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The 'Fleuve Manche': the submarine sedimentary features from the outer shelf to the deep-sea fans

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ABSTRACT: Bathymetric, seismic and coring surveys have been carried out since the beginning of the 1990s on the outer shelf, the slope and the continental rise of the Western Approaches margin. Most of the sedimentary features studied belong to a sedimentary system built up since the Oligocene and fed by a palaeoriver, the 'Fleuve Manche' that flowed in the English Channel during eustatic lowstands. A geomorphological map details the spatial distributions of the palaeovalleys on the outer shelf, the drainage-basin-like organised canyons on the slope and the channel–levee and lobe complexes on the rise. The obvious channel–canyon connections and the assessed palaeovalley–canyon links demonstrate that the 'Fleuve Manche' was the single source for terrigeneous fluxes of the Armorican Deep Sea Fan when it was one of two sources of the Celtic Deep Sea Fan. Amongst parameters controlling the sedimentation, two factors play a major role. (i) Subsidence controlled the possibly Messinian riverine incision, the turbidite activities during lowstands, as well as marine infilling of the seawards part of the 'Fleuve Manche'. (ii) Quaternary sedimentary supplies were influenced by the melting ice-sheets and the connections with the onshore catchment basins. Copyright © 2003 John Wiley & Sons, Ltd.

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KEYWORDS: palaeoriver; palaeovalley; drainage system; canyons network; channel–levee; Messinian.

Introduction

An integrated approach, without the constraint of present physiographic boundaries associated with on-land and offshore distributions, allows the necessary conditions for defining and studying large river systems. The 'Fleuve Manche' or Channel River is one such large river system because its catchment included the continental drainage systems of major west European rivers. It transports part of their sediment discharge through a submarine course of more than 1500 km from the present estuaries to the abyssal depocentres.

Processes associated with deglaciations and sea-level variations have eroded the continental shelf, removing some elements of the river system over time. Recent discoveries of two deep sea fans (Auffret *et al.*, 2000; Le Suavé *et al.*, 2000), detailed mapping of the slope (Bourillet and Loubrieu, 1995) and new insight into the stratigraphy and the geomorphology of the continental shelf (Lericolais, 1997) show elementary features that belong to the 'Fleuve Manche' system, and allow the reconstruction of the submarine pathways of the system since the Oligocene.

Off the present estuaries, the palaeovalleys represent an anastomosed pattern in the Eastern English Channel (Larsonneur *et al.*, 1982). They converge towards the eastern end of a large depression in the middle of the Channel, the Hurd Deep (see the article by Lericolais *et al.*, 2003). Westward of the deep, neither incised valleys nor palaeocoastlines are apparent. Palaeovalley systems and giant sandbanks reappear 200 km further southwest, close to the shelf-break (Bouysse *et al.*, 1976). Some of these palaeovalleys are connected to systems canyon on the slope that are organised similar to on-land drainage basins. These catchment areas feed two mid-sized turbidite systems: the Celtic and Armorican Fans. This set of sedimentary features represents the fluvial pathways to the deep-sea depocentres. After a short review of the basement geology of the Western Approaches margin and recent data sets, three sections describe the sedimentary architecture: the palaeovalleys of the outer continental shelf, the canyons of the continental slope and the deep-sea fans. The original geomorphological map highlights the spatial relationship between these features. Lastly, four specific points of the evolution of the 'Fleuve Manche' are discussed: age of the incision of the palaeovalleys, palaeogeographical evolution, sedimentary dispersal systems and late Pleistocene–Holocene events of the 'Fleuve Manche'.

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Geological setting of the western approaches margin

The distal part of the 'Fleuve Manche' system evolution in the late Neogene is largely controlled by the structure of the Western Approaches margin (Ziegler, 1987). This segment of the European Atlantic margin has a horst-and-graben geometry partly inherited from the interplay of N70° Variscan lineaments of the Western Channel area with the N140° normal faults of the Bay of Biscay (Vaillant, 1988). The 70 °N trending Western Approaches (WA) Basin originated from the dextral strike-slip reactivation of the late Palaeozoic (Variscan, 300 Ma) orogenic suture between the Laurasia and Gondwana palaeocontinents, still marked by meta-ophiolites in the Alderney–Ushant fault zone (Ziegler, 1987). The 5000 m of WA Basin infill is controlled by Permian and Triassic post-orogenic extension (normal faulting) and by Jurassic thermal relaxation (Evans, 1990). At the end of Early Jurassic times, the Western Channel Basin evolved to an overfilled epicontinental carbonate platform connected to the Paris–London basin. The Bay of Biscay rifting and opening started in Middle Jurassic times and controlled (i) the dissection of the former 70 °N basin into tilted blocks bounded by 140 °N trending listric faults, which continued into Early Cretaceous times (de Charpal *et al.*, 1978; Guennoc, 1978; Montadert *et al.*, 1979; Sibuet *et al.*, 1994), and (ii) the thermal subsidence of the margin up to Paleogene times, allowing deposition of 500 m of chalk (Evans, 1990).

During Cenozoic times, two main Alpine tectonic phases controlled deposition in the WA Basin. First, middle Eocene subduction of the Atlantic beneath Iberia triggered Oligocene inversion of the Paleogene sub-basins of the WA, namely the compression and folding of the southeast border of the WA Basin, during which the basin acquired its present-day east-northeast synclinal structure (Ziegler, 1987). Second, the Western Alps collision brought a general uplift of about 100 m in the Paris Basin and Channel sectors during Late Miocene times, with maximum uplift in the WA Basin (Evans, 1990). This alpine inversion of the WA Basin is expressed by (i) the seawards stepping of two prograding deltaic wedges (Miocene Jones and Cockburn Formations, see below), which downlap seawards on to the folded chalk infilled basin (Evans and Hughes, 1984); (ii) Pliocene exhumation of the area, responsible for the network of valleys incised on top of the Miocene wedges (Little Sole Formation, see below).

Plio-Quaternary block-related tectonics occur in the outer part of the WA Basin, expressed by (i) the obliqueness of the Pliocene valley to the present-day shelf dip (Bouysse *et al.*, 1976); (ii) the occurrence of Pliocene slumps on the continental slope (Evans and Hughes, 1984); (iii) some hints of faulting within the incised valley (Vanhauwaert, 1993).

Data sets

Since the beginning of the 1990s, several surveys have been carried out within the framework of national or European programmes, such as the IFREMER SEDIMANCHE, the French EEZ and the STARFISH and ENAMII Mast programmes (Fig. 1): Belgica (1992, 1996), ZEE Gascogne (1992, 1997), Sédimanche (1992, 1993) and Sédifan (1997). The results of boreholes in the British sector were published in a synthesis by Evans (1990), and the record of the DSDP 400 (leg 48) hole, located on the continental rise, is suitable for sedimentological purposes. Stratigraphical studies were based on cores from MD-Image 1 (1995), Acores (1996), Modenam and Gascor (1986), Margas (1975) and Geogas (1972) cruises.

The continental shelf: sedimentary architecture

Neogene deposits of the Southwestern Approaches shelf overlie consolidated Palaeogene and Cretaceous strata of the Western Channel east-northeast syncline. The southern limb of the fold is broken by the mid-Channel fault bundle and by the southerly Alderney–Ushant fault bundle that delimit the Western Channel basin and the Iroise basin (Bois *et al.*, 1991a). The Neogene deposits (Fig. 2, and see Fig. 12) are composed of four main lithostratigraphical units (Evans, 1990):

1 early to mid-Miocene Jones Formation of progradational calcilutites (Evans and Hughes, 1984), the main depositional stage of which is now attributed to the Aquitanian to Serravalian interval (Powell, 1988),
2 mid- to late Miocene Cockburn Formation of deltaic, possibly tidal calcarenites (Evans and Hughes, 1984), the age of which is also attributed to Pleistocene by some authors (Powell, 1988),
3 Pliocene to Pleistocene Little Sole Formation that forms either a narrow wedge along the shelf-break, aggradational (in the north) to incised (in the south) fluvial deposits, or shelfal deposits (Bouysse *et al.*, 1976; Pantin and Evans, 1984; Reynaud *et al.*, 1999c),
4 unconformable Melville Formation made up of the bulk of the Celtic Banks on the outer shelf. The lithology of the unconsolidated Pliocene and Quaternary deposits comprising this Formation, as well as the thick mobile sediment cover of the WA basin, remains partly unknown, except at the sea-floor, where they dominantly consist of bioclastic gravelly sands.

The sand banks

The Melville Formation mostly comprises the bulk of the Celtic Banks. According to various authors, the interpretations based on recent data sets lead to different conclusions for the origin of the banks (Reynaud *et al.*, 2003). The banks could be relics of estuarine to deltaic features related to early Quaternary or even Pliocene sea-level falls (Lericolais, 1997), with an important role attributed to Upper Quaternary lowstand erosion in their origin as erosional offshore sand ridges (Berné *et al.*, 1998). It seems unlikely, however, that old sediment bodies could have survived the strong wave and tidal ravinement caused by the last sea-level fall (20 ka), one of the lowest Quaternary sea-levels determined from isotopic studies (Shackelton and Opdycke, 1976; Chapell *et al.*, 1996). The coupling of the glacio-hydroisostatic rebound resulting from the influence of the British ice-sheet would have significantly enhanced the relative sea-level fall (Wingfield, 1995). In this perspective, the Celtic Banks could be tidal sand banks wholly reworked at the last post-glacial sea-level rise from former lowstand deposits (Bouysse *et al.*, 1976; Pantin and Evans, 1984; Tessier, 1997; Marsset *et al.*, 1999; Reynaud *et al.*, 1999b). However, these hypotheses remain speculative as no samples of the banks core are available (Reynaud, 1996).

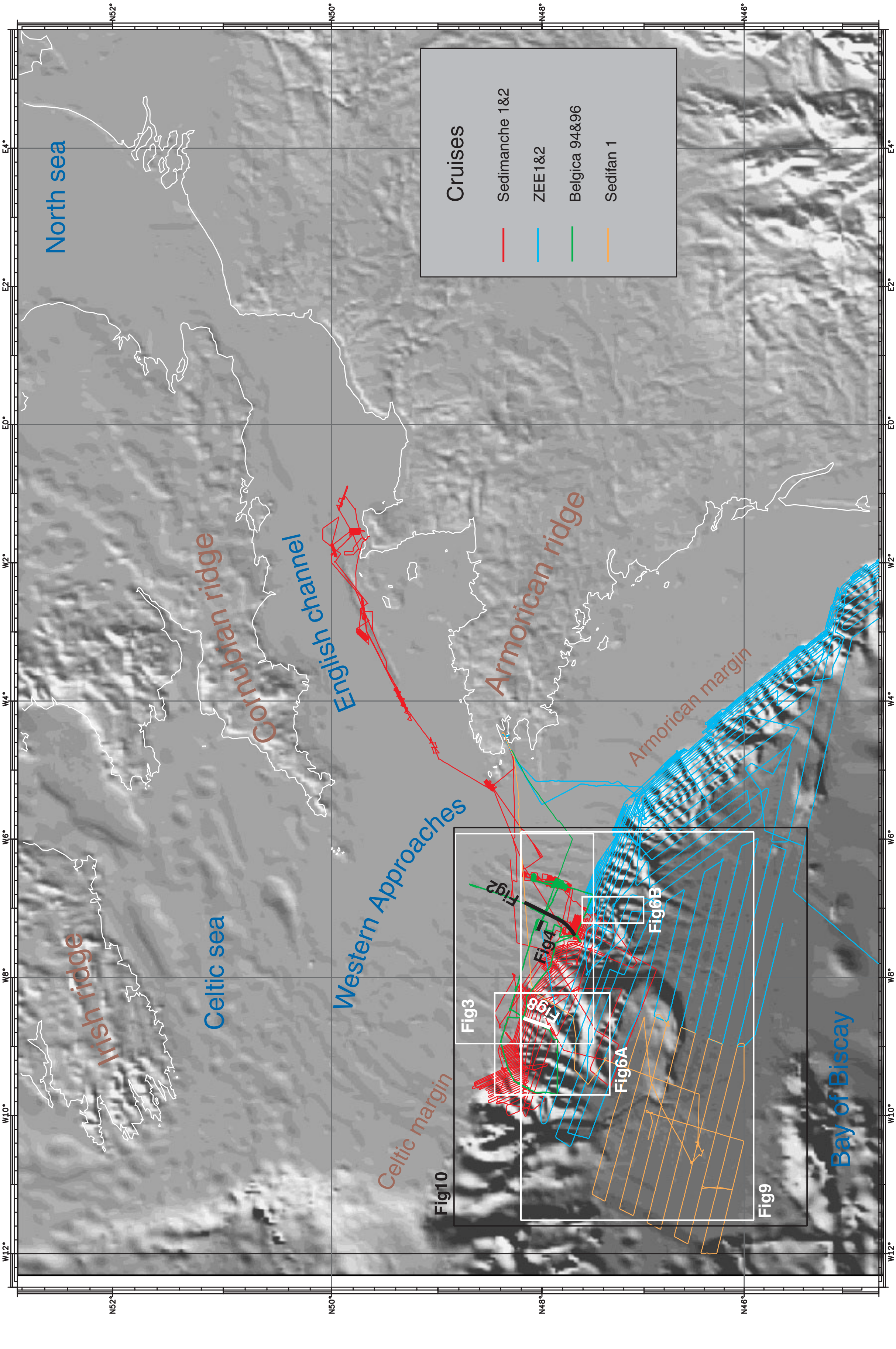

Figure 1 Location map of the submarine 'Fleuve Manche' system. Black or white boxes and bold lines correspond to the location of the figures

