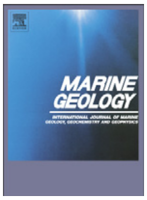
Marine Geology 295–298 (2012) 113–127

Contents lists available at SciVerse ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo



Present deep-submarine canyons activity in the Bay of Biscay (NE Atlantic)

T. Mulder [a,*], S. Zaragosi [a], T. Garlan [b], J. Mavel [a], M. Cremer [a], A. Sottolichio [a], N. Sénéchal [a], S. Schmidt [a]

[a] Université de Bordeaux, UMR 5805 EPOC, Avenue des facultés, 33405 Talence cedex, France
[b] Service Hydrographique et Océanographique de la Marine (SHOM), 13 rue du Chatellier, 29200 Brest, France

ARTICLE INFO

Article history:
Received 29 June 2011
Received in revised form 8 December 2011
Accepted 9 December 2011
Available online 21 December 2011

Communicated by D.J.W. Piper

Keywords:
Bay of Biscay
canyon
sedimentary record
current meter
in situ measurements
internal tides
turbulent surge

ABSTRACT

Present sedimentation in three canyons of the Bay of Biscay (Audierne, Blackmud and Capbreton) is studied by the combined analysis of cores and current meter data collected over a 7 month period. At the current meter mooring locations, interface cores were collected to characterize the recent sedimentation processes. In the two canyons located in the Northern part of the Bay of Biscay (Audierne and Blackmud), there is no evidence of recent sedimentary deposits. Canyons are by-passing or erosive areas. In the southern part of the Bay of Biscay (Capbreton), recent turbidite are deposited. In the three canyons, current meters recorded energetic currents with velocities showing alternating upslope and downslope motions, and a period corresponding to the semi-diurnal component M2. These currents are supposed to be related to deep internal tides. The high speed of the current (1 m/s) in Audierne and Blackmud is consistent with the lack of preservation of recent sediments on the canyon floors. In Capbreton Canyon, the magnitude of currents is less and recent turbidites are preserved. In addition to periodical current motion, small magnitude gravity event corresponding to a low-concentration turbulent surge or a high-concentration nepheloid layer initiated during a storm was recorded during the mooring period. These results suggest that deep-sea canyons in the Bay of Biscay have behaviour at present varying between by passing or erosion areas and sediment trapping. These examples suggest that sediments are moved up and down by low-energy, tide-initiated hydrodynamic events during most of the time. During higher magnitude, short-duration gravity events, the sediments are transferred down canyon towards the deep sea.

1. Introduction

Canyons are the largest morphological features that shape the present continental margins (Reading and Richards, 1994). Recent studies demonstrated that active processes remain active during highstand sea level conditions allowing them to maintain their morphology (Shepard, 1981; Pratson et al., 1994). These processes include turbidity currents, hyperpycnal flows or hydrodynamic processes (Normark and Piper, 1991).

Processes of sediment transport and deposition in a canyon is a key issue for understanding sediment transfer on margins because canyons are the main conduits for terrigeneous sediment fluxes (Shepard and Dill, 1966). Xu et al. (2010) estimate at ~500,000 m^3 of sediment transported yearly by turbidity currents through the single Monterey Canyon.

Canyon activity is defined according to the frequency of particle-laden currents. This activity depends on the distance of the canyon head from the sediment source and its connection with a river mouth. For example, turbidity current activity is high for canyons with their head incising the river estuary such as the Zaire (Babonneau et al., 2004), moderate for canyon supplied by hydrodynamic processes (e.g., Whittard Canyon; Toucanne et al., 2009, Ogooué; Bourgoin et al., 1963), but is low or nil for non-connected canyons (e.g. the US Atlantic canyons (Twichell and Roberts, 1982)). The capture by canyon head and of sedimentary particles supplied by river load or by the longshore drift depends on the distance between the canyon head and the shoreline or shallow water areas (bathymetry<20 m).

Inman (1970) and Shepard et al. (1977) in situ recorded along-bottom turbid flow with velocities ranging from a few decimeters to a few meters per second in La Jolla Canyon, Gennesseaux et al. (1971) recorded low concentration (<1 g/l), fast-speed (1.2 m/s) thin (<2 m thick) currents in the Var Canyon. Similar measurements by Khripounoff et al. (2003) in the Zaire Canyon showed the presence of fast (1.2 m/s) and thick (150 m above seafloor) currents at 3800 m water depth, carrying sand and plant remnants and spilling laterally at least 13 km away.

Using submarine cable failures, Gennesseaux et al. (1980) estimated the speed of the turbidity current related to Nice airport slump to 11 m/s in the upper part of the Var Canyon along a 12% slope and 2 m/s in the Var channel, at more than 50 km from its source. Using same type of data, Heezen and Ewing (1952), Kuenen (1952) and Hughes-Clarke et al. (1990, 1992) estimated the speed of the 1929 Grand Bank turbidity current in the Laurentian Channel close to 25 m/s. Using cellular automata numerical modelling, Salles et al. (2008) calculated a speed of

---

* Corresponding author.
E-mail address: t.mulder@epoc.u-bordeaux1.fr (T. Mulder).

0025-3227/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.margeo.2011.12.005

2–3 m/s for the head and 1–1.6 m/s for the tail of the turbulent surge generated in December 1999 in the Capbreton Canyon. The modelled maximum head thickness was approximately 35 m. Recent in-situ measurements in Californian canyons showed important sediment fluxes, most of them related to storm-related turbidity currents (Puig et al., 2003, 2004; Xu et al., 2004, 2010; Xu, 2010).

Turbidity currents are not the only active process in deep sediment transport mechanisms. Tidal bottom currents dominate the flow field in many submarine canyons (Shepard et al., 1974). They are also recognized as efficient forcing for sediment transport and reworking, as they can reach maximum velocities of 25–50 cm/s (Shanmugam, 2003). Under favourable conditions in topography and in vertical stratification, internal tides can be generated (Wang et al., 2008), which can significantly enhance energy flux in canyons compared with the barotropic tide (Lee et al., 2009). In-situ measurements in canyons located along the Portuguese margin, Nazaré (de Stigter et al., 2007), Lisbon-Setubal and Cascais (De Stigter et al., 2011) demonstrated the impact of internal wave in sediment resuspension. A similar phenomenon is also observed by Gardner (1989) in Baltimore Canyon. Dense water cascading and capture of current from continental shelf circulation are other processes involved in recent sediment transport in canyons (Canals et al., 2006, 2009; Palanques et al., 2006, 2009). However, although these processes are frequent in the Western Mediterranean where water densities are contrasted and north flowing wind can cool down surface water, there is no evidence that such processes are frequent enough in the Atlantic to explain permanent hydrodynamic observations. In the Bay of Biscay, such hydrodynamic patterns are still poorly documented and there are scarce evidences of their effect on sedimentary processes. Reid and Hamilton (1990) recorded cyclic currents with a maximum speed of 16 cm/s in nine locations of the Whittard and Shamrock canyons using current meters moored one meter above the seafloor at a water depth extending from 3575 to 4370 m. The average current speed was globally decreasing downslope. According to the shortness of their record (211 h for the longest), they related the cyclic signal directly to the semi-diurnal surface tide. This record of bottom current along the seafloor was consistent with the presence of sediment waves indicating the presence of slope-parallel bottom currents. Moreover, the presence of several fields of asymmetric sandwaves oriented orthogonal to the canyon axes indicate sediment transport into the canyon heads from hydrodynamic processes oriented perpendicular to the margin (Cunningham et al., 2005).

In this paper, the main objective is to describe present sedimentation record in three canyons of the Bay of Biscay. By using unpublished mooring records available we tentatively explain the differences in respective sedimentation patterns. Taking advantage of the lucky record of an exceptional event, these new data provide additional examples of the behaviour of present deep-sea submarine canyons on a passive margin.

