derived material occurred onto the Armorican margin. The highest MAR associated with prominent values of the Ti/Ca ratio occurred between ca 160 and 150 ka, i.e. within mid-MIS 6, with values comparable to those detected at the end of the last glacial period (Fig. 7). A 2.5-m-thick laminated facies, very similar to the laminated facies dating from the Termination I (Fig. 8) and composed of 198 IRD-rich units, is observed in core MD03-2692 at around 155 ka. We conclude that the substantial increase of the terrigenous input onto the Armorican margin between ca 160 and 150 ka originate from a strong strengthening of the 'Fleuve Manche' activity and, by analogy with the sedimentary process described for Termination I, that 'Fleuve Manche' discharges were combined with sufficiently cold conditions to form anchor-ice in the 'Fleuve Manche' palaeoriver during this period. The monospecifism of the polar planktic foraminifera *N. pachyderma* (s) in cores MD03-2692 (Fig. 7), MD04-2818 and MD01-2448 indicating cold sea-surface temperature in the Bay of Biscay supports our interpretation. Because both the thickness of the laminated facies and the number of IRD-rich units are greater than during MIS 2, we deduce that more sediment-laden discharges, able to transport sediment-rich ice as far as site MD03-2692, occurred at ca 155 ka than at ca 18 ka, reinforcing the idea of an episode of extreme 'Fleuve Manche' activity within the ca 160–150 ka interval. The seasonal imprint of the fluvial discharges indicated by the deposition of the laminated facies preclude the large sediment input to the Armorican margin within the ca 160–150 ka interval as evidence of a megaflood event proposed by Gupta et al. (2007) during the Saalian Stage. Nevertheless, the succession of numerous huge 'Fleuve Manche' discharges into the subaerially exposed English Channel were possibly able to produce the shelf valley systems and associated major erosional features described by these authors. The fluvial erosion is supported by the very high ratio of Cretaceous to Palaeogene dinocysts from calcareous formations of the 'Fleuve Manche' catchment present in the laminated sediment of core MD03-2692 as reported by Eynaud et al. (2007).

The close correlation of the benthic oxygen isotope records from cores MD03-2692 and ODP-980 reveals that the substantial increase of the 'Fleuve Manche' activity coincides with a lightening of benthic $\delta^{18}0$ values of about 0.55‰ at site ODP-980 (Figs. 4 and 7), interpreted as representing a global rise of sea level of about 15–20 m by Waelbroeck et al. (2002) and hence corresponding to a decrease in global ice volume. Therefore, the extreme episode of 'Fleuve Manche' discharges probably reflects a large-scale meltwater event and was most likely the result of a significant retreat of the European ice sheets. This demonstrates therefore that the Dover Strait was open and that the Bay of Biscay was a major outlet for glacial meltwaters at this time. We suggest that the net loss of mass of the European ice sheet was most probably the result of the precessional forcing which increased both the Northern Hemisphere summer insolation and the seasonality (related to 'warm' summers and 'cold' winters) between 163 and 151 ka (Fig. 7). The process previously discussed regarding the episodic rainout of IRD downstream of the 'Fleuve Manche' supports both the pattern of a glacially-fed 'Fleuve Manche' and a well-developed seasonality, considering that anchor-ice was formed during the winter when the 'Fleuve Manche' activity was relatively low then expulsed seaward during the strongest melting episodes (i.e. in springtime) of the European ice sheet. Mid-MIS 6 'Fleuve Manche' activity and associated deep-sea sedimentation show disconcerting similarities to those described during the last deglaciation. However, the insolation maximum described at ca 150 ka was not as high as those causing the Termination I because the insolation maximum at the precession and tilt cycles were out of phase at this time (e.g. Ruddiman, 2006). If we assume that orbital forcing was not strong enough to induce a full deglaciation of the ice sheet during mid-MIS 6, our data show, however, that it was important enough to cause a partial melting of the southern ice-sheet margin, usually considered as the most sensitive to climate changes (e.g. Boulton et al., 2001). Significant lightening of planktic δ^{18}O values of about 2‰ in the central Adriatic Sea at ca 150 ka (Piva et al., 2008) could evidence substantial Alpine meltwater input from the Pô river in response to the partial melting of Alpine glaciers (Fig. 1). Moreover, numerous studies show strong palaeoenvironmental and palaeoclimatic changes at time of the increasing Northern Hemisphere insolation during the mid-MIS 6 (e.g. Petit et al., 1999; Ayalon et al., 2002; Kawamura et al., 2007; Hodge et al., 2008; Wang et al., 2008), corroborating the concept of a reorganisation of the southern margin of the European ice sheet and Alpine glaciers within the ca 160–150 ka interval.