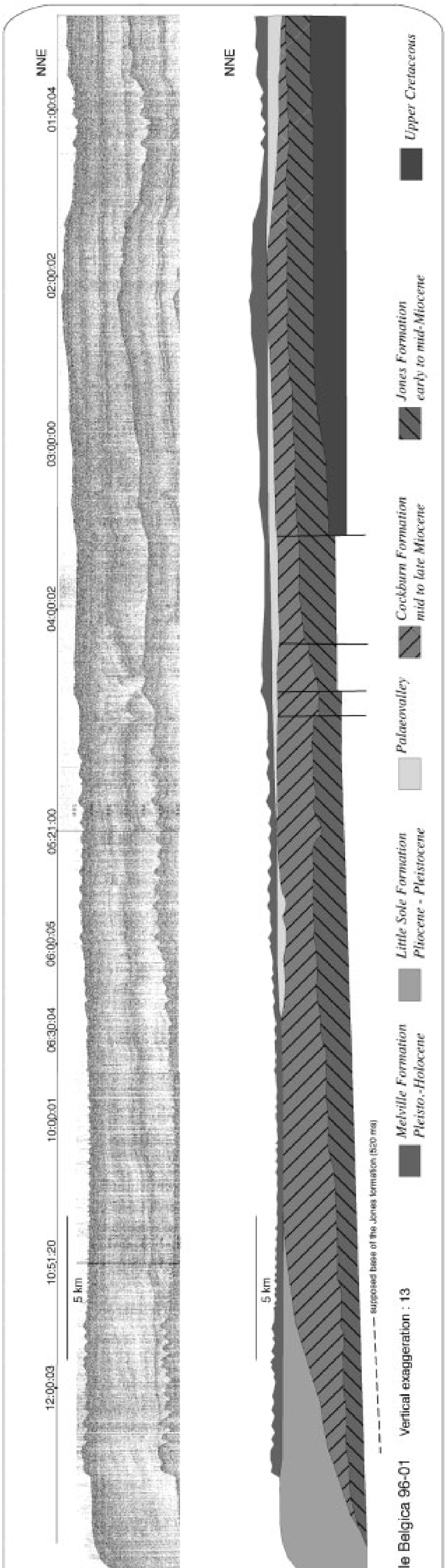

Figure 2 Section of the Neogene succession of the South Western Approaches (Bourillet and Lericolais, 2003). For location see Figs 1 and 3

The palaeovalleys

The lower unit, the Upper Little Sole Formation, is found below a flat surface that can be followed across the shelf at the base of the Celtic Banks. In the British sector of the Western Approaches and in the southern Celtic Sea, this formation forms a blanket that thickens up to 60 m towards the northwest. The seismic records show a high acoustic amplitude package of cross-bedded strata (Pantin and Evans, 1984), resting on an irregular, sinuous erosional surface incised on to the Eocene and Neogene prograding wedges of the outer shelf described by Evans and Hughes (1984). Pantin and Evans (1984) proposed a fluvial origin for these deposits because of the numerous cut-and-fill, channel-like internal structures.

A Network of valleys

In the French sector of the Western Approaches, the Upper Little Sole Formation is much thinner than in the British sector, so that its irregular base locally merges on to the shelf surface. Therefore it crops out in this sector as a network of fluvial palaeovalleys (Bouysse *et al.*, 1976).

The spatial distribution

The valley incisions in the axis of the Western Approaches are about 100 km long from the landwards limit of the data set at about 140 m b.p.s.l. (below present sea-level), down to the shelf-break at about 180–200 m b.p.s.l. The shelf in this area is steeper than in the Western Channel (0.5 : 1000 versus. 0.25 : 1000). The slope gradient at the base of the valleys is greater than the dip of the shelf, so that the valley depth increases from 20 ms twtt (15 m) around the landwards limit, to more than 70 ms twtt (50 m) at their seawards end, where the valley bases are incised down to 260 m b.p.s.l.

New seismic record interpretations allow extension of the work of Bouysse as well as the recognition of nine distinct valleys named, A and Espérance for the western part, C, C′ and Levneg for the central part, and Castor, Parson, Kaiser-i-Hind and Dompaire for the eastern part (Fig. 3). Lack of seismic records, however, do not allow to their limits to be drawn further north than 48°40′N. Flowing south-southwest towards the shelf-break, they cut the Cockburn Formation and in places the top of the Jones Formation. The valley widths vary from a few kilometres to several tens of kilometres. Valley cross-sections show either a wide U-shape with one or more narrow deeper incisions (western valleys) or a narrow U-shape with or without extra additional incision. The shape of the narrow incision is asymmetric with a steeper side and a more gentle side. This fact confirms the sinuous characteristic of the channel beds already observed on the courses mapped from the seismic profiles. The wide U-shape could correspond to a flood plain. The upstream Levneg valley shows one sharp turn towards the east then a second to the south, giving a Z shape to the course. The C and C′ valleys are aligned south-southwest but with some deviations (Fig. 3). For this reason, the C and C′ valleys are interpreted as abandoned valleys. The Levneg and the four narrow eastern valleys have parallel south-southwest courses but the upstream parts runs south-southeast or southeast. Thus each valley diverges from the western adjoining valley, showing a migration towards the southeast. The palaeovalley network exhibits a delta shape but the point corresponding to the mouth of the palaeoriver is outside the studied area.

According to the few existing seismic records, the eastern valleys stop 10 to 40 km before the shelf-break, where the western valleys are connected to the canyon network: the Espérance Valley to the Shamrock Canyon and the A valley to a tributary of the Shamrock Canyon. The C and C′ valleys seem to be linked to the Blackmud Canyon. The Levneg valley grades suddenly towards a tributary of the Blackmud Canyon, 10 km before the shelf-break. There is no data to evaluate the relationship between canyons and the four eastern valleys.

Detailed architecture of the palaeovalley infill

The Kaiser-i-hind valley has been studied in detail using high-resolution seismic techniques (Reynaud *et al.*, 1999c). The shape of the valley incision and the valley-fill architecture, with at least seven units, indicate a complex history (Fig. 4). The valley walls exhibit several terraces so that the valley widens upward. The terraces can be followed from the main valley up its tributaries and show the same level on both valley sides. They are steeper than the shelf, so that they deepen seawards.

The valley-fill sedimentary succession comprises parallel sedimentary units with flat to slightly concave upward erosional bases. Each unit occupies the entire valley width, resting on the terraces at the valley edges. As for the terraces and the valley floor, the units infilling the valley dip seawards at a steeper angle than the shelf. The units comprise two seismic facies: (i) the flat and parallel bedded reflectors correspond to a low-energy facies, which rests above the erosional base of the unit; (ii) the numerous concave-up cut-and-fill reflectors correspond to a high-energy facies incised into the former facies. The high-energy cut-and-fill facies represents proximal deposits that dominate the landwards part of each unit, whereas the low-energy aggradational facies corresponds to distal deposits better developed in the seawards sector of the valley. The vertical stacking pattern of these facies within the valley in its thickest seawards section shows a relative increase and then decrease of the proximal deposits, pointing to an overall progradational–retrogradational evolution of the valley fill (Reynaud *et al.*, 1999c). Whereas the large-scale mapping of the valleys suggest they are fluvial in origin, the facies and stratal architecture of deposits making up the units inside points to an estuarine to marine origin. Reynaud *et al.* (1999c) used the stratigraphical model of incised valleys developed by Zaitlin *et al.* (1994) to integrate these features. In their interpretation, the flat, erosional bases of the units were interpreted as transgressive wave ravinement surfaces. Such erosional surfaces can be well developed in transgressive estuaries not yet closed by a barrier (Allen, 1990). Thus the cut-and-fill facies would correspond to stacked fluvial and deltaic channels and the flat, parallel-bedded facies would correspond either to estuarine bay or to marine sediments. Because of the absence of barrier remnants below the possible wave ravinement surface, Reynaud *et al.* (1999b) favoured an estuarine interpretation for this latter facies. Whatever the case, the whole valley filling would represent sequences of deposits laid down during at least five cycles of relative sea-level variations. These cycles were interpreted as a response to higher order glacio-eustatic cycles (Reynaud *et al.*, 1999c).

The continental slope

The continental slope of the Western Approaches (from 11 °W to 6 °W) is a consequence of the opening of the Bay of Biscay