2. Settings

2.1. Morphologic and geologic context

The Bay of Biscay is a passive margin sedimentary basin extending in the northwestern Atlantic Ocean (Fig. 1) over more than 1000 (900,000 km^2) and reaches a water depth of 4975 m. It includes the Armorican and the Aquitaine margin and is bounded by the Celtic margin in the north, and the North-Iberic margin in the south (Boillot et al., 1973, 1974, 1979). The continental shelf is 1000 km-wide on the Celtic margin, 300 km-wide along the Armorican margin and less than 80 km-wide along the Aquitaine margin. The continental slope is steep (average slope is 8°) with a “canyon dominated” slope (Celtic and

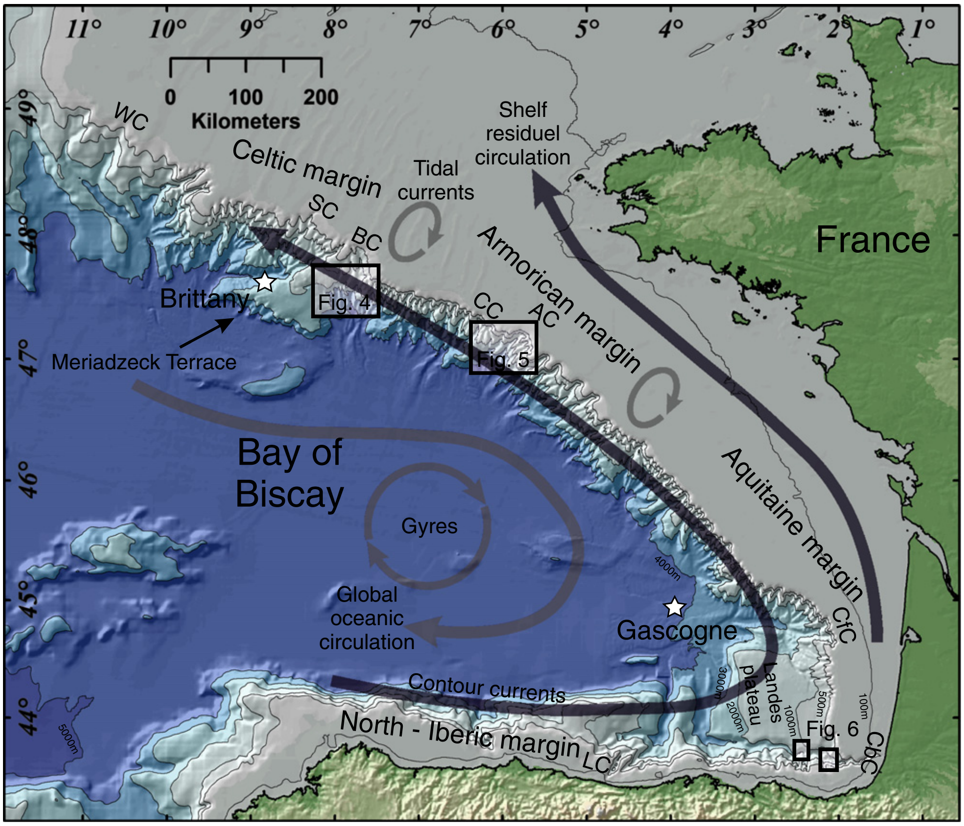


Fig. 1. Location of the study area. Shaded bathymetry of the Bay of Biscay showing the location the three monitored canyons: (Blackmud (BC), Audierne (AC) and Capbreton (CbC). The stars show the positions of the buoys Brittany and Gascogne. Bathymetry and elevation data are from GEBCO database and from Ifremer ZEE Atlantic DEM (Le Suavé, 2000). Whittard (WC), Shamrock (SC) and Cap-Ferret (CfC) canyons.

Armorican) and a “tectonic dominated” slope (Aquitaine). The morphology of the continental slope is characterized by spurs and canyons organized in submarine drainage basins (Bourillet and Lericolais, 2003).

A particular feature of the Armorican and Celtic margins is that their turbidite activity is slightly influenced by the sea-level changes during the last climatic cycles. Recent works directly correlate the turbidite supplies on these margins with the inputs from the Manche Paleoriver system. (Toucanne, 2008; Toucanne et al., 2009). The activity of the Manche Paleoriver is linked with the paroxysm of ice melting of the European ice sheet and with a high rate of turbidite deposition in the Whittard, Shamrock, Blackmud and Crozon channel-levee systems. During lowstands and glacial maximum the turbidite activity was low.

The Aquitaine continental slope is smooth and is extended by the marginal Landes Plateau dipping gently westward. It is bordered by steep slopes that form the south flank of Cap-Ferret Canyon in the North, Capbreton Canyon in the South, and Llanes Canyon in the West. In the south, Capbreton Canyon is bordered by the Basque-Cantabrian continental margin with very steep slopes. It is an atypical canyon for the Bay of Biscay with a meandering course (Cirac et al., 2001). The margin has a low sedimentation rate and a low subsidence rate (Boillot et al., 1979; Thinon, 1999).

The margin is cut by approximately 35 submarine canyons (Berthois and Brenot, 1960; Kenyon et al., 1978; Le Suavé, 1999; Auffret et al., 2000; Zaragosi et al., 2000, 2001, 2003; Zaragosi, 2001; Bourillet et al., 2005). From north to south the main canyons are Whittard, Shamrock, Blackmud, Audierne, Cap-Ferret and Capbreton (Fig. 1). Audierne and Blackmud canyon are on the Armoricain Margin. Capbreton Canyon is on the Aquitaine margin.

The Blackmud Canyon is relatively straight and oriented S–SE down to 1500 m water depth (Fig. 1). Canyon direction is almost perpendicular to tide wave (NE–SE). At 500 m water depth, the canyon is narrow with an incision that does not exceed 200 m (Fig. 2C). At 1500 m, the incision is deeper (400 m). Below 1500 m, the canyon axis is located 150 m below the terraces. The slope of Blackmud Canyon is convex-up and irregular (Fig. 2A). Along the Mériadzek Terrace, the average value of the slope is only 2° down to 2000 m water depth. Deeper than 2000 m, the slope increases to 9° down to the abyssal plain.

The Audierne Canyon is slightly more sinuous with an average orientation NE–SW, parallel to tide waves (Fig. 1). Its slope profile is typically concave-up (Fig. 2A). The canyon head is located close to 500 m water depth. At 1500 m water depth, the canyon is large and deep with a bathymetry difference of 700 m between the talweg axis and terraces (Fig. 2B). It decreases from 7° between 500 and 1500 m water depth to less than 1° where the canyon connects with the abyssal plain (average slope value is 4.5°). Both canyons are disconnected from any river source. Their head is located close to the continental shelf break making infrequent the sediment supply during sea-level highstands such as Holocene.

The Capbreton Canyon deeply incises the Aquitaine continental slope and shelf over more than 2000 km (Cremer, 1983; Cirac et al., 2001). Its slope is low and regular (Fig. 2A). It shows a complex meandering shape. The head of the canyon forms a deep and wide amphitheatre opening towards the coast with numerous slump scars (Fig. 1; Froidefond et al., 1983; Gaudin et al., 2006). Transversal bathymetric profiles show a V-shaped cross section of the canyon (Fig. 2D). The two sides of the axial talweg are bordered by terraces with a height of tens to a few hundreds of meters. Failure scars are frequently observed along the canyon flanks (Gaudin, 2006). At 500 m water depth, the bathymetric difference between the talweg axis and terraces is 500 m. This difference is 600 m at 1500 m water depth (Fig. 2D).