Besides detecting a large-scale reorganisation of the European ice sheet within mid-MIS 6, our results also indicate that an extensive advance of the European ice sheet as far as the southern North Sea basin occurred during the first part of the MIS 6 sufficient to force the meltwater to flow southward through the Dover Strait. We assume that this major ice advance almost certainly corresponds to the Drenthe glaciation and we suggest, therefore, that the extreme 'Fleuve Manche' discharges detected at ca 155 ka reflect the retreat of the ice sheet between the Drenthe and Warthe advances (Figs. 7 and 9). The sharp decrease of Northern Hemisphere summer insolation between 150 and 140 ka could indeed favour a re-growth of the European ice sheet in the latter phase of the MIS 6. Such a pattern closely corresponds to terrestrial geological evidence for an absence of interglacial sediments between the glaciogenic sequences of the Drenthe and Warthe glaciations (Ehlers et al., 2004). As a result, the Drenthe and Warthe advances could have occurred within the intervals ca 175–160 ka and ca 150–140 ka, respectively, when the Northern Hemisphere summer insolation sharply decreased (Figs. 7 and 9). The presence of typical interglacial vegetation in Northern Iberia (Leymarie, 2008) and high phytoplanktonic productivity in the Bay of Biscay

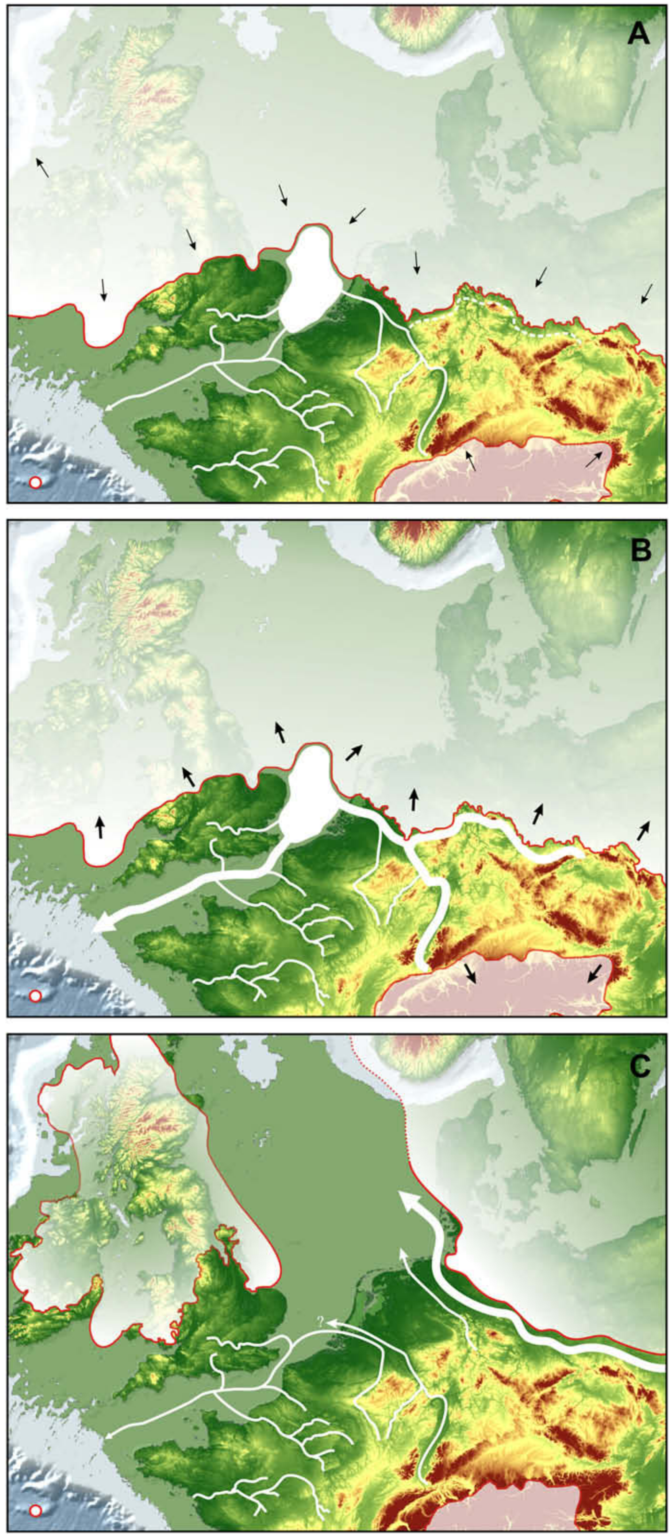

Fig. 9. Palaeogeographical reconstructions during the penultimate glacial period (i.e. MIS 6). Glacial limits from Ehlers and Gibbard (2004) in accordance with the chronology discussed in the text. (A) Drenthe advance (ca 175 ka to ca 160 ka); the extensive ice advance forced the central European rivers to flow southward through the Dover Strait. The relatively low 'Fleuve Manche' activity was most likely the result of the weak ice-sheet runoff. (B) Mid-MIS 6 (ca 155 ka); maximum 'Fleuve Manche' activity induced by a significant retreat of the southern ice margin. (C) Warthe glaciation (ca 150 ka to ca 140 ka) and Termination II (ca 140 ka to ca 130 ka); the 'Fleuve Manche' activity was low because meltwater from the southern ice margin flow northward through the North Sea basin via the Aller-Weser marginal valley. Extent of the BIIS during the Warthe Substage is not known, therefore a modified version of the Late Weichselian limit has been used in map C to provide an approximative view of the potential limit (see Ehlers and Gibbard (2004) for a thorough review).

(Penaud et al., submitted for publication) until ca 175 ka provide a limiting age for the onset of the Drenthe Substage advance.

Termination II shows moderate MAR, in comparison to the MAR detected at ca 155 ka, in cores MD03-2692 (Fig. 7), MD04-2818 and MD01-2448, indicating that 'Fleuve Manche' discharges were of lesser importance. Comparison with Termination I also reveals that the 'Fleuve Manche' activity was more important at the end of the last glaciation than during Termination II. This assumption is supported by the absence of a laminated facies at site MD03-2692 even though two strong cold events, characterised by monospecifism of *N. pachyderma* (s) and a discrete IRD peak, interspersed the end of MIS 6 (Fig. 7). These intervals, interpreted as Heinrich events (Lototskaya and Ganssen, 1999; McManus et al., 1999; de Abreu et al., 2003), were probably cold enough to