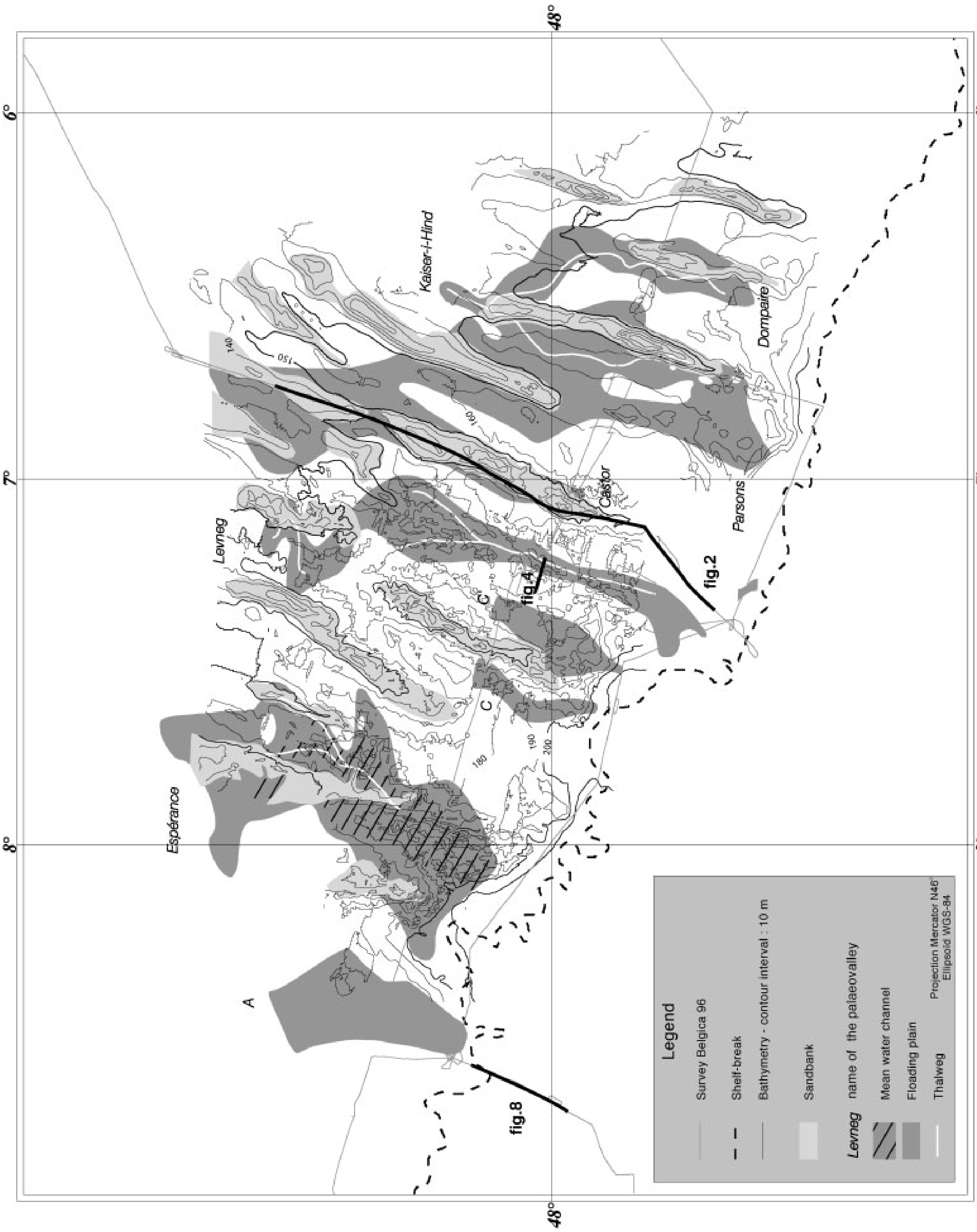

Figure 3 Palaeovalley network (from Peyre, 1997). For location see Fig. 1

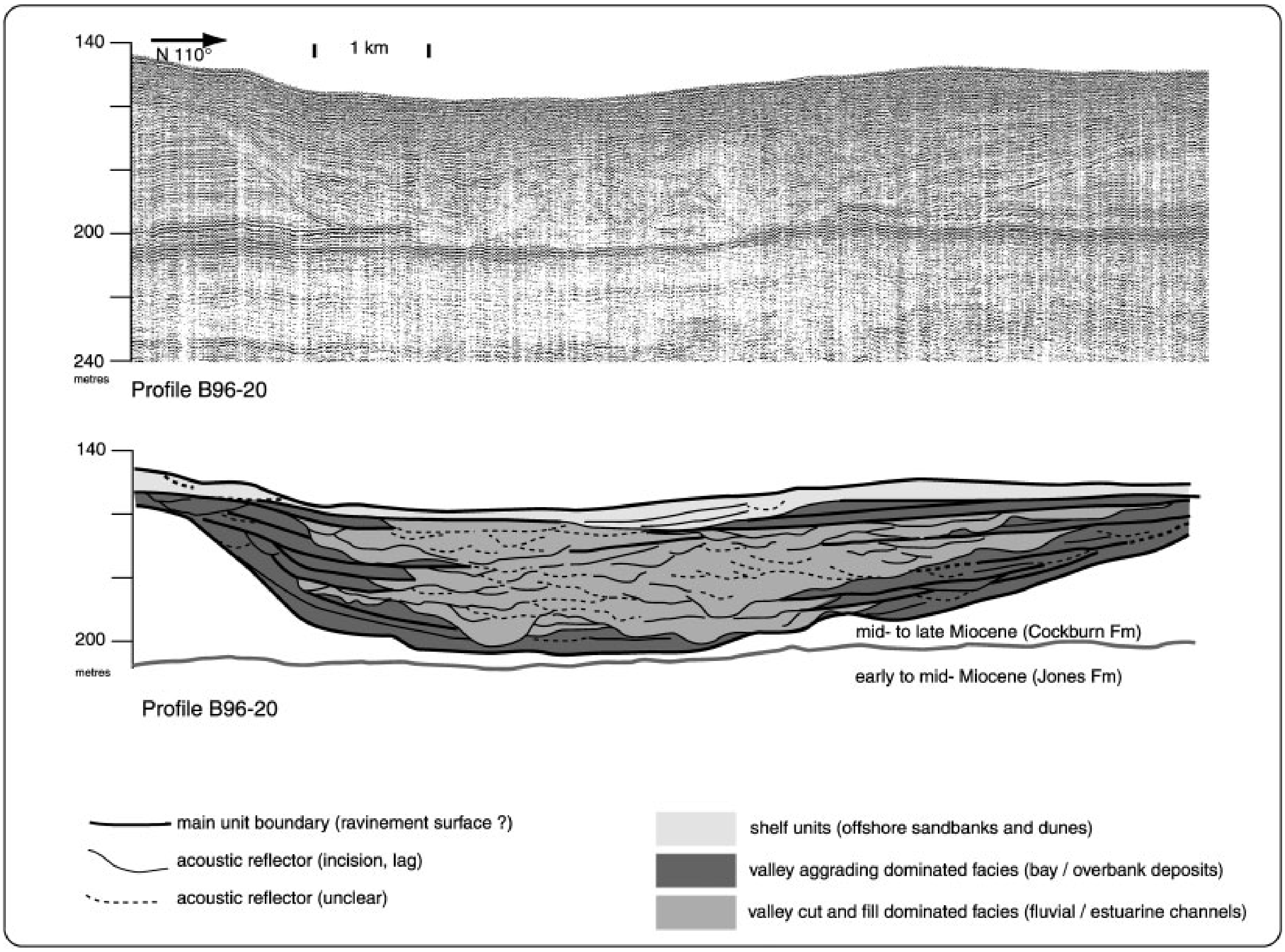

Figure 4 Cross-section of Levneg palaeovalley. For location see Figs 1 and 3

(Olivet *et al.*, 1984) and of sedimentary processes on the tectonic framework. The western segment belongs to the wide (110 km) Celtic Margin characterised by tilted blocks such as the 'Meriadzek Terrace', normal faults and a 115 °N direction, whereas the eastern segment belongs to the narrower (ca. 60 km) Armorican Margin with normal faults and a 135 °N direction. The upper limit of the slope, defined as slopes greater than 2° (Bourillet and Loubrieu, 1995), corresponds to the shelf-break and lies between −180 m and −220 m of water depth from east to west. The lower limit, defined as slopes less than 1°, runs at the foot of the slope in water depths ranging from −4200 m to −4400 m. The slope, 4000 m in amplitude, with an average slope of 4°, is the major pathway for transport of sediments eroded from the continent and shelf to the deep marine. The main geomorphological characteristic of this slope is a well-developed network of canyons that delineates interfluves (Vanney, 1977).

Network of canyons

The canyons constitute the major morphological feature of this portion of margin: more than 30 canyons are incised along the 300 km of the shelf-break.

Steep and linear escarpments (>30°) indicate the evolution of the sides of the canyons and the amplitude of the incision (>700 m). Semi-circular escarpments correspond to knick points of the long profiles and form the termination of reaches as a kind of 'submarine waterfall', for example, the Petrock Escarpment of the Blackmud canyon (Fig. 5). These scarps are located below the −1100 m isobath to the west and either above −1000 m or between −1500 m and −3000 m to the east of the area.

Morphology of the canyons

Analysis of long profiles of the canyons indicates the large diversity of profile shape and length (Fig. 5):

1 concave profiles are close to the equilibrium profile, e.g. the short Audierne canyon (60 km);
2 upper convex and lower concave profiles are the most common shape, e.g. the Buache canyon and the Shamrock canyon, which is the longest (>200 km);
3 stair-like profile with an upper and a lower linear section linked by a steep slope, e.g. the Blackmud canyon with slopes greater than 20° where the course crosses the Petrock Escarpment.

The canyons with concave profiles show courses more rectilinear and conformable with the regional dip, in contrast with the others whose courses reveal a tectonic influence, for example, the Shamrock canyon, which passes round tilted blocks.

The higher magnitudes of incision are located between −2000 and −3000 m of water depth and reach 700–800 m.

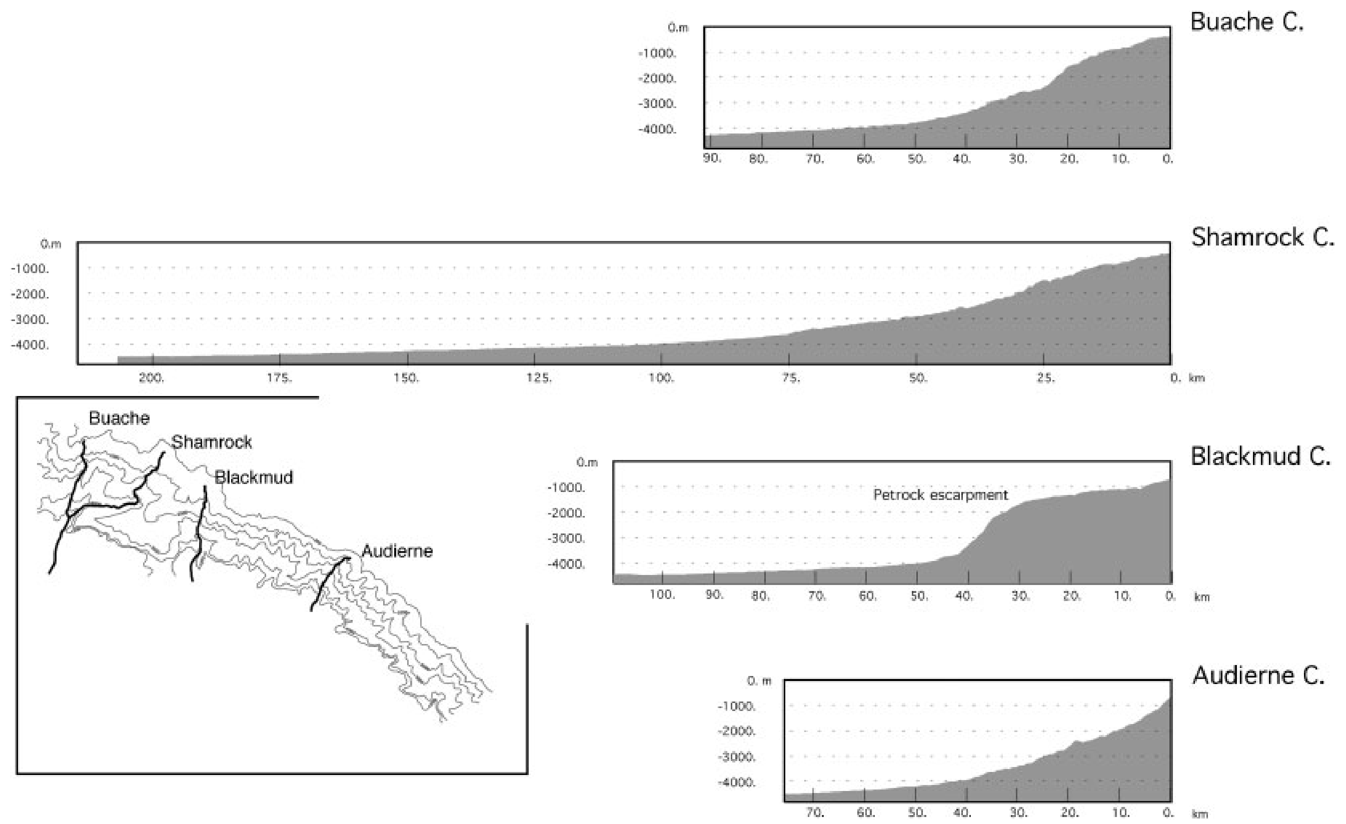

Figure 5 Long profiles of the canyons

From −3000 m, canyons broaden (1–3 km) and the embanking decreases rapidly according to the deepening of the interfluves.

In contrast to the East Atlantic margin where the Neogene sedimentary supply is in part trapped on the upper slope either on the interfluves or in the canyons (Mountain *et al*., 1996), there is no evidence of buried canyons or valleys on the Western Approaches continental slope.

Distribution of canyons

The first surveys of the Western Approaches margin (Day, 1959; Francis, 1962; Vanney, 1977) correctly determined the spatial distribution of canyons in a dendritic pattern. However incomplete data led the former authors to discard structural causes as a potential origin. Now thanks to a complete bathymetric survey of the slope (Le Suavé *et al*., 2000), the whole thalwegs from the shelf-break to the continental rise can be analysed with classic tools of geomorphology (Howard, 1967; Schumm and Ethridge, 1994). The canyons show a large diversity of pattern (Fig. 6):

1 linear pattern suggests that the sedimentary processes prevail over tectonic processes—generally, the upper slope thalwegs of small order and the eastern canyons present this pattern together with a direction conformable with the dip (Fig. 6B);
2 pinnate pattern (Howard, 1967) along or oblique to the regional dip, e.g. the left bank of the Blackmud canyon;
3 dendritic pattern, e.g. the fifth-order La Petite Sole canyon with more than 140 tributaries (Fig. 6A);
4 contorted pattern, e.g. in its mid-slope course (−1100 m to −3000 m) the Shamrock canyon passes round tilted blocks;
5 complex pattern—the majority of canyons have superimposed patterns reflecting changes of control along their course.