The axial talweg width enlarges from tens of meters up to the hundred meter scale. The morphology, size and curvature of meanders are

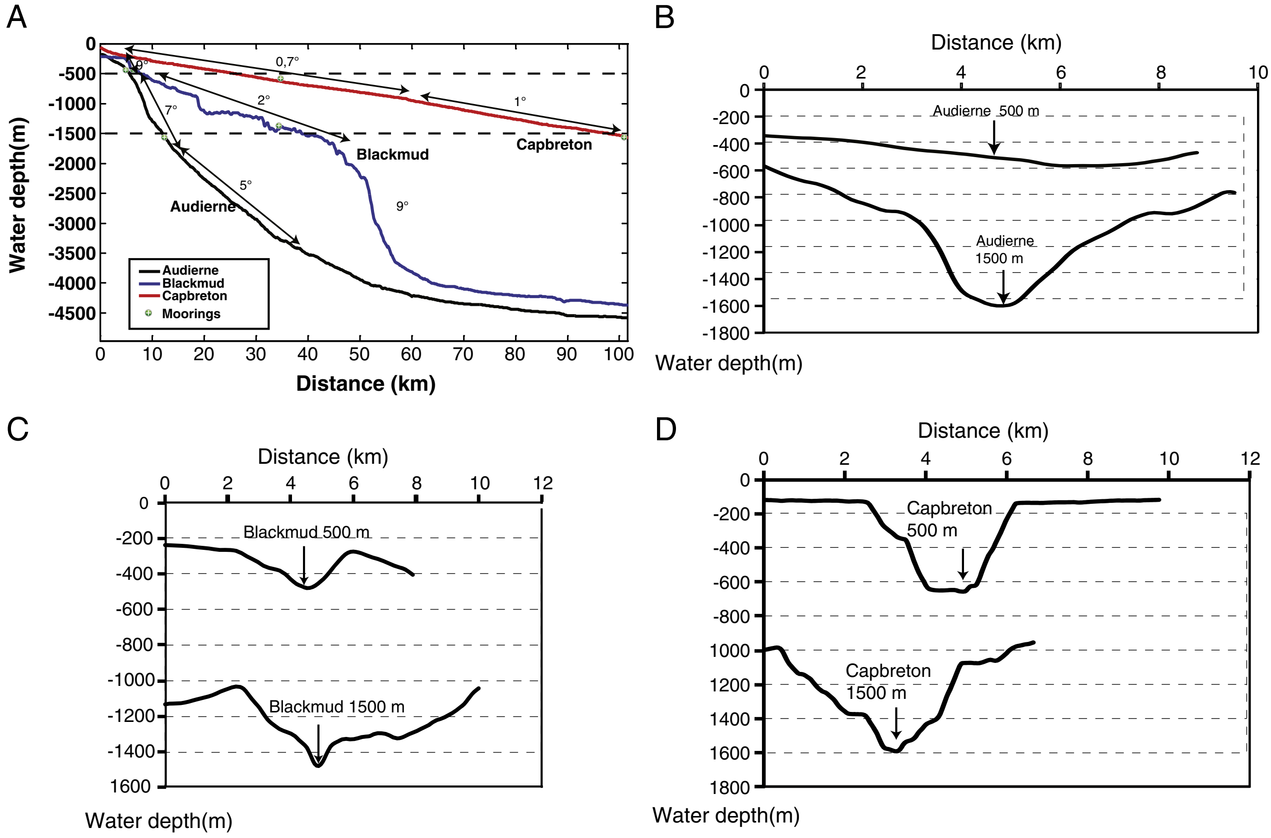


Fig. 2. A: Slope profiles of Blackmud, Audierne and Capbreton canyons. B: Cross sections at 500 m and 1500 m water depth in Blackmud Canyon (profile locations in Fig. 3A). C: Cross sections at 500 m and 1500 m water depth in Audierne Canyon (profile locations in Fig. 4B). D: Cross sections at 500 m and 1500 m water depth in Capbreton Canyon (profile locations in Fig. 3C and D, respectively).

irregular. Westward of W1°50 the canyon becomes asymmetric with the southern flank much higher and steeper than the northern flank (Gaudin, 2006; Gaudin et al., 2006). The slope of the canyon head is steep (Fig. 2A; 4° in average along the first kilometer with maximum values up to 7° over a few hundreds of meters). The average slope along the first four kilometers of the Capbreton Canyon is 2°. Downward from the canyon head, the average slope decreases to 0.8° and remains constant over more than 100 km. Capbreton Canyon has been historically disconnected from the Adour River in 1578 AD. However, its head is located at a water depth of about 15 m making easy a direct supply by the strong longshore drift that acts in this part of the Bay of Biscay.

2.2. Bay of Biscay oceanography

In the Bay of Biscay, the deep-sea oceanic circulation is the result of four superimposed water masses with different densities (Durrieu de Madron et al., 1999). From surface to bottom, they are: 1) the Eastern North Atlantic Water (ENAW), 2) the Mediterranean Outflow Water (MOW), 3) the Labrador Sea Water (LSW) and 4) the Bottom Water (BW).

The ENAW is formed from the North Atlantic Current Water (NACW; Sverdrup, 1942). The ENAW extends down to 500–600 m water depth. It is thicker in winter than in summer because it is colder and mixed by the frequent storms. The MOW corresponds to the intermediate water mass. It flows between 700 and 1300 m water depth. The LSW may appear at the bottom of the intermediate water mass (below than 1000 m water depth) but in the Bay of Biscay, it tends to merge with the MOW. The BW is located below 1500 m water depth. It is formed by both the Northeast Atlantic Deep Water (NADW) and the Antarctic Bottom Water (ABW). These two cold (2–3 °C) water masses enter the Bay of Biscay west of the Galicia Bank flow northward along the north Iberic continental slope down to the Abyssal plain.

The surface hydrology is controlled by contour currents and cyclonic or anticyclonic gyres. Contour currents are mainly formed by the NACW. When the NACW enters the Bay of Biscay close to Mériadzeck Terrace, it divides into two branches. One branch flows towards northwest and forms the ENAW. The other branch flows towards southwest and forms the slope contour current. Instabilities of currents alongslope form westward anticyclonic gyres called SWODDIES (Slope Water Oceanic eDDIES; Serpette et al., 2006).

Internal tides are an important hydrological process in the Bay of Biscay. They are formed close to the 200-m isobath and propagate simultaneously both on shelf and into the ocean as deformed progressive waves (Pingree et al., 1986). They are caused by the amplification of the tide amplitude on the continental slope. Consequently, they are internal waves with a tide frequency. This generates a vertical component of the tide current and the motion of water particles with a speed of 2–4 m/s. Because of the combination of bathymetric variations at the top of the continental slope and the water mass stratification, this current speed has strong spatial variations that are transmitted with depth along the isopycnal surfaces. This transmission forms the internal tides that propagate from NE towards SW (Pichon and Correard, 2006). The continental slope of the Bay of Biscay is considered as the most energetic area of the world concerning internal tides (Jézéquel et al., 2002).

2.3. Recent sedimentary processes in Capbreton Canyon

Along the Aquitaine margin, the main conduit from sedimentary processes is the Capbreton Canyon. This canyon is also the only one amongst the three studied canyon for which we have the evidence for present active sedimentary processes. A turbidite deposited by a turbulent surge (sensu Ravenne and Beghin, 1983) generated by the December 27th 1999 Martin storm has been recovered in an interface core (Mulder et al., 2001). Below this turbidite, at least two additional turbidites are younger than a century (Mulder et al., 2001; Chaillou,et al., 2008; Chaillou et al., 2003). The turbulent surge responsible of the deposition of the Martin storm turbidite could have been triggered by three processes: 1) an intensification of the longshore drift. 2) A slump due to an increase of the interstitial pore pressure because of the 12-m swell, and 3) the dissipation of the 1–2 m bulge due to the nearshore accumulation of water because of the combination of eastward wind and low atmospheric pressures. Numerical modelling using cellular automata (Salles 2006; Salles et al., 2008) showed that this surge generated substantial erosion. However, the frequency and magnitude of turbidity current in the canyon at present are high enough to maintain the freshness of the canyon flanks but is insufficient to explain the canyon formation (Mulder et al., 2004).

3. Methods and data

Twenty interface cores have been collected using the interface coring system developed by Ifremer (Apprioual, 2001; Table 1). The system allows collecting 1 m-long interface cores. These cores were then described and photographed. A 1 cm-thick slab was sampled along

Table 1
Core location and length. Core numbers in bold are presented in Fig. 5. $^{210}Pb_{ex}$ activity measured below top of the cores is also indicated.