induce formation of anchor-ice in the 'Fleuve Manche' but we assume that the meltwater discharges did not have the capacity to transport sediment-rich ice as far as site MD03-2692. As a result, the drainage configuration of the 'Fleuve Manche' during Termination II was almost certainly different from that Termination I, although the ice-sheet configuration at the end of the MIS 6 and MIS 2 were very similar (Ehlers and Gibbard, 2004). This is in spite of the fact that the Warthe maximum really occurred between ca 150 ka and the termination. We assume that a substantial portion of the meltwater from the ice margin probably flowed northwards through the North Sea basin, implying that continental ice did not covered the North Sea basin during the Warthe advance (Fig. 9). Such a pattern corroborates the geological evidence which suggests that meltwater from the southern ice margin drained via the Aller-Weser marginal valley ('urstromtal') towards the North Sea during the Warthe Substage glaciation (Ehlers et al., 2004). This drainage network may explain the strong increase of sediment input in the southeastern Nordic seas in the late MIS 6 (Brendryen et al., 2008). The moderate MAR detected at site MD03-2692 during the Termination II may result from the river Rhine and the disintegrating Alpine glaciers. Busschers et al. (2008) partially demonstrate such a possibility, showing that the Dover Strait drainage pathway was occupied, at least, by the river Meuse at this time.

The timing of sediment input via the 'Fleuve Manche' palaeoriver during MIS 8 shows many similarities to those described during the penultimate glacial period. Indeed, MAR and Ti/Ca ratio reveal that maximum input of continentally-derived material to the Armorican margin occurred not during Termination III (ca 250 ka) but in phase with the previous increase of Northern Hemisphere summer insolation, between ca 275 and 265 ka (Fig. 7). The seaward transfer of sediment to the Armorican margin during MIS 8 increased, therefore, at the time of an expected deterioration of Northern Hemisphere ice sheets, suggesting that an orbitally driven oscillation and partial melting of the European ice sheet at around 270 ka could have triggered a strengthening of the 'Fleuve Manche' activity. However, there is no evidence of massive ice sheets over the British Isles and the Northern European lowlands during MIS 8 (e.g. Bowen, 1999; Ehlers et al., 2004) and continental ice in Europe was probably restricted to mountainous areas, such as the Scottish Highlands, Scandinavia and the Alps. The moderate MAR, in comparison to the MAR estimated for the penultimate and last glacial period, strongly demonstrates that 'Fleuve Manche' activity was not as important at around 270 ka as at ca 155 ka and ca 18 ka, thus supporting the concept of discrete ice masses over Europe and ice-free conditions in the North Sea basin during MIS 8. As a result, we suggest that the moderate increase of sediment input via the 'Fleuve Manche' between ca 275 and 265 ka could have been caused either by the partial melting of Alpine glaciers, thus implicating that the Rhine flowed through the Dover Strait, or from the direct consequence on climate, vegetation and hence soil erosion of an increased flux of freshwater into the North Atlantic from disintegrating Northern Hemisphere ice masses.