Furthermore, the canyons converge down to the continental rise towards feeder channels. The drained part of the slope can be compared with a continental drainage basin. Four of the eight submarine drainage basins of the Bay of Biscay (Bourillet *et al*., 1999) are located within the Western Approaches margin (see Fig. 10). They are from west to east:

1 The 'Grande Sole' drainage basin from Goban Spur (11 °W) to Brenot Spur (9°30′W). The Whittard canyon, the main collector runs southeast towards the Celtic Deep Sea Fan via the Whittard channel.
2 The 'Petite Sole' drainage basin from Brenot Spur to Berthois Spur (7°50′W) and Meriadzek Terrace (Fig. 6A). This sixth-order basin is a complex basin that gathers dendritic, subcontorted and subparallel patterns for, respectively, the 'La Petite Sole', 'Shamrock' and 'Buache' sub-basins. The downstream course of Shamrock canyon runs west along the north flank of Meriadzek Terrace and broadens at the same time as the degree of incision decreases. It crosses and collects the other thalwegs on its northern bank before it flows southwards into the Whittard channel.
3 The 'La Chapelle' drainage basin from Berthois to Delesse (7 °W) spurs formed by two fourth-order adjoining sub-basins with two parallel feeder canyons and an overall 'chandler like' pattern. The thalwegs are mainly linear or sublinear, even those that cross the Petrock Escarpment, down to −3500 m. Downstream, their courses are deflected by west–east spurs (extensions of the Meriadzek Terrace and Delesse spur) that play the role of a natural dam (see Fig. 10). The collectors of the western and eastern sub-basins flow respectively eastwards and westwards without

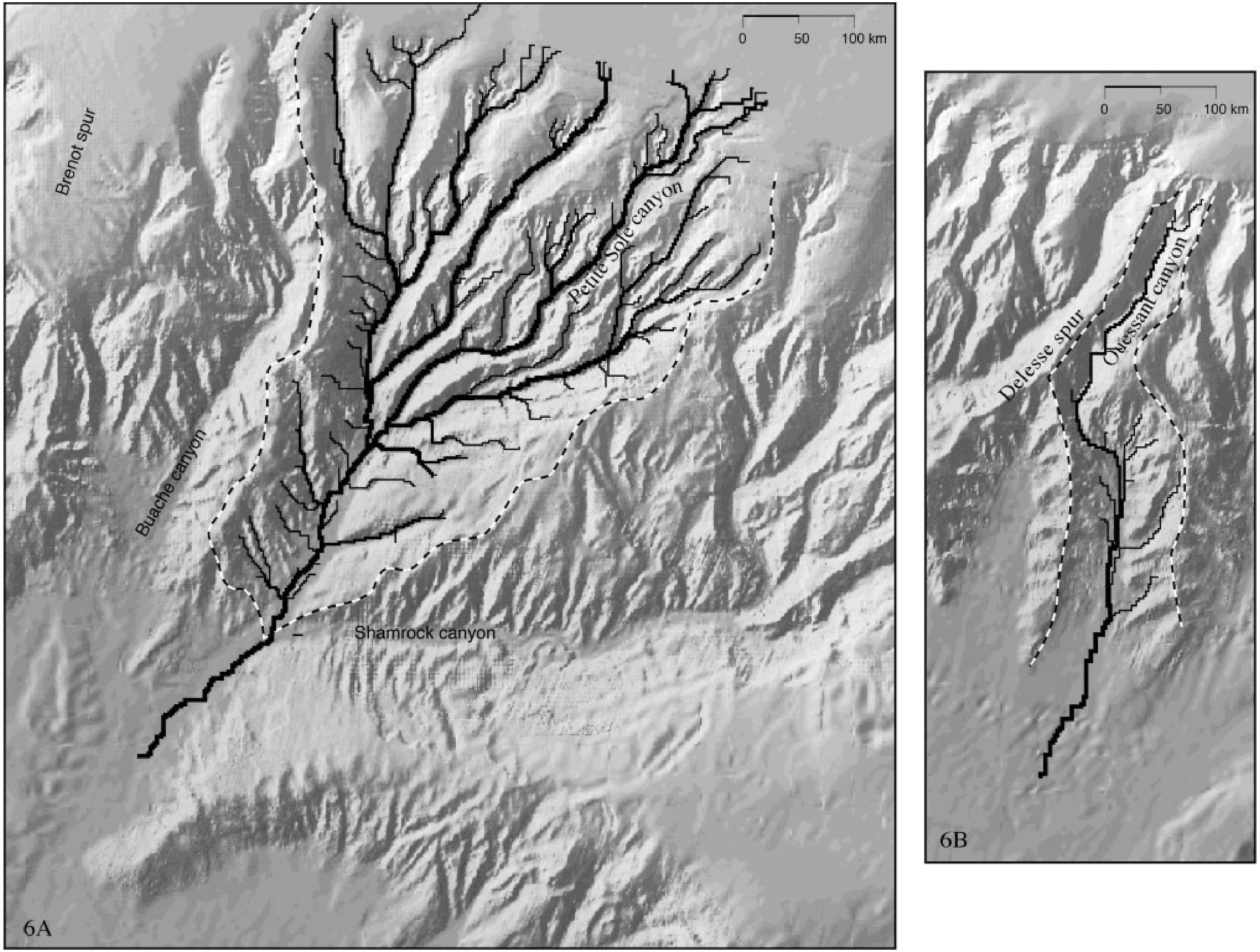

Figure 6 Canyon networks: (A) catchment area of the Petite Sole canyon with a dendritic pattern; (B) catchment area of Ouessant canyon with a linear pattern. Continuous lines represent automatically extracted thalwegs of the canyon; dotted lines represent the limits of the catchment area. For location see Fig. 1

merging, both turning south towards the Armorican Deep Sea Fan.

4 The 'Ouest-Bretagne' drainage basin from Delesse spur to Beaugé spur (6°10′W) formed by three linear, contorted or subdendritic canyons (Fig. 6B). They converge and flow together deeper towards the Armorican Deep Sea Fan.

Spatial evolution of canyons

Analysis of the spatial distribution of canyons permits reconstruction of their spatial and temporal evolution (Fig. 7). Three generations of canyons can be distinguished from the shelf to the rise:

1 the upper slope canyons (type III), which cut the Neogene prism according to the regional dip, favouring the hypothesis of an autocyclic control and consequently a youthful stage (Farre *et al.*, 1983)—the majority of them show a subdendritic hierarchy and converge downwards as tributaries of canyons of type II;
2 type II canyons cut deeply into the calcareous formations of the mid-slope and/or contorting blocks—some of them showing a subdendritic hierarchy;
3 type I groups the wide and low embanked 'valleys' and are tectonically controlled.

Types II and I meet up all along the margin. Type III of 'La Petite Sole' drainage basin stretches 20 km landwards. Elsewhere canyons of type III are either merged with type II canyons or condensed over few kilometres, e.g. 'La Chapelle' basin.

Canyon interfluves

The upper slope of the Western Approaches represents the same Neogene formations as the outer shelf (Fig. 8), but escarpments and deep canyons intersect their continuity between 1100 and 1900 m of water depth so it is impossible to connect the layers of the shelf to those of the continental rise.

Present-day sedimentation

The stratigraphic architecture of the interfluves results from various and still active sedimentary processes, such as:

1 hemipelagic sedimentation;
2 deposition or remobilisation of sediments in response to the hydrodynamic conditions (tidal and waves currents) in up to 300 m of water depth;

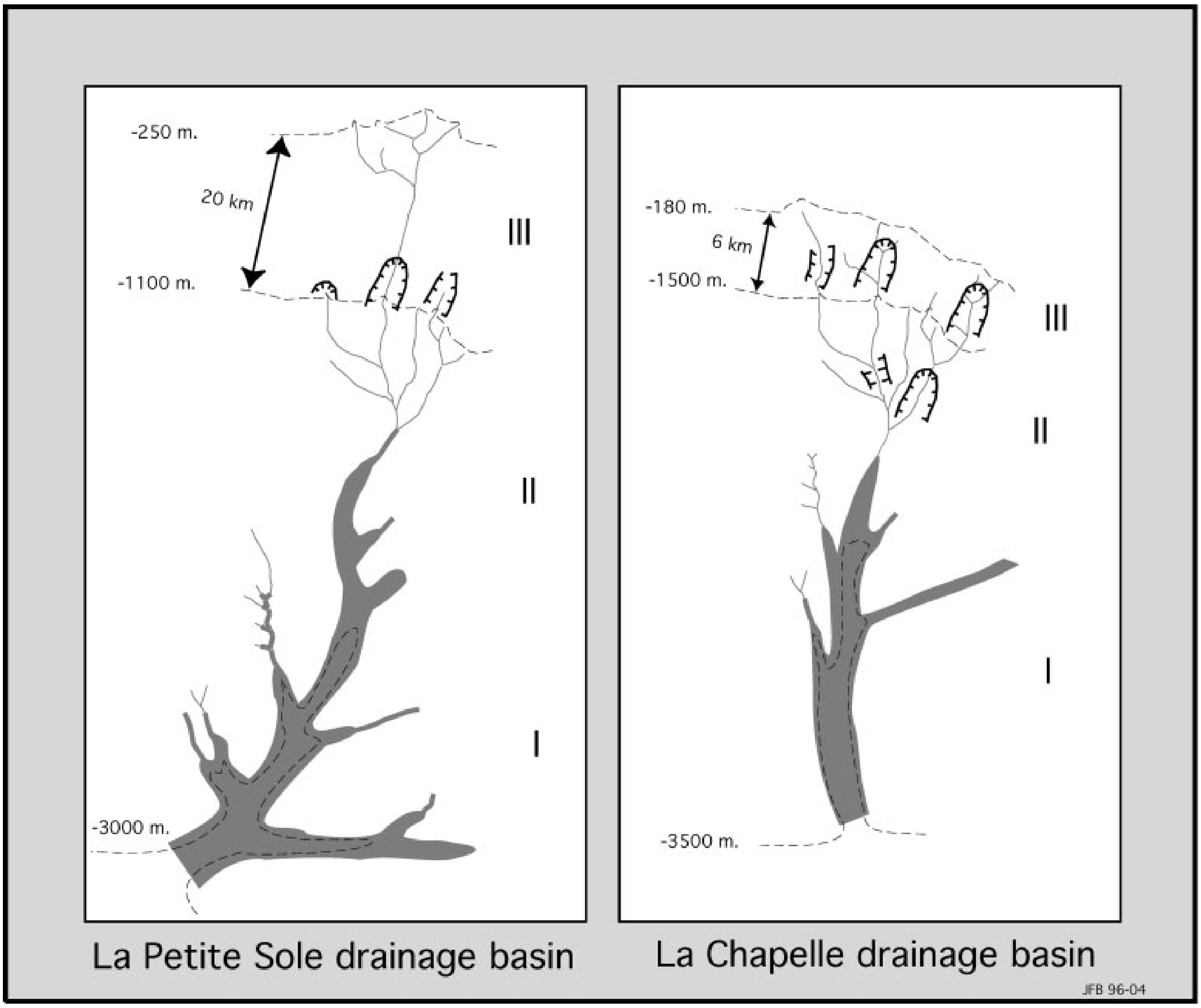

Figure 7 Spatial evolution of the canyon network

3 slope deposits originating from the polar geostrophic current. Contourites and sediment waves are mainly located on the upper part of spurs, e.g. Brenot spur (see Fig. 10). Seismic profiles show sigmoïdal reflectors (Fig. 8B) that could suggest the existence of slides or creeping features. Interpretation as buried sediment waves, however, is more likely because the structures are similar to those found northwards in the northeast of Rockall Trough and southwards in the 'Landais' marginal plateau in the Bay of Biscay (Faugères *et al.*, 2002) or in the Mediterranean Sea (Migeon *et al.*, 2000).
4 Gravity-driven deposits. The low average slope gradient masks a wide range of slope values. Large differences in gradient exist in the form of sea cliffs at the mid-slope, e.g. Petrock Escarpment (47°36′N and 8 °W to 7°45′W) with more than 1250 m between the foot of the terraces and spurs. In addition to the escarpments located within the valleys of the canyons (see below), the area presents numerous scarps and gullies such as at the limits between the interfluve and the upper canyon walls, where scars of slides are located mainly at the heads of the canyons and are the result of retrogressive erosion. All these features are generated and maintained by slides, debris flows or turbidity currents.

The interfluves, however, are also the result of past processes, such as fluvial sedimentation during lowstands of sea-level when coastlines were close to the shelf-break, and glaciomarine sedimentation during the decay of the British ice-sheet.