Core number	Area	Latitude	Longitude	Water depth	Core length	Max. depth of $^{210}Pb_{ex}$ activity
KI 05	Audierne 1500 m	47 11.354 N	005 46.464 W	1550	0.08	/
KI 06	Audierne 1500 m	47 11.436 N	005 46.363 W	1516	0.23	/
KI 07	Audierne 1500 m	47 11.348 N	005 47.629 W	1723	0.45	/
KI 08	Audierne 1500 m	47 11.987 N	005 47.756 W	1472	0.60	/
KI 09	Audierne 1500 m	47 09.420 N	005 50.316 W	2198	0.29	/
KI 10	Audierne 1500 m	47 11.364 N	005 46.455 W	1563	0.10	/
KI 11	Blackmud 500 m	47 54.956 N	007 45.464 W	386	0.05	/
KI 12	Blackmud 500 m	47 54.653 N	007 44.912 W	531	/	/
KI 13	Blackmud 500 m	47 54.858 N	007 45.329 W	451	/	/
KI 14	Blackmud 1500 m	47 40.069 N	007 40.850 W	1366	0.37	/
KI 19	Capbreton 500 m	43 37.5641 N	001 42.8623 W	652	0.30	/
KI 20	Capbreton 500 m	43 37.803 N	001 42.936 W	638	1.13	77 cm
KI 21	Capbreton 500 m	43 37.724 N	001 42.912 W	639	0.94	57 cm
KI 22	Capbreton 500 m	43 37.645 N	001 42.880 W	640	0.71	35 cm
KI 23	Capbreton 500 m	43 37.700 N	001 43.339 W	663	0.09	/
KI 24	Capbreton 500 m	43 37.6709 N	001 42.2002 W	636	0.38	/
KI 26	Capbreton 1500 m	43 38.0182 N	002 10.0190 W	1574	0.04	/
KI 28	Capbreton 1500 m	43 38.137 N	002 10.024 W	1560	0.13	/
KI 30	Capbreton 1500 m	43 38.027 N	002 10.270 W	1561	0.24	/
KI 32	Capbreton 1500 m	43 37.790 N	002 10.262 W	1511	0.99	35 cm

each core for X-radiography using the Scopix system (Migeon et al., 1999). Grain size was measured using a laser diffractometer Malvern Mastersizer. The age of the most recent deposits was determined by counting the activity of radiogenic isotope $^{210}Pb_{ex}$ (half-life = 22.4 yrs, Table 1). It was counted over 20 h using a high-resolution gamma spectrometer with a semi-planar detector. $^{210}Pb_{ex}$ = total $^{210}Pb - ^{226}Ra$. Maximum detection period corresponds to five to six times the half-life at the maximum, i.e. approximately a century (Jouanneau et al., 1988; Gouleau et al., 2000).

Hydrological parameters were collected using Nortek Aquadopp current meters. Six current meters were moored in three canyons (from north to south: Blackmud, Audierne and Capbreton canyons) during the Sedymane-Leg 1 cruise (from 19/04 to 02/05/2007 on the RV Pourquoi-Pas?). Moorings in Audierne and Blackmud canyons were recovered during the Sedymane-Leg 2 cruise (04–12/05/2007 on the RV Pourquoi-Pas?) while in Capbreton Canyon moorings were recovered later, during the Sedymane-Leg 3/Congass cruise (3–10/12/2007 on the RV Thalassa). From the top to the bottom, each mooring is composed of a 4 m-long buoy, a 4 m-chain, and a 10 m-long wire with the Aquadop Current meter in the middle, a MORS release system and a 5 m-long chain anchoring the whole system to a 77 kg concrete ballast on the seafloor. The current measurements are thus located 11.4 m above the seafloor. In the three canyons, current meters were moored during approximately 7 months at 500 and 1500 m water depths.

Current is measured every 450 s and the recorded value corresponds to the speed averaged over 30 s. The current direction is provided by a compass that measures the inclination of the earth magnetic field with an accuracy of 2°. A temperature sensor measures the water temperature with an accuracy of 0.1 °C and an internal response time of 10 min. The pressure (in dbar) is measured by a sensor with an accuracy of 0.25%. It is converted in depth of water using a seawater density of 1024 kg/m^3. Current velocities are measured on a cylindrical water slice of 2.1 m in diameter to avoid friction effects that slow down currents in the neighbourhood of the current meters. Velocity components are measured along three orientations: eastward, northward and vertical. The horizontal current speed corresponds to the sum of the E and N velocities. The accuracy of measurements is 1 cm/s. The tilt of the current meter (in degrees) is also recorded.

All the current meters were located in the canyon talweg except for those located in Audierne at 1500 m water depth. The slope and the orientation of the canyon talweg at the mooring location are provided in Table 2.

The buoys Brittany and Gascogne (Fig. 1) provided swell and meteorological data: wave height, wave period, wind intensity and orientation over the period of current meter mooring. In this paper, we used the data from Brittany buoy because it is located in the open ocean when compared to the Gascogne one and for this reason; the wave heights are less attenuated. However, the storm event that occurred during the mooring period is recorded on both buoys and the interpretation based on any buoy data would be identical, whatever the used buoy is. The tide characteristics (dominated in this area by the semi-diurnal components M2 and S2) at the position of the moorings were calculated using the Marmonde model developed by the Service Hydrographique et Océanographique de la Marine (SHOM) and calibrated using tidal gauge records in Concarneau (Garlan, 2004).

Table 2
Morphologic data concerning the Audierne, Blackmud and Capbreton canyons (talweg slope and orientation) at current meter location.

Current meter	Slope	Talweg orientation
Blackmud 500	9°	N 132°
Blackmud 1500	4.5°	N 170°
Audierne 500	4°	N 215°
Audierne 1500	4.5°	N 280
Capbreton 500	2.5°	N 260°
Capbreton 1500	0.8°	N 265°

4. Results

4.1. Interface cores

Only 7 of the 20 interface cores penetrated substantially in the seabed and are consistently described and illustrated. The thirteen other, usually very short, are still of some interest because they indicate ancient lack of recent sedimentation or erosion, and are briefly described.

1) Blackmud Canyon
In Blackmud Canyon four cores were collected. Three were collected at 500 m water depth but KI 12 and KI 13 did not penetrate the seafloor. Only one core penetrated 5 cm deep in the sediment (KI 11) and collected the Miocene limestone substratum in the canyon talweg. A 37 cm-long interface core (KI 14; Figs. 3A and 4) was collected at 1500 m water depth. It shows compact silt over brown to grey silty clay and clay.
2) Audierne Canyon
In Audierne Canyon, six cores (KI 05 to KI 10) were collected (Fig. 3B), all at 1500 m water depth. KI 05 (8 cm-long) shows homogeneous fine sand containing shell fragments, KI 06 (23 cm-long; Fig. 4) shows graded shelly sand with clayey sand in surface. KI 07 (45 cm-long; Fig. 4) shows graded shelly sand (from coarse to medium) interpreted as a turbidite. It is covered by sandy silt containing shell fragments on the surface. KI 08 (60 cm-long) shows very fine silty sand containing shell fragments passing to silt with shell fragments in surface. KI 09 (29 cm-long) shows fine silt overlain by foraminifer ooze and homogeneous silty clay. KI 10 (10 cm-long) shows fine silt with shell clasts.
In both Audierne and Blackmud canyons, no $^{210}Pb_{ex}$ activity has been measured except at the very top of some cores, suggesting that either no sediment accumulated recently in the canyons or that the potential sediment accumulation has been removed.
3) Capbreton Canyon
In Capbreton Canyon, ten cores were collected. Six cores were collected at 500 m water depth (KI 19 to KI 24; Fig. 3C). KI 19 (30 cm-long) shows homogeneous medium to fine sand with vegetal fragment overlain by a few cm of light brown silty-clay. KI 20 (113 cm-long; Fig. 4) shows at least three superposed beds graded from very fine sand or silt to clay interpreted as turbidites separated by fine-grained bioturbated mud interpreted as hemipelagites. KI 21 (94 cm-long; Fig. 4) shows at least five beds graded from very fine sand or silt to silty clay overlain by a few centimeter-thick underconsolidated silty-clay. KI 22 (71 cm-long) shows at least three superposed beds graded from fine sand to clay interpreted as turbidites separated by fine-grained bioturbated mud interpreted as hemipelagites. KI 23 penetrated only 9 cm-deep in the canyon talweg and shows micaceous sand. KI 24 (38 cm-long; Fig. 4) shows fine to very fine sand graded beds becoming more clayey at the top and overlain by a few centimeter-thick light silty-clay layer. At 1500 m water depth, four cores have been collected (Fig. 3D). KI 26 did not penetrate the underconsolidated talweg bottom sediment. KI 28 (13 cm-long) shows a 10 cm-thick homogeneous layer rich in monosulfide overlain by a few cm-thick light-brown, slightly-consolidated mud. KI 30 (24 cm-long) shows a clay breccia overlain by a few cm-thick brown, slightly-consolidated mud. KI 32 (99 cm-long; Fig. 4) shows the superposition of more than thirty, millimeter- to centimeter-thick fine-grained beds, each graded from silt (rarely very fine sand) to clay and interpreted as turbidites. A $^{210}Pb_{ex}$ activity has been measured at 35 cm below the top of this core (Table 1). Three other cores collected in Capbreton Canyon (KI 20, KI 21 and