4.3. Comments on the timing of major 'Fleuve Manche' discharges and climate changes over the last 350 kyr

Our reconstructions of the 'Fleuve Manche' palaeoriver activity show that increased discharges, detected at ca 340 ka (MIS 10), ca 270 ka (MIS 8), ca 155 ka (MIS 6) and ca 18 ka (MIS 2), correlate with strong decreases of the $\delta^{13}C$ at site ODP-980 (Fig. 7), thereby demonstrating coincident reduction in both the rate of deep-water formation and the strength of the Atlantic thermohaline circulation (THC) (McManus et al., 1999). $\delta^{13}C$ data for ODP-980 reveals that glacial collapses of the THC with magnitude comparable to those detected at time of increased 'Fleuve Manche' discharges are relatively rare during the last 350 kyr, all coinciding with increasing Northern Hemisphere summer insolation (Fig. 7). Because of the close relationship between the THC and the poleward oceanic heat transport, glacimarine conditions pointing to the occurrence of Heinrich-type events prevailed in the North Atlantic during these periods, as suggested by large abundance of *N. pachyderma* (s) and IRD input both in the Bay of Biscay and at site ODP-980 (Fig. 7).

Numerical models demonstrate that the THC is highly sensitive to the freshwater forcing (e.g. Rahmstorf, 1995). Moreover, some abrupt decreases of the THC and climate cooling during the Late Pleistocene have been directly linked to increased freshwater flux into the North Atlantic (Broecker et al., 1989; Clark et al., 2001, 2002; Rahmstorf, 2002). The excellent agreement of the timing of strong reductions of the THC with periods of increasing Northern Hemisphere summer insolation, following large expansion of continental ice sheets, supports the idea that freshwater forcing from disintegrating ice sheets played a key role in the occurrence of some Heinrich-type events throughout the last 350 kyr. We assume that the attendant increases of European ice sheet runoff and of 'Fleuve Manche' discharges corroborate this assumption and we suggest, therefore, that the 'Fleuve Manche' palaeoriver could have impinged, probably together with other meltwater sources, on the vigour of the THC. For the last glacial period, the huge 'Fleuve Manche' discharges dating from ca 18 ka correlate with significant freshwater fluxes from the circum-North Atlantic ice sheets, as reported from the FIS (Kleiber et al., 2000; Dahlgren and Vorren, 2003; Lekens et al., 2005; Rasmussen et al., 2007), the BIIS (Zaragosi et al., 2001; Hall et al., 2006; Ménot et al., 2006; Toucanne et al., 2008) and the LIS (Clarke et al., 1999; Tripsanas and Piper, 2008), indicating that the 'Fleuve Manche' activity reflected a large-scale event of meltwater releases. Geochemical and isotopical data from numerous cores from the North Atlantic show a sharp concomitant decrease in the rate of deep-water formation leading to the HE 1 and a collapsed THC until ca 16 ka (McManus et al., 2004; Gherardi et al., 2005; Hall et al., 2006). If massive iceberg releases from the LIS sustained a weakened THC between ca 17 and 16 ka by freshening and increasing buoyancy of the Northern Atlantic surface water (Broecker, 1994; Vidal et al., 1997; Elliot et al., 2002; McManus et al., 2004), the synchronicity between the increased meltwater discharges from the circum-North Atlantic ice sheets and the sharp reduction of the deep-water formation at ca 18.3 ka strongly suggest the onset of cold conditions over the North Atlantic (e.g. Elliot et al., 2001; Naughton et al., 2007) and the subsequent re-advance of the European ice masses (e.g. McCabe and Clark, 1998; McCabe et al., 2007) as a response to a freshwater-forced reduction in the THC. The similarities, regarding the Northern Hemisphere summer insolation and the magnitude of the collapse of the THC, between the HE 1 and Heinrich-type events dating from ca 340 ka, ca 270 ka, ca 155 ka, ca 130 ka (HE 11, Lototskaya and Ganssen (1999)) and ca 60 ka (Fig. 7) strongly imply a similar pattern, thus indicating that each period of full (i.e. Terminations) or partial (e.g. mid-MIS 6, see discussion above) melting of the Northern Hemisphere ice sheets was punctuated by meltwater-forced Heinrich-type events. As demonstrated for the last deglaciation and HE 1 (e.g. Knutz et al., 2007), the expected Northern Hemisphere warming events were aborted by these episodes of large freshwater inputs, thus leading to a sustained climatic divergence between the hemispheres. Indeed, recent temperature reconstruction from Antarctica over the last 350 kyr demonstrates warming of the Southern Hemisphere within the ca 350–335 ka, ca 280–260 ka and ca 160–150 ka intervals (Kawamura et al., 2007) while glaciomarine conditions overran site ODP-980 and the Bay of Biscay despite the significant rise of the Northern Hemisphere summer insolation. Even if the discharges were not always as important as at ca 155 ka or ca 18 ka, depending on the extension of the European ice sheets and from the drainage configuration of the NW European rivers, the 'Fleuve Manche' activity achieved its maximum during these periods and, therefore, probably participated to the collapse of the THC.