Late Pleistocene and Holocene sedimentation

The evolution of sedimentary supply on the continental slope can be determined by the sedimentation on the spurs and by the sedimentation on quiet areas characterising the regional hemipelagic regime. The Berthois spur, a narrow sedimentary ridge—3 km in the northeast to 10 km in the southwest—offers an example of such an interfluve. Its extension, the Meriadzek Terrace and the seawards Trevelyan Escarpment, are also areas of relatively calm sedimentary environments, apart from the turbidite supplies which mark the slope and basin plain margin, beyond the influence of tidal and storm currents (Auffret *et al.*, 1996). The new stratigraphy and chronology, summarised in Table 1, is a compilation (Zaragosi, 2001) based on an existing time-scale (Pujol and Turon, 1986). Unfortunately, the older cores correspond only to Marine Oxygen Isotope Stage (MOIS) 3.

Analysis of cores on Berthois Spur shows that during MOIS 2 the accumulation rates remain high from 15 to 46 cm kyr^{-1} (KS02, KS03 and KS05; Table 1). The stratigraphical hiatuses observed on the three other cores were studied by geotechnical analyses (Baltzer *et al.*, 1995). Overconsolidation states observed in cores KS03 and KS05 suggest that a thickness of 3–5 m is missing to (taking into account ±2 m), consistent with a partial or total lack of MOIS 1 and 2. This overconsolidation state does not correspond to diagenetic processes as no evidence of such processes has been observed. We suggest erosional processes such as mass wasting or current winnowing to explain the removal of the upper part sedimentary column.

In contrast, the protected areas such as Meriadzek Terrace (core MD95-2002) and Trevelyan Escarpment (core AKS01) present similar evolutions (see Fig. 14). Their correlation with the history of sea-level variations is clear: the maximum sedimentation rates (30–55 cm kyr^{-1} for AK SO1 and 40–400 cm kyr^{-1} for MD95-2002) observed between 24 000 yr BP and 14 000 yr BP concur with sea-level lowering from −90 m to −120 m. A remarkable peak of sedimentation occurred between 15 and 14.4 ka, which is not clearly connected to a change in sea-level.

After 14 ka, sedimentation rates decreases to 3–10 cm kyr^{-1} for the Holocene, according to sea-level rise. Associated with this temporal evolution, a spatial evolution is observed downwards to the basin. The sedimentation rate of Trevelyan Escarpment is 2 to 15 times lower than that of Meriadzek Terrace, according to its distance from the shelf-break (sediment supply).

The cores of the Berthois Spur show low sedimentation rates compared with that of Meriadzek Terrace and reveal that most of the sedimentary succession had been bypassed, slumped or eroded downslope.

Table 1 Upper Pleistocene and Holocene sedimentation rates for the submarine 'Fleuve Manche'. Continental environment from Woillard and Mook (1982). For core location see Figure 9.

			Armorican Fan	Celtic Fan	Trevelyan Escarp.	Meriadzek	Berthois Spur				
Local stratigraphy	**Isotopic stage**	**Age (B.P.)**	**72 104** Ma KS03	**MK S03**	**AK S01**	**MD95-2002**	**K S02**	**K S03**	**K S05**	**Environment** marine	continental**
Holocene	1	10 000	12	7	3	10				Temperate	mixed forest
Würm4-(Younger Dryas)		11 000	65-70	60	4-5	60-70	>2.5 *			Cold	Steppe, tundra
Würm 3/4-(Bölling-Alleröd)		12 000								Temperate	Boreal forest
Würm 3	2	12 700			4-5	70	33 *	15 *		H1 Very cold	Steppe, tundra
		14 000			55	400	>15.4 *	28 *	46 *		
Würm 2/3		15 000 16.5 18.5 20 000			50	100				Temperate to fresh (LGM) 2 warm NAD events H2 Very cold	
		24 000			20-30	40				Temperate to fresh	
Würm 2	3	28 000				40				H3 Very cold	

Sedimentation rates (cm/ka) NAD : North Atlantic Drift H1 Heinrich event * more indicative than quantitative ** from Woillard and Mook, 1982

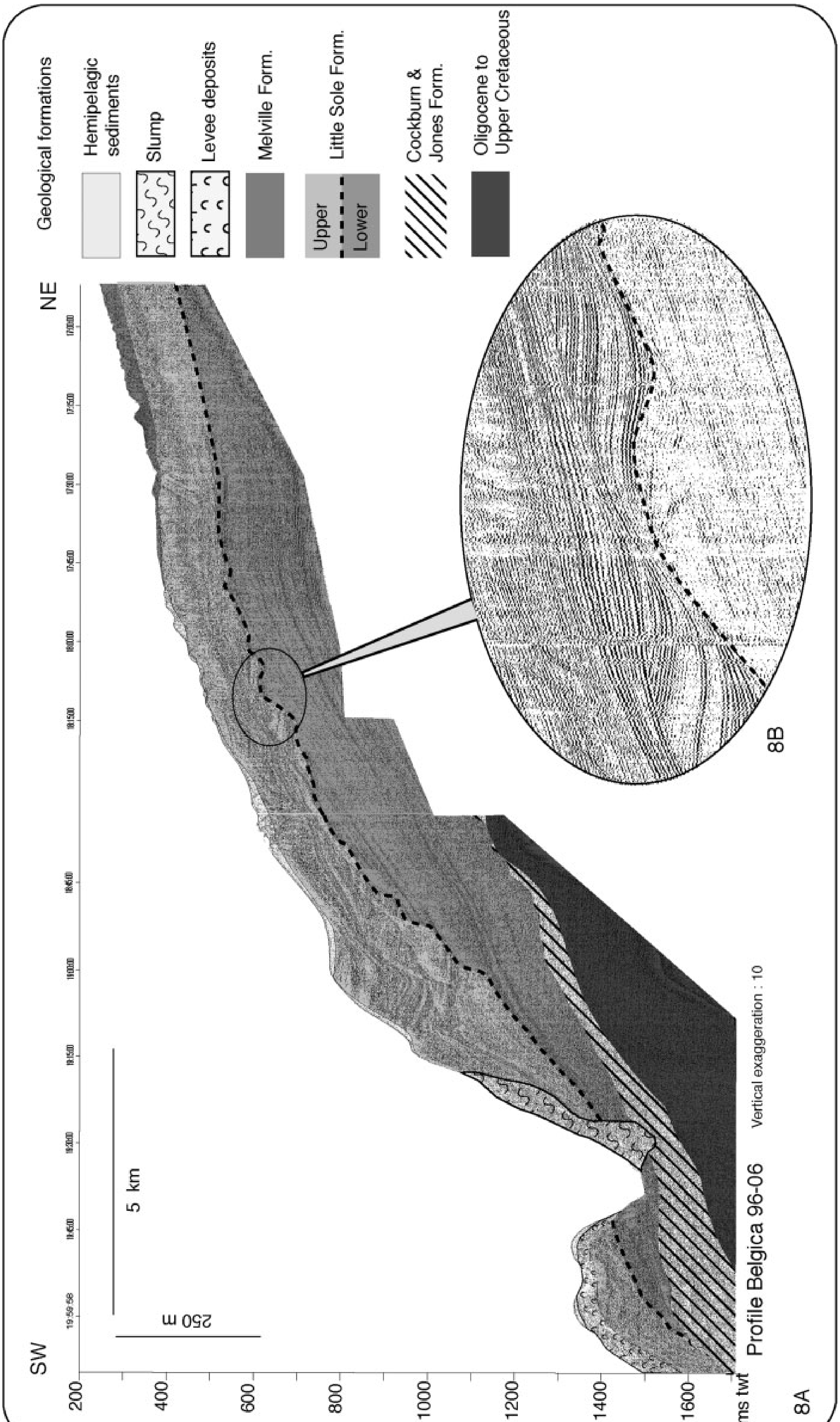

Figure 8 Section of the upper slope of the Western Approaches: (A) overview and interpretation; (B) detail of the sigmoïdal reflectors (Bourillet and Lericolais, 2003). For location see Figs 1 and 3

The continental rise

The Celtic and the Armorican deep-sea fans are situated on each side of the Berthois Spur–Meriadzek Terrace–Trevelyan Escarpment system (Fig. 9).

The Celtic Deep Sea Fan

The Celtic fan lies at the foot of the Celtic Margin between 4200 and 4900 m of water depth (Auffret *et al.*, 2000). The fan is approximately 170 km long and 210 km wide and spreads over more than 20 000 km^2. The basal turbiditic facies (IIB in Fig. 12) are early Miocene in age (Droz *et al.*, 1999) and the present morphology was developed during a relatively stable tectonic context. The whole system is a mature, mud–sand-rich fan (Zaragosi *et al.*, 2000). The fan is connected with the Celtic margin slope by two major deep channels: (i) the Whittard Channel, with a large, persistent, sinuous channel–levee system, which is supplied by the 'Grande Sole' slope drainage basin and (ii) the Shamrock Channel, with a medium sized channel–levee system, which is supplied by the 'Petite Sole' slope drainage basin (Bourillet and Loubrieu, 1995). These two tributary channel–levee systems merge before the upper–middle fan limit. The middle and lower fans correspond to divergent braided secondary and associated lobes (Fig. 9).

On the upper fan, overflow deposits indicate the occurrence of relatively low-density turbidity currents during MOIS 2 and during the beginning of MOIS 1 (Bølling–Allerød, Younger Dryas and early Holocene). Very recent sandy layers (<2000 yr BP) located in the middle and the lower fan indicate Holocene episodic turbidite supplies (Zaragosi *et al.*, 2001a).

The Armorican Deep Sea Fan

The Armorican Fan is connected with the margin by the Blackmud and the Guilcher Channels, which are fed by the 'La Chapelle' slope drainage basin and by the 'Ouest Bretagne' slope drainage basin. It lies at the base of the Armorican margin, in a water depth of 4100 to 4900 m. With a length of greater than 150 km and a width of 160 km it covers approximately 20 000 km^2.

The survey of this area, completed by IFREMER in 1997 (Le Suavé *et al.*, 2000) provides a general overview of the seafloor morphology and superficial sediment distribution of this fan and the adjacent depositional system. It also reveals the presence of another system of lesser extent (1000 km^2) fed by the 'Sud Bretagne' drainage basin.

As on the Celtic fan, similar differences between sea-level lowstands and highstands are observed (Zaragosi *et al.*, 2001b), but the passage between the lowstand low-density turbidity currents and the highstand hemipelagic sedimentation with episodic high-density turbidity currents occurs earlier at the Pleistocene–Holocene boundary (10 000 yr BP).

Geomorphological map

The geomorphological map (Fig. 10) synthesises the physiographic elements described above. The bathymetry is derived from a 1 km grid based mainly on the EEZ data set (Le Suavé *et al.*, 2000) and was improved for the shelf area using a digitised map of the Celtic banks (Bouysse *et al.*, 1976). The bathymetry is represented by the 500 m isolines. The boundaries between the shelf, slope and rise physiographic provinces are determined from the slope gradient grid (Bourillet and Loubrieu, 1995): slopes over 2° and those below 1°, respectively, indicate the continental slope and the continental rise. The 1° value fits well with the erosion/deposit limit. Two prominent bathymetric highs are detached from the margin: the marginal plateau Meriadzek Terrace and the structural block Trevelyan Escarpment. The contours of the palaeovalleys of the shelf (Figs 3 and 10) are based on an existing map (Bouysse *et al.*, 1976), but are modified from recent seismic data interpretation (Peyre, 1997). The flood plain, the mean water channel and the thalweg are represented when they are distinguishable on seismic records. Boundaries of the sandbanks on the shelf and of the sedimentary ridges on the rise are determined from the slope gradient grid except those of the two western banks, which are determined from a British Geological Survey map.

On the continental slope, three sets of features are represented (Fig. 10):

1 areas with slopes greater than 30° represent large features such as escarpments and canyon walls;
2 areas with slopes less than 30° indicate active processes such as retrogressive erosion of canyons heads, sediment waves on the spurs and scars of slides;
3 upper limits of the walls of canyons.

The networks of canyons have been computed from a 250 m by 250 m bathymetric grid (Raoul, 1999) according to an algorithm of drainage network extraction (Soille, 1992; Soille and Gratin, 1994) adapted by Quiniou (1998). The algorithm is limited to convergent fluxes. Therefore, divergent fluxes such as associated with a braided river, delta or fan cannot be extracted. Thus, the study focused on the continental slope as defined above. Results allowed the reconstruction of canyon, thalwegs and boundaries of slope catchments (Figs 6 and 10). Canyons of type I represent the main collectors.