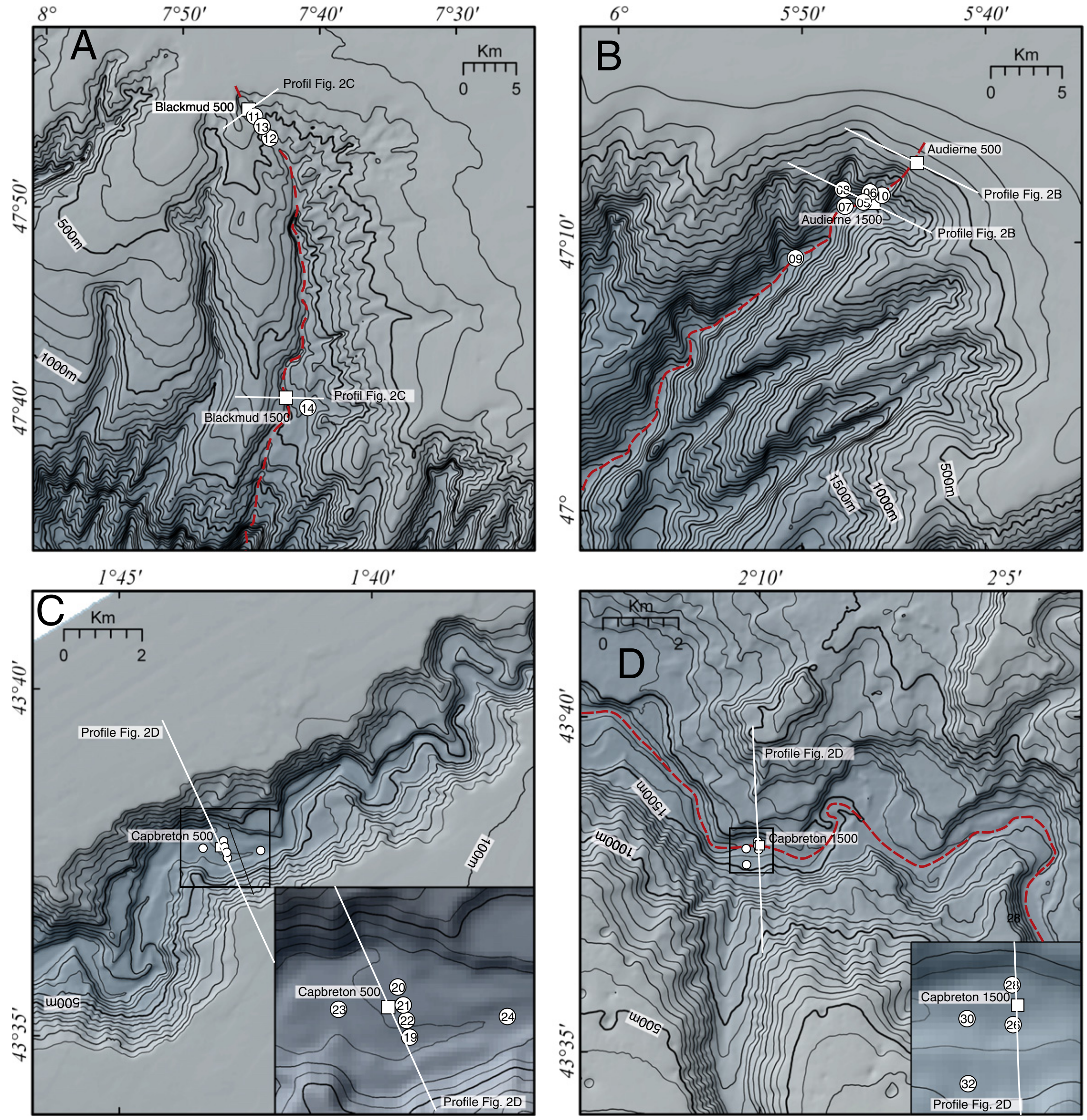


Fig. 3. Shaded bathymetry of the Blackmud Canyon showing the location of the current meter moorings at 500 and 1500-m water depths, collected cores and the location of profiles in Fig. 2. A: Blackmud Canyon moorings at 500 m and 1500 m and cores KI 11 to KI 14. B: Audierne Canyon at 500 m and 1500 m and cores KI 05 to KI 10. C: Capbreton Canyon at 500 m and cores KI 19 to KI 24. D: Capbreton Canyon at 1500 m and cores KI 26, KI 28, KI 30 and KI 32. Bathymetric contours are from Le Suavé (1999) for A and B and from Cirac et al. (2001) for C and D.

KI 22) show a significant $^{210}Pb_{ex}$ activity at 77, 57 and 35 cm below core top, respectively.

4.2. Deep currents

Currents are represented in a rose diagram (Fig. 5). Blue dots are raw data values. The average direction of currents is figured by sectors with intervals of 18°. The Eulerian residual current speed (estimated over the whole period) is figured by a green arrow aligned on the rose diagram radius. The length of the arrow is proportional to the current speed. The downcanyon orientation of the axial talweg at the location of the current meter is figured with a red arrow.

In the three canyons, the current velocities vary periodically from an upslope to a downslope orientation (Figs. 5 and 6; Table 3). Four sites (all the 500-m location and Audierne 1500 m) showed dominant down canyon flow while two showed upcanyon. Secondary flows in the opposing direction were observed at all sites.

Spectral analysis was computed from 5120 point ensembles corresponding to time series of nearly 28 days (with 50% overlap) that were individually tapered with a Hamming window. Associated degree of freedom is 30 for each harmonic analysis. Both pressure and current harmonic analyses indicate the semi-diurnal M2 component to be significant at the 98% confidence interval in the three canyons. In Audierne and Blackmud canyons, (Fig. 6A–D; Table 4), spectral analysis also showed a significant peak at the quarter-diurnal M4 component consistent with previous observations (Le Cann, 1990). A focus on the semi-diurnal band also indicates the presence of the S2 component leading to the neap-spring tidal cycle, consistent with previous observations and modelling (Pairaud et al., 2008).