5. Conclusions

The 'Fleuve Manche' palaeoriver activity over the last four glacial periods has been reconstructed using mass accumulation rates (MAR) and X-ray fluorescence (XRF) intensities of Ti from long piston cores retrieved from the Bay of Biscay. The reconstruction has allowed the determination of the timing and the amplitude of the 'Fleuve Manche' discharges during each glacial period, yielding detailed insight into the Middle and Late Pleistocene glaciations in Europe and the drainage network of the western and central European rivers over the last 350 kyr. The following conclusions can be drawn:

1. Episodes of 'Fleuve Manche' discharges occurred each time that Northern Hemisphere ice-sheet decay is predicted by orbital configuration. This strongly suggests that the 'Fleuve Manche' palaeodischarges were directly controlled by European ice-sheets' behaviour during glacial stages MIS 10, MIS 8, MIS 6 and MIS 4–2.
2. 'Fleuve Manche' activity during the glaciations MIS 10 and MIS 8 was significantly less than during MIS 6 and MIS 2. This implies that European ice-sheets and glaciers during the penultimate and last glacial periods were extensive in comparison to the two previous glaciations. We correlate the significant 'Fleuve Manche' activity, detected during MIS 6 and MIS 2, with the extensive Saalian (Drenthe) and the Weichselian glaciations, respectively, thus assuming that the major Elsterian glaciation precedes the glacial MIS 10.
3. Detailed analysis and reinterpretation of the laminated deposits described downstream of the 'Fleuve Manche' palaeoriver during MIS 6 and MIS 2 reveal periods of episodic, even seasonal, massive fluvial discharges accompanied with fluvial sediment-laden ice at ca 155 ka (mid-MIS 6) and ca 18 ka (Termination I). During these intervals, it is proposed that the seasonality in Europe was sufficiently strong to induce formation of anchor- and frazil-ice in the 'Fleuve Manche' and to trigger massive and brutal ice-sheet runoff, followed by substantial 'Fleuve Manche' discharges, during winters and springs, respectively.
4. No significant episode of fluvial discharges is described during Termination II, contrary to those during Termination I. This suggests that meltwater from the disintegrating European ice sheet and glaciers did not flow through the Dover Strait at the end of the MIS 6. It is assumed that a strong modification of the drainage network in the North Sea basin occurred during mid-MIS 6, related to an orbitally driven retreat of the European ice sheet at ca 155 kyr, followed by ice-free conditions between the British Isles and Scandinavia until Termination II. This allowed meltwater to flow northwards through the North Sea basin in the second part of the MIS 6. We assume that this glacial pattern corresponds to the Warthe Substage maximum, therefore indicating that the presented data here correlated to the Drenthe and the Warthe glacial advances at ca 175–160 ka and ca 150–140 ka, respectively.
5. Apart from the fact that the 'Fleuve Manche' discharges occur at the time of partial or complete melting of the European ice masses, they were also synchronous with strong decreases in both the rate of deep-water formation and the strength of the Atlantic thermohaline circulation leading to glacimarine conditions in the wider North Atlantic. It is concluded that massive 'Fleuve Manche' discharges over the last 350 kyr probably participated, with other meltwater sources, in the collapse of the thermohaline circulation by freshening the northern Atlantic surface water.

Finally, the results presented herein strongly demonstrate the importance of studying the southernmost part of the continental ice sheets in order to determine the land–sea–ice interactions during glaciations. The mid-latitude region of the extensive continental ice sheets are the most sensitive to climate change and the evidence presented suggests that oscillations of the southern ice-sheet margins, not necessarily in phase with those in the north (Ehlers and Gibbard, 2004), have strongly affected, via freshwater inputs, the oceanic circulation and the poleward heat transport during the recent glaciations.

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