On the continental rise, depositional areas and sediment dispersal pathways are mainly derived from the lineaments map interpreted from the 3.5 kHz and multibeam imagery records (Figs 9 and 10). They include mass wasting, levees, crests of sediment waves, the Celtic Deep Sea Fan and the Armorican Deep Sea fan with, when possible, the extension of the superficial lobes. The pathways correspond to the feeder channels of the deep-sea fans that extend from the type I canyons, the possible associated valleys in the case of meandering thalwegs and the superficial channels of the mid-fans.

Discussion: evolution of the 'fleuve manche' system

Age of the palaeovalleys

The single direct evidence for the age of the palaeovalley on the shelf comes from grab samples recovered from the uppermost sediments of the valley-fill succession and indicates a Early Pleistocene age (Evans and Hughes, 1984). The recovered sediments, originating from the top of a valley located in the North Celtic Sea at a present-day depth of 170 m, were interpreted by the authors as having been deposited in about

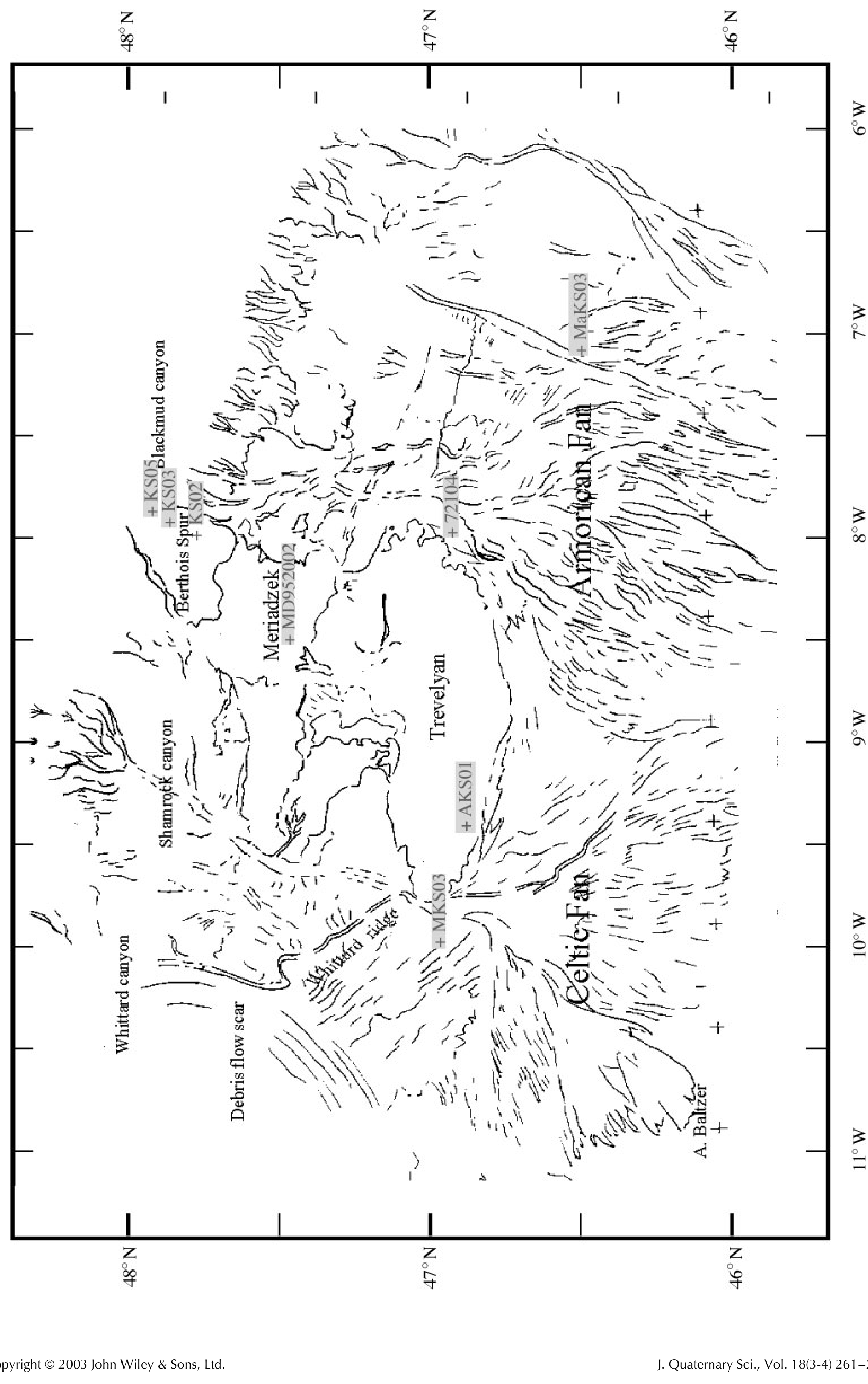

Figure 9 Spatial distribution of the fan lobes. Lineations are derived from the multibeam imagery on the Celtic and Armorican fans. +MKS03: name and core location. For location see Fig. 1

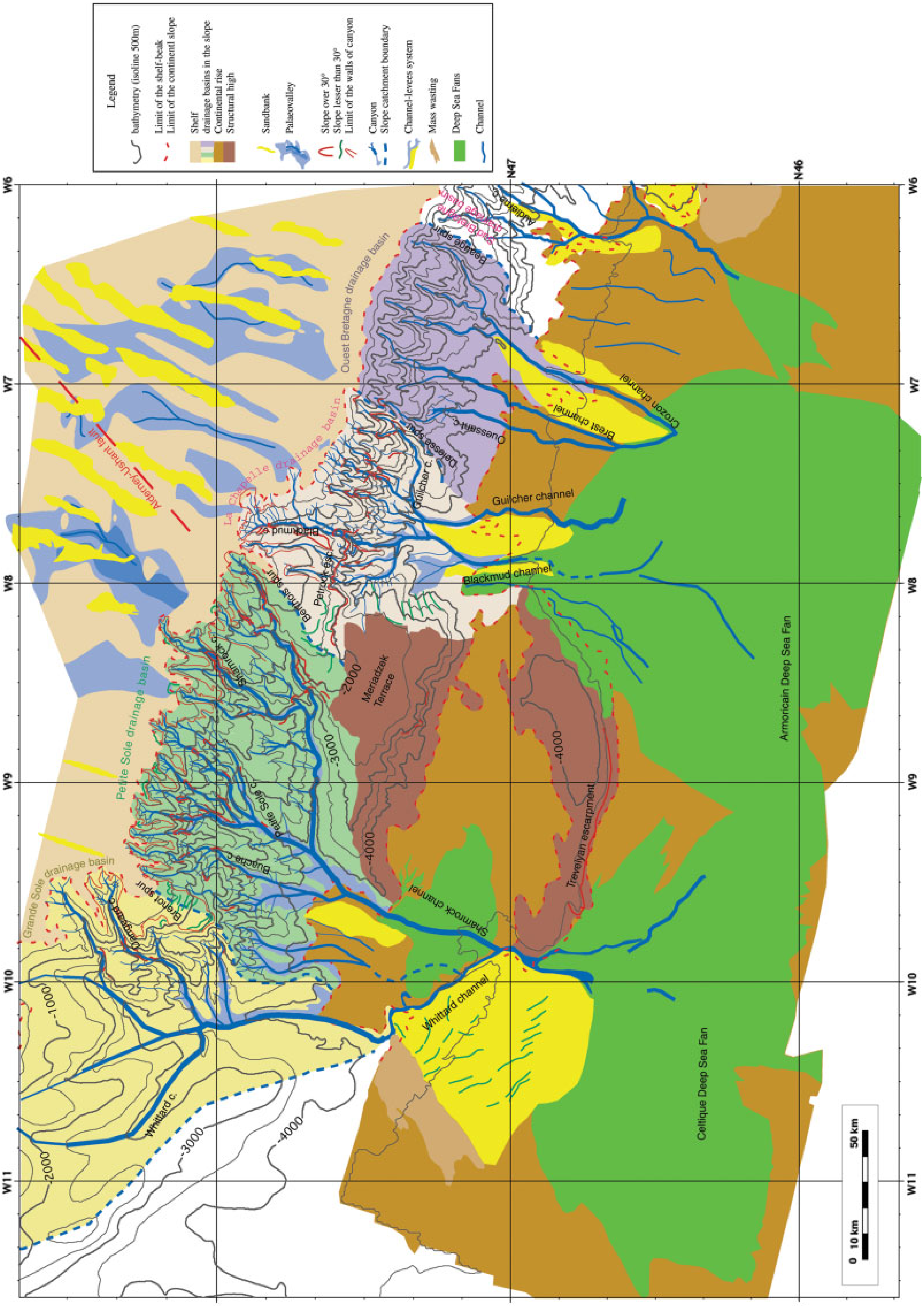

Figure 10 Geomorphological map. For location see Fig. 1

50 m water depth. The age of the incision and the duration of the fill are poorly constrained.

The age of the incision

The interpretation of the palaeovalleys as incised valleys and their infill as estuarine deposits, implies, according to the models of Zaitlin (Zaitlin *et al.*, 1994), that during their incision sea-level was below or close to the level of the palaeovalley floor. The depths of palaeovalley floors were migrated from seismic records (Fig. 11). Two groups of palaeovalleys can be differentiated: (i) the shallowest ones reach the shelfbreak at −240 m b.p.s.l. and correspond to the four eastern valleys located eastwards of 7 °W (Castor, Parson, Kaiser-i-Hind and Dompaire palaeovalleys; Fig. 3); (ii) the deepest ones (−280 m b.p.s.l.) group together the four western valleys located at the centre of the Channel syncline (A, Espérance, C and C′ palaeovalleys). The ‘Levneg’ palaeovalley has a peculiar behaviour: it belongs to the western group for its upstream part and to the eastern group for its downstream part. The hypothesis of Bouysse (Bouysse *et al.*, 1976) implies a Quaternary lowstand (i) at least at 240 m b.p.s.l. which occurs (ii) earlier than the Weichselian glaciation. The lowest eustatic sea-level falls occurred late in the Quaternary, but it is now generally accepted from oxygen isotope studies that the absolute sea-level lowstands did not exceed 125 m b.p.s.l. (Shackleton *et al.*, 1984; Fleming *et al.*, 1998).

Relative local sea-levels are influenced by glacio-hydroisostatic rebound or subsidence. The peripheral bulge resulting from glacio-hydroisostatic compensation of the ice loading above the British Isles is still debated, especially for the Irish Sea (Eyles and McCabe, 1989; Knight, 2001; McCarroll, 2001; McCarroll *et al.*, 2001). Recent analysis (Scourse and Furze, 2001) demonstrates that relative sea-levels were lower than envisaged in glaciomarine models (Eyles and McCabe, 1989; Wingfield, 1995). However, most numerical models on the viscoelastic response of the lithosphere, taking into account the estimated British and Fennoscandian ice-sheets, do not predict more than few metres for the isostatic component in the Western Approaches shelf.

Another influential parameter is subsidence of the margin. The ‘normal’ rate of thermal subsidence of a mature passive margin, such as the Celtic and Armorican margins, is about 10–25 m myr^{-1}. For the South Celtic basins on the shelf, a rate of total subsidence of 5–6m myr^{-1} was computed from the SWAT 5 profile, 250 km north of the valleys (Dyment, 1987; Bois *et al.*, 1991b). Quaternary subsidence of the outer shelf reaches only 50 m with the highest value and the deduced sea-level, contemporaneous with incision, corresponds to 190 m b.p.s.l. It does not fit the absolute level of 125 m b.p.s.l. and weakens the second argument of the hypothesis of Bouysse.

The vertical subsidence which matches the depth of the palaeovalley floor (240 m b.p.s.l.) and a lowstand of 125 m b.p.s.l. represents 115 m with a duration ranging from 12 myr to 5 myr according to the ‘normal’ rate range (10–25 m myr). This suggests that the Messinian is the most likely event for valley incision, based on the fact that Neogene eustatic sea-level falls would have been of similar amplitudes during the upper Quaternary (Haq *et al.*, 1988).

Subsidence rate

With the additional hypothesis that the western and the eastern valleys were cut at the same time, we can argue that the subsidence rate of the western valleys and the Western Approaches sedimentary basin is (280 − 125)/(240 − 125) = 4/3 higher than the rate of the eastern valley and the Armorican block. Thus, values are respectively of 32 and 24 m myr^{-1} with a possible Messinian incision. This differential subsidence is also supported by the observation of the difference in shelf-break depth along either side of the Alderney–Ushant fault (−220 m in the west and −180 m in the east), as indicated by the geomorphological analysis of this area.