Despite the spectral analysis showing semi-diurnal S2 and M2 components, the intensity of the currents is not perfectly synchronous with

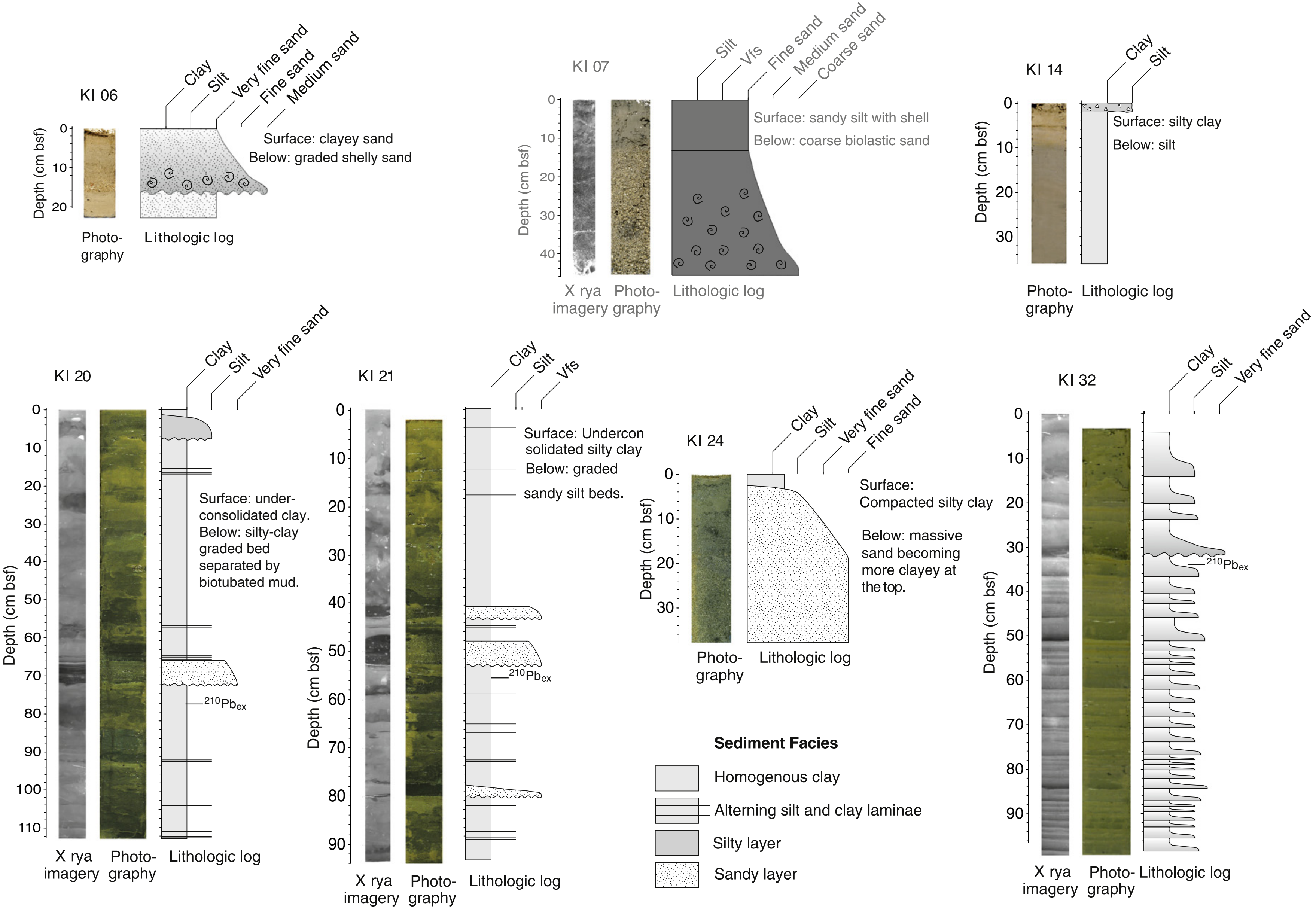
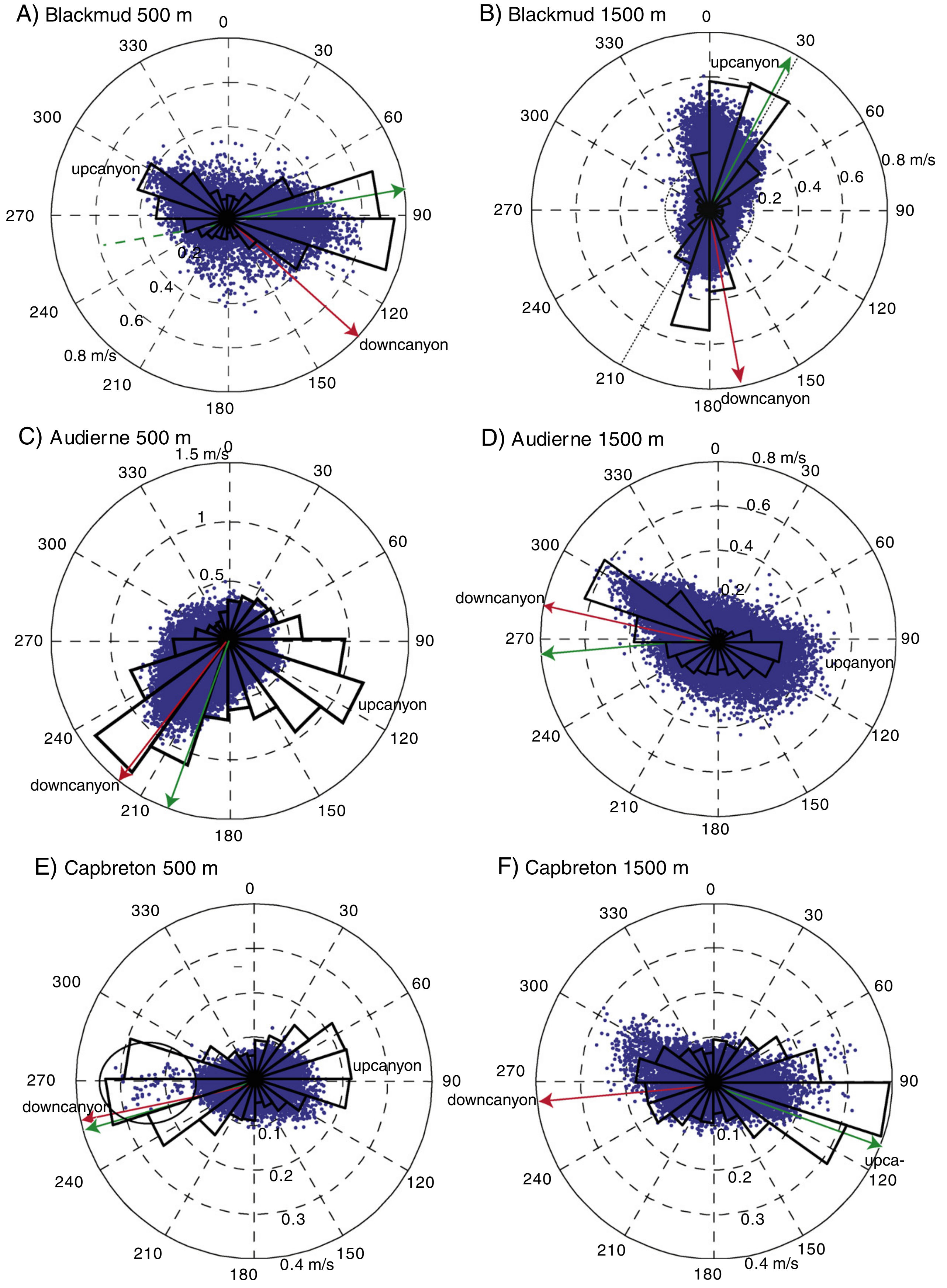


Fig. 4. Lithologic logs and X-ray images of selected cores in Audierne Canyon at 1500 m (KI 06 and KI 07), Blackmud Canyon at 1500 m (KI 14), Capbreton Canyon at 500 m (KI 21 and KI 24) and 1500 m (KI 32).

the tide amplitude measured at Brittany Buoy (Fig. 6A and B). At 500 m, the equinox tide in September (E.T. in Fig. 6) is not linked with peak current velocities both in Audierne and Blackmud canyons (Fig. 6A and C). Conversely, peak current velocities at 1500 m are synchronous to this equinox tide for the two canyons. In Capbreton Canyon, even if the periodicity is not as clear as in Audierne and Blackmud canyons, spectral