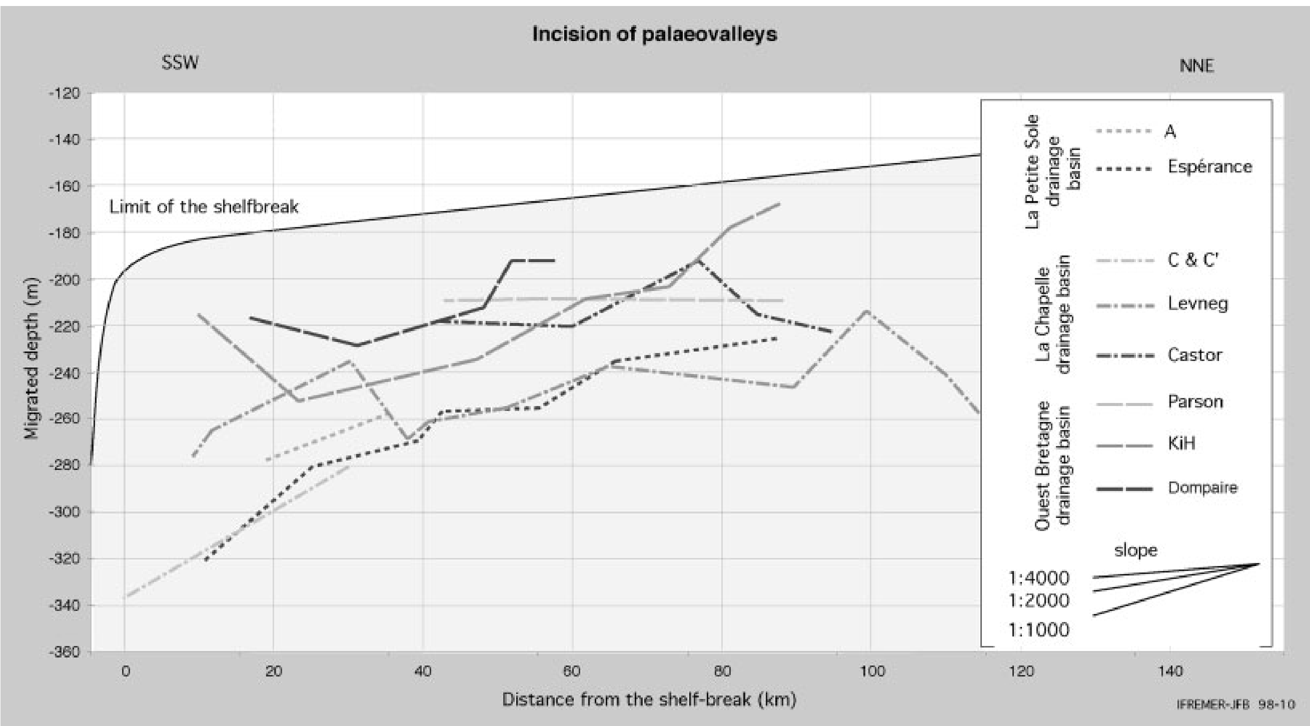

Figure 11 Incision of palaeovalleys. For location see Figure 3

The duration of the palaeovalleys fill

For the duration of the valley filling, seven sequences were related to 40-ka sea-level cycles, implying that valley filling was completed in perhaps 280 kyr (Reynaud *et al.*, 1999c). This duration is a minimum and the infilling could have taken much longer if incisions or non-deposition occurred within this time interval. The upper part of sequence was deposited in greater water depths (relative decrease of proximal deposits) than the lowest. This part of the sequence also implies an overall minimum subsidence of 50 m (the average thickness of the filling) over at least 280 kyr. In this short period of time, the area should have been drowned at a rate of 250 m myr^{-1}, which is equivalent to a highly subsiding deltaic environment or sediment deposition on the Gulf of Lion shelf. The latter deposits are related to 100-kyr sea-level cycles (Rabineau, 2001). Furthermore, such a sharp change in the rate of drowning does not match the subsidence on a passive margin. With a mean 25 m myr^{-1} subsidence rate, 50 m of accommodation could be obtained for 2 myr and a post-Messinian filling could be completed within the Pliocene period. This is in agreement with the occurrence, in the superficial sediments of one bank, of Pliocene molluscan faunas that are likely to be reworked from the valley fillings, if not drifted from very distant areas (Reynaud *et al.*, 1999a). Hence, if the hypothesis of a Messinian incision is correct, it is likely that the valley infilling took longer than 280 kyr. This implies either that the sequences of deposits inside are not 40-ka cycles or that some ravinement surfaces are hiatus surfaces.

Palaeogeographical evolution of the ‘Fleuve Manche’

Oligocene inversion along the Western Approaches margin was responsible for the development of the Hurd Deep on the shelf (Lericolais *et al.*, 1996) and the onset of turbidite deposits in the Celtic and Armorican deep-sea fans (Droz *et al.*, 1999). A thick Miocene carbonate prism developed on the outer shelf and on the upper slope (Jones and Cockburn Formations). Turbidites were fed through the type I and type II canyons of the slope and occasionally debris flows, originating from the sedimentary cover of the interfluves, fed the deep channel–levee systems and lobes.

On the shelf, a palaeovalley network was incised into the prism in response to the Messinian lowstand. Some of these palaeovalleys were located close to the shelf-break and connected to canyons of the slope (Figs 6 and 10). At this time, the ‘Fleuve Manche’ shows its maximum extension. The onshore drainage basins were directly connected to the slope and some canyons evolved from a youthful to a mature stage, characterised by more continuous erosion of valley floor and walls attributable to fluvial discharges. The relationship remains unclear for some canyons, however, unlike the New Jersey continental slope (Pratson *et al.*, 1994), the Delaware River and the Wilmington Canyon (McGregor *et al.*, 1982; Twichell *et al.*, 1977), and the Adour river and the ‘Gouf de Capbreton’ (Cirac *et al.*, 2001), where a single palaeovalley is obviously connected to a single canyon.

A second deltaic sandy progradational prism (Little Sole Formation) developed above the Messinian erosional surface and truncated the shelf-break during Pliocene times (Fig. 2); palaeovalleys were drowned and infilled with several sequences linked to eustatic fluctuations. A large number of type III canyons cut the seawards front of this Pliocene prism. The progradation of the prism could also explain the loss of continuity of the palaeovalley–canyon junctions either by erosion or burial. Subsequently, ravinement of the shelf was intense during phases of Quaternary sea-level rises. This tentative relative chronology is summarised in Fig. 12.

Submarine sedimentary dispersal systems of the ‘Fleuve Manche’

The source of sediment for the fans during low and high sea-level stands was derived from the outer shelf but with differing origins, as demonstrated for the Last Glacial Maximum (Zaragosi *et al.*, 2001a). Episodic turbidites carried marine palimpsest sands from the shelf during the highstands whereas

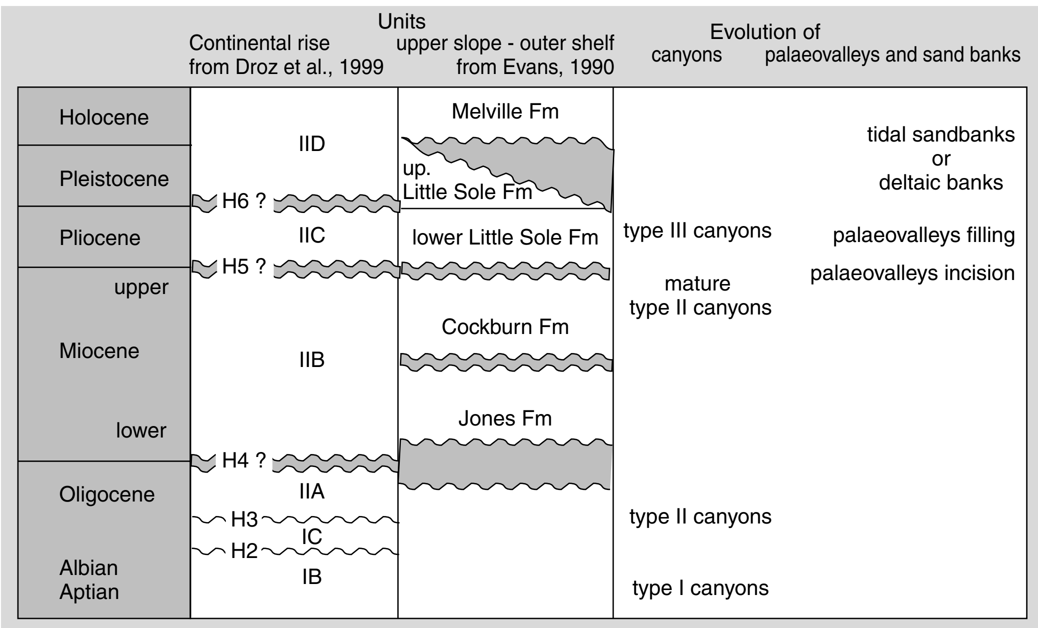

Figure 12 Stratigraphical relationships between the features of the deep sea and the outer shelf, and evolutionary pattern of canyons and palaeovalleys

low-density turbidites carried estuarine or deltaic material from the palaeoriver during the lowstands. The extension of the 'Fleuve Manche' was at its maximum during lowstands but did not reach Messinian limits. During these periods, the upstream Quaternary catchment basin of the 'Fleuve Manche' (Fig. 13) varied through time. It gathered the drainage from the Seine, Somme and Solent palaeorivers (Gibbard, 1988; Lautridou *et al.*, 1999), of the Loire palaeoriver up to the Late Pleistocene (Tourenq and Pomerol, 1995) and of the Rhine, Meuse and Thames palaeorivers, either from Messinian (Van Vliet-Lanoe *et al.*, 1998) or from 420 ka (Gibbard, 1995), depending on the age of opening of the Dover strait.

Prior to and during the infilling of the palaeovalleys, the continental drainage basins were connected to the two deep depocentres via the outer shelf valley network and the canyon networks of the slope (Fig. 10). It is possible to reconstruct the pathways from source to sink at least during the Pliocene 'fluvial' connection. The Celtic Deep Sea Fan would have been connected to (i) the Celtic Sea via the 'Grande Sole' drainage basin and the Whittard channel and to (ii) the 'Fleuve Manche' by the two western palaeovalleys of the outer shelf, the 'Petite Sole' drainage basin and the Shamrock channel. Consequently, the Celtic fan is a multisource fan. The Whittard Channel drained the present south and east of Eire, Wales and west of England (but there is no available record of fluvial systems in the Irish Sea) when the Shamrock Channel drained part of the basin of the 'Fleuve Manche' (south of England, northwest France and sometimes east of England and part of central Europe). The Armorican Deep Sea Fan would have been connected to the 'Fleuve Manche' by the 'La Chapelle' drainage basin and the twin Blackmud and Guilcher channels and by the 'Ouest Bretagne' drainage basin and the Brest and Crozon channels. Upstream the four feeder channels, the two drainage basins and the seven eastern palaeovalleys of the 'Fleuve Manche' indicate that the Armorican Deep Sea Fan is a single-source fan with a huge catchment basin. Finally, during the Pliocene, the terrigeneous fluxes of the 'Fleuve Manche' fed either the Celtic Deep Sea Fan if they flowed into the two western arms of the delta (the present palaeovalleys 'A' and 'Espérance') or the Armorican Deep Sea Fan if they flowed into one of the seven others.

Late Pleistocene and Holocene events

The stratigraphic history of the submarine depocentres of the 'Fleuve Manche' is known accurately only since MOIS 3 owing to the lack of long cores or boreholes. Samples from the Meriadzek Terrace provide details on the regional sedimentation trends throughout the last climatic cycle. The cores situated on the Celtic and Armorican fans reveal similar sedimentation rates (60–70 cm kyr^{-1}) to that from Meriadzek Terrace for 12 to 10 ka. After 10 ka there is a decrease in sediment supply. In contrast, shallow spurs or isolated highs, such as Trevelyan Escarpment, show low sedimentation rates compared with Meriadzek Terrace.