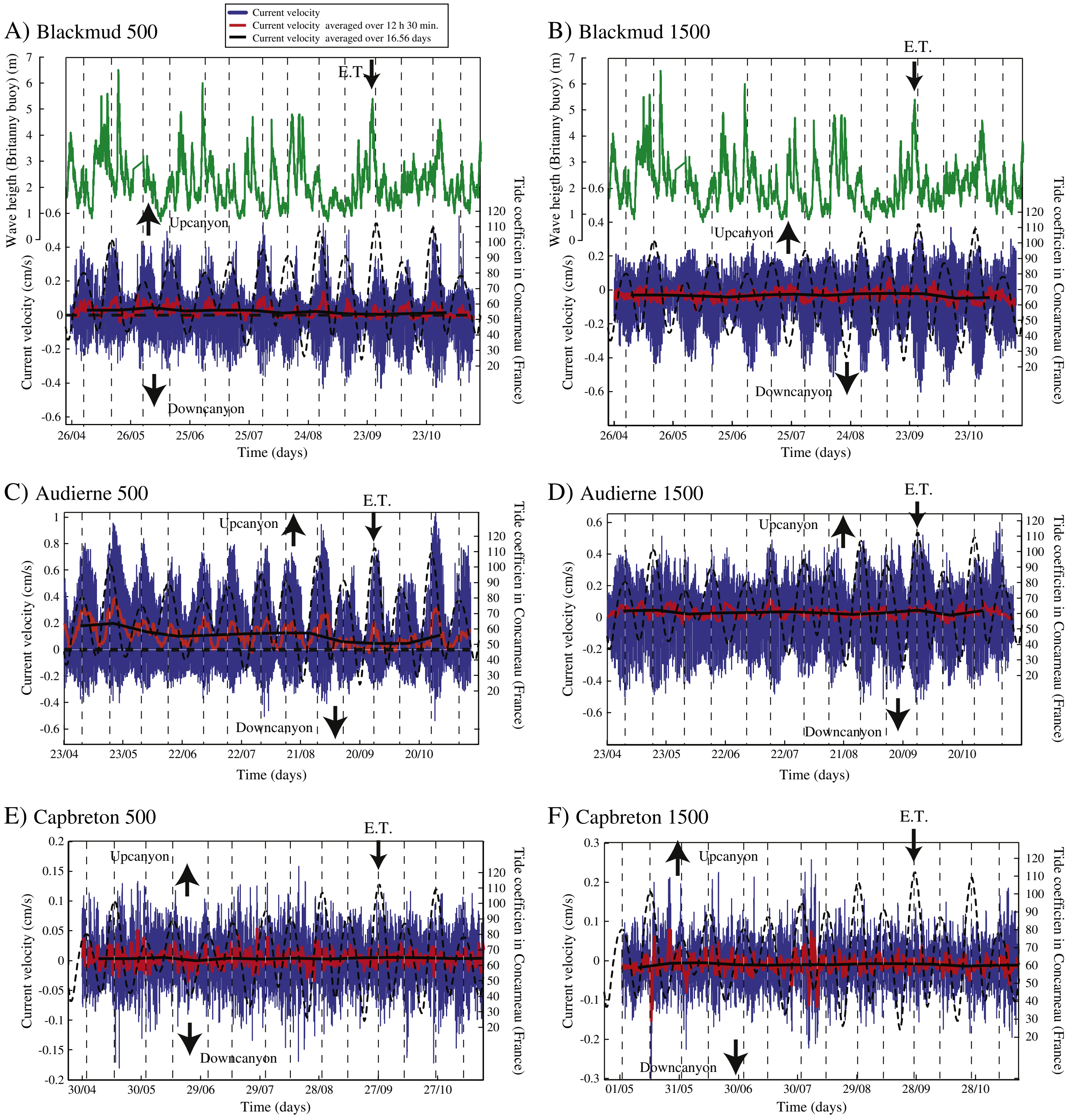


Fig. 6. Speed record (time series) from 25/04/2007 to 20/11/2007. A: Blackmud Canyon 500 m. B: Blackmud Canyon 1500 m. C: Audierne Canyon 500 m. D: Audierne Canyon 1500 m. E: Capbreton Canyon 500 m. Circled points represent data related to the exceptional hydrologic event of December 2007. F: Capbreton Canyon 1500 m. In A and B the wave height recorded at Brittany Buoy is given. The normalized tidal range ("tide coefficient") recorded at the coast is represented by the black dashed line.

analysis indicate the semi-diurnal M2 component to be statistically significant (Lam et al., 2004).

The maximum currents are mostly oriented downcanyon with some exceptions (Blackmud and Capbreton at 1500 m water depth).

Maximum current speed in Audierne and Blackmud canyons is relatively high, especially in Audierne at −500 m. At this station, downcanyon currents can exceed 0.8 m/s at spring tides, and are even close to 1 m/s at the end of October (Fig. 6C). In Capbreton

Fig. 5. Current meter data: current orientations and speeds. A: Blackmud Canyon 500 m. B: Blackmud Canyon 1500 m. C: Audierne Canyon 500 m. D: Audierne Canyon 1500 m. E: Capbreton Canyon 500 m. F: Capbreton Canyon 1500 m.Current is represented in a rose diagram (0–360°). The orientation of currents is figured by a sector of 18°. Current speed is represented along the rose diagram radius. The green arrow represents the Eulerian residual current speed. The axis of the axial talweg at the location of the current meter is figured with a red arrow. The circled values in E represent the data related to the exceptional event recorded during December 2007. Note that the scale on diagram radius is different for each canyon.

Table 3
Synthesis on measured data about current orientation and intensity in Audierne, Blackmud and Capbreton canyons.

Canyon	Main current orientation	Direction	Maximum current orientation	Secondary current orientation	Maximum current speed (m/s)	Secondary flow speed (m/s)	Max. upcanyon current speed (m/s)
Blackmud 500 m	Downcanyon	100°	Downcanyon	295°	0.61	0.45	0.40
Blackmud 1500 m	Upcanyon	25°	Upcanyon	190°	0.60	0.4	0.60
Audierne 500 m	Downcanyon	225°	Downcanyon	115°	1.00	0.53	0.50
Audierne 1500 m	Downcanyon	295°	Downcanyon	100°	0.62	0.57	0.55
Capbreton 500 m	Downcanyon	270°	Downcanyon	80°	0.17	0.15	0.15
Capbreton 1500 m	Upcanyon	100°	Upcanyon	275°	0.33	0.30	0.33

Canyon, current patterns are substantially different. The maximum velocities are lower than 0.17 m/s. The resulting current over the period of mooring is lower than 0.1 m/s downcanyon. The currents are slightly faster at 1500 m water depth than at 500 m water depth. Maximum velocities are more than 0.3 m/s and most of the current velocities are higher than 0.1 m/s.

On December 3rd, 2007, an exceptional event was recorded in Capbreton Canyon on the current meter moored at 500 m water depth (Fig. 7). The event clearly disrupted the cyclic signal of current variation in orientation and speed. It took place 2 h 30 min after the cyclic pressure reversal and 1 h 30 min after the related change in current orientation from 20° (upslope) to 270° (downslope). It is marked by an abrupt and simultaneous change in three measured parameters (Fig. 7): (1) current speed (see also in Fig. 5), (2) current meter heading and (3) pressure. A fourth parameter (water temperature) varied more steadily. The event took place during a relatively bad weather period, with significant wave recorded by Brittany buoy height reaching 5.5 m (Fig. 7), which is much larger than the average values (1–2 m). Wave height is slightly attenuated on Gascogne buoy. On the other side, this value needs to be compared to the swell value (12 m) measured during the Martin storm (1999). The storm recorded in 2007 is a classical winter storm while the Martin storm is interpreted as a decennial event (Mulder et al., 2001). At 18:30, the current increased abruptly from 0–5 cm/s to 32 cm/s and turned from upslope to downslope. Then the speed remained high (and downslope) during 10 h 30 min after the abrupt change, before decreasing progressively to values similar as those before the event after approximately 18 h. The variation also affected the heading of the current meter. During all the mooring period except the event, the heading was oriented N120°, i.e., upcanyon. During the event, the current meter rotated abruptly at 265° before stabilizing (after 1 h 30 min) at 200°, i.e. downcanyon. It remained then stable between 250° and 300° until the end of the mooring deployment. The pressure also increased abruptly (7 dbar increase from 659.7 to 666.7 dbar) but this increase is based only on one measure. After this short event, the pressure stabilized quickly at 661 dbar, i.e. a value 0.5 dbar higher than previous to the event. As the recorded measure of peak pressure represents the average of four measured values, this suggests that the peak increase of pressure was substantially higher than 7 dbar. After this peak event, the pressure came back to cyclic variations but with a shift of 1.3 dbar when compared to values preceding the event. It finally stabilized with a cyclic variation similar to what happened before the events (amplitude and period of cycles) but cycles were shifted upward to about 0.5 dbar.