The late Quaternary evolution of these sedimentation processes seems to be closely related to the meltwater of the British and the European ice-sheets. At 20–22 ka, the British ice-sheet reached its maximum extension somewhere between the present south coasts of Ireland and the Central Celtic Sea (Scourse *et al.*, 1990, 2000). Sedimentation rates on Meriadzek Terrace and Trevelyan Escarpment reveal a very similar sediment supply. During the Last Glacial Maximum, between H2 and H1 (19.5 to 15 ka), sedimentation rates increase, enhanced by sea-level fall and the augmentation of fluvial fluxes related to heat and moisture supplies connected with the northward penetration of the North Atlantic Drift (Eynaud, 1999; Zaragosi *et al.*, 2001a). The massive deglaciation of the British and European ice-sheets (ca. 20–13 ka) led to another increase in the fluvial fluxes towards the Porcupine continental margin (Scourse *et al.*, 2000) and the 'Grande Sole' drainage basin. Sedimentation rates (Fig. 14) reached their maximum values (up to 400 cm kyr^{-1} on Meriadzek Terrace at 15 ka, four times greater than fluxes during the LGM). This event has been interpreted by Zaragosi *et al.* (2001a) as a European precursor melting event corresponding to a purge of sediment of the Channel and Irish palaeorivers. From 14 ka the sedimentation rates decreased, drastically on the Trevelyan Escarpment, linked with the rising sea-level masking the fluvial input and the beginning of forestation. From 12 ka to 10 ka, sedimentation rates observed on the Celtic and Armorican fans are similar to the rate observed on the Meriadzek Terrace, which could indicate a similar source of sediment, or at least a source situated at the same distance.

Holocene sedimentation shows a hemipelagic signature. On the Armorican fan, terrigeneous supply stopped at 10 ka but continued until 7 ka on the Celtic fan. According to the previous account of the submarine pathways, cessation of the 'Fleuve Manche' flux implies that the canyons of the 'Petite Sole', 'La Chapelle' and 'Ouest Bretagne' slope drainage basins, and consequently the Armorican fan, were no longer be fed. The growth of the Celtic fan would, in that case, be controlled only by its other source, the 'Grande Sole' basin. The sediment supply therefore would have came from the North Celtic Sea, which received the terrigeneous fluxes of rejuvenated highlands initiated by the onset of glacio-hydroisostatic uplift of the British Isles (Lambeck, 1996). This concurs with evidence for a more active Whittard channel (Droz *et al.*, 1999) and could explain why sedimentation on the Celtic fan continued for longer than on the Armorican fan. The end of the terrigeneous supply between 10 and 7 ka, synchronous with the connection between the North Sea and the Channel, triggered the disappearance of the 'Fleuve Manche'.

Conclusions

All the sedimentary features described belong to the 'Fleuve Manche' system, which has developed since the Oligocene. The results allow the proposal of various explanations and hypotheses.

1. Incision of the palaeovalleys on the outer shelf is older than previously envisaged and has a possible Messinian age. The duration of the infilling ranges between 2 and 3 myr. The comparison of the maximum depths of the palaeovalley incision leads to estimated values for the Plio-Quaternary subsidence rate of, respectively, 32 m myr^{-1} and 24 m myr^{-1} for the northwest and the southeast outer shelf sectors, apart from the Alderney–Ushant fault.
2. At least five filled palaeovalleys on the outer shelf, out of nine, were connected to canyons of the slope. This suggests the 'Fleuve Manche' was directly connected to the continental slope. The upper slope canyons (type III) developed during or after the build up of the Pliocene prism on the shelf.
3. During lowstands, the outer shelf palaeovalleys scattered the sedimentary fluxes of the 'Fleuve Manche' throughout the shelf-break towards three submarine drainage basins of

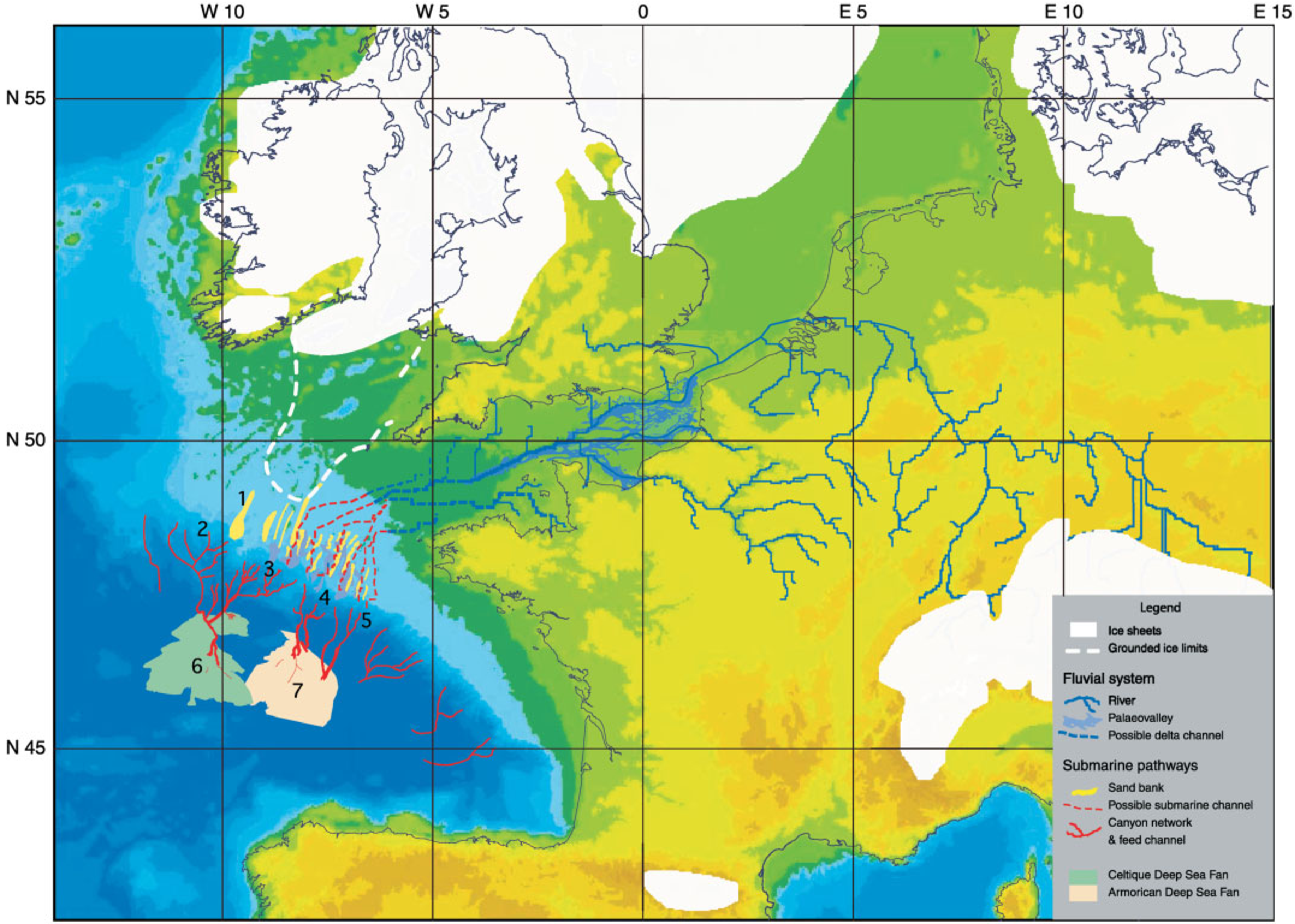

Figure 13 The 'Fleuve Manche' and the submarine pathways at the LGM: 1, sand banks of the outer shelf; 2, 'Grande Sole' slope drainage basin; 3, 'Petite Sole' slope drainage basin; 4, 'La Chapelle' slope drainage basin, 5: 'Ouest Bretagne' slope drainage basin; 6, Celtic Deep Sea Fan; 7, Armorican Deep Sea Fan. Ice-sheet boundaries for the British Isles from BGS (Holmes *et al.*, 1994) and for the Alps from Furrer *et al.* (1982); present northwest Europe relief from Bourillet *et al.* (1999), modified according to the glacio-hydroisostatic movement (Lambeck, 1996) and to the eustatic curve (Fairbanks, 1989); fluvial network extracted with the algorithm of Soille (1992); palaeovalleys of the Eastern Channel from Larsonneur *et al.* (1982)

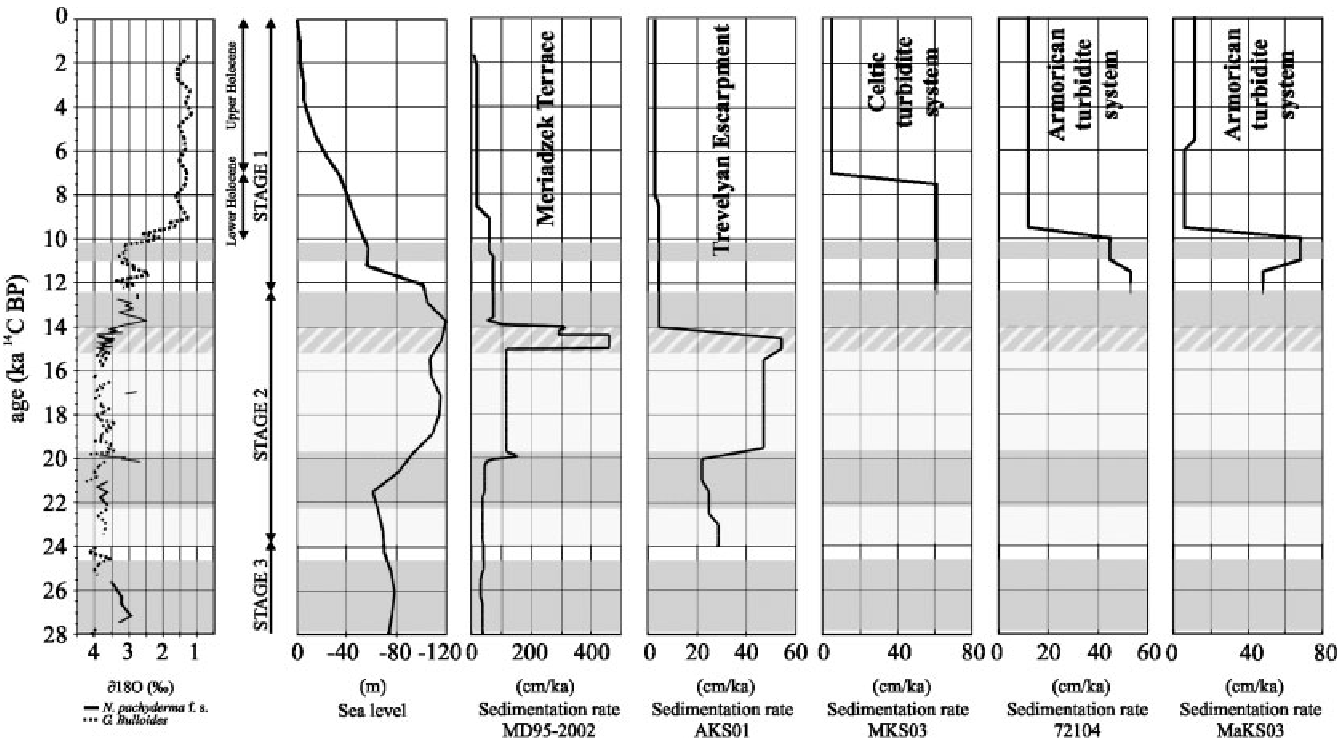

Figure 14 Time-scale of sedimentation rates for depocentres (modified from Zaragosi *et al.*, 2001a). For core location see Fig. 9

the slope. The 'La Chapelle' and 'Ouest Bretagne' basins led down to the Armorican Deep Sea Fan, a single source fan, whereas the 'Petite Sole' basin led down to the Celtic Deep Sea Fan. The latter is a multisource fan because it was also fed by the 'Grande Sole' basin draining sediments originated from the British Isles.

4 The late Quaternary sedimentation rates of the two deep sea fans seem to be linked to the rapid melting of the British and European ice-sheets and the sedimentary supply from onshore catchment basins.

Acknowledgements This work is a synthesis of numerous sea surveys carried out within Starfish and Enam I Mast 2 programmes, Enam II Mast 3 programmes and the French ZEE and Sedimanche projects. We would like to thank the crews of the R/V Belgica, Le Suroît, Nadir and L'Atalante. We are also indebted to technical support from B. Loubrieu, E. Ledrezen and A. Crusson. We specially thank P. Gibbard, G. Lericolais, L. Droz and J. P. Lautridou for reviewing the manuscript. S. Gupta and J. Scourse are thanked for their helpful reviews.

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