Current orientation and current meter heading remained oriented downslope 19 h 30 min after the beginning of the event. During this period, the cyclic variations of these two parameters disappeared and the current speed remained oriented downslope.

Table 4
Time period of variation of current speed from spectral analysis.

	Blackmud	Audierne	Capbreton
Period 1	15 d 18 h 29 min	16 d 10 h 19 min	16 d 22 h 19 min
Period 2	12 h 13 min	12 h 11 min	12 h 33 min

The increase in temperature began exactly at the same time as the other changes in physical parameters but the variation is slower. The temperature increased from 10.9 °C to 11.3 °C in 8 h and reached a peak of 11.4 °C, 16 h after the abrupt change of other parameters.

The combined new data in this study show three main results:

1) No recent sediments are observed in canyons located in the northern part of the Bay of Biscay (Audierne and Blackmud canyons). Conversely, recent sedimentation related to downslope gravity processes are observed in Capbreton Canyon (South of the Bay of Biscaye.
2) At all mooring locations, current meter data show that the canyons are swept by periodic currents with orientation alternating between downslope and upslope. In two cases (Blackmud 1500 m and Capbreton 1500 m water depth), maximum speeds have a downslope orientation. In all other cases, currents with maximum speeds are oriented downslope but upslope currents have high speeds.
3) An acyclic, sedimentary event is recorded sporadically in Capbreton Canyon and overprints the cyclic currents recorded during the mooring period.

5. Discussion

5.1. Recent sediment deposition in the canyons

The core we collected from Blackmud and Audierne canyons showed no recent sedimentation along the canyon floor. In some cases, the corer could not penetrate the indurated surface sediment. The presence of concentrated shell hash in Audierne Canyon cores KS06 and KS 07 (Fig. 4) is also a good indicator of low canyon activity. When cores recovered sediment, the collected sediments show ancient rocky substratum outcrops (KI 11) or overconsolidated sediment interpreted as ancient sediments (ante Holocene). Consistently, no activity of short lifespan radiogenic isotopes has been detected at the top of these cores. These sediments are always coarser than silt suggesting either fine particle did not reach the core location recently, or that fine particles cannot settle because of high-speed currents and have been deposited seaward (by passing) or have been removed by bottom currents after deposition. The present floor of the canyon talweg would thus correspond to a lag deposit. In KI 06 and KI 07, the graded deposits interpreted as turbidites suggest that turbidity currents occurred in the past in Blackmud and Audierne canyons. However, at present, no sediment is deposited along the canyon floor. Turbidity currents might still occur but in this case, they are either not depositional or their deposits are eroded by more energetic hydrodynamic processes. In addition, Gaudin (2006) showed that no recent (Holocene) hemipelagic drape is observed on the canyon floor suggesting that high-energy processes exist and remove hemipelagites or prevent their deposition. Audierne and Blackmud canyons can thus be considered as inactive canyons or active canyons with little or no modern sedimentation or by passing areas, with the small sediment supply prevented from deposition because of the strong permanent currents bathing the canyon floor.

In Capbreton Canyon, $^{210}Pb_{ex}$ activity in KI 20, 21, 22 and 32 (age < 100 yrs; Table 1; Fig. 4) suggests present high sediment accumulation. This explains why two collected cores have a length close to 1 m

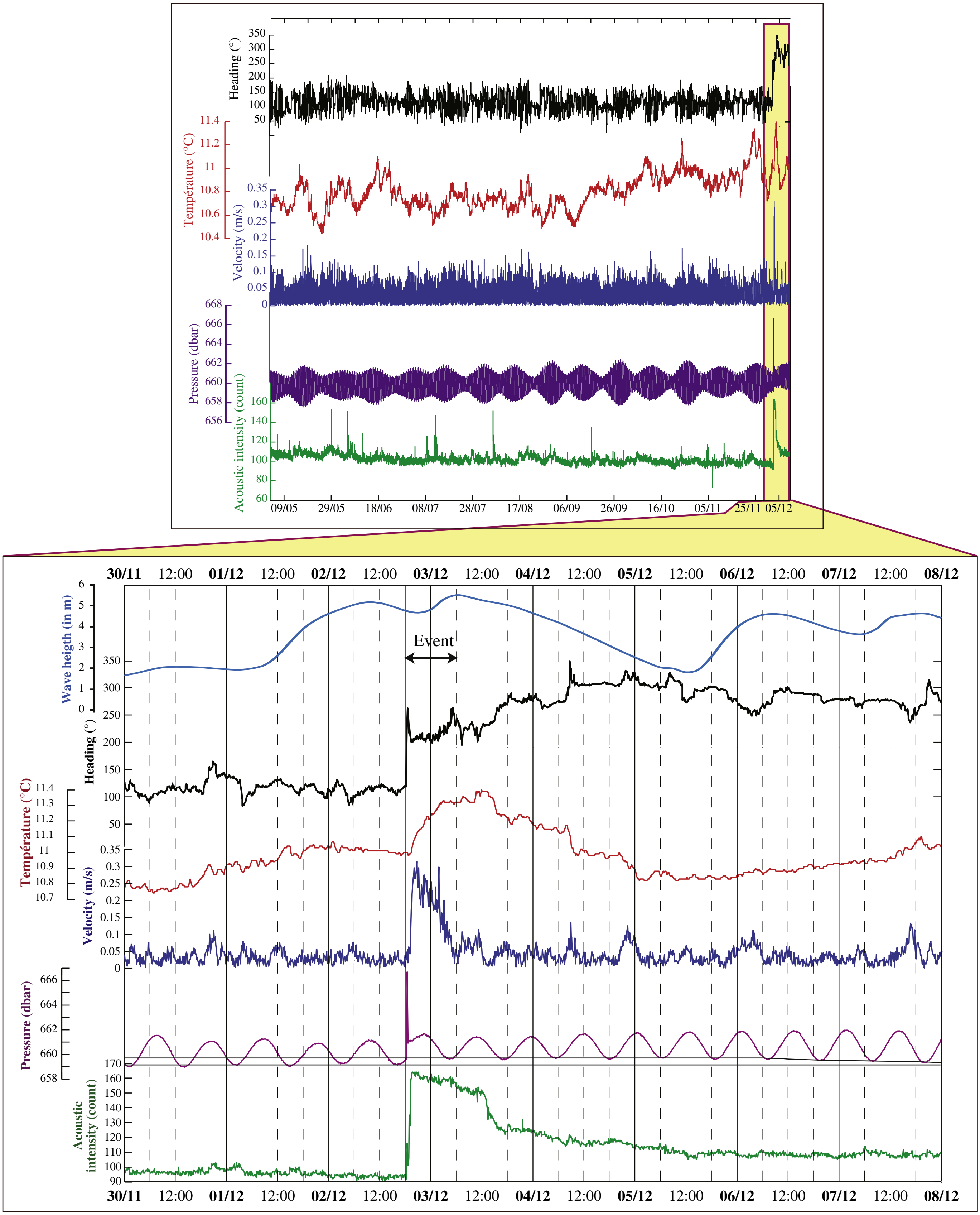


Fig. 7. Hydrological parameters recorded in the Capbreton Canyon at 500 m water depth from 30:11:2007 to 08:12:2007 and showing a particular event on 02:12:2007. Recorded current meter parameters: current meter heading (°), sea water temperature (°), current speed (m/s), water pressure (dbar), acoustic intensity (count). On the enlarged par in bottom, same parameters are figures for the exceptional event duration. The Significant wave height (m) is added at the top to give information on meteorological conditions.

(i.e. the maximum corer length) suggesting the presence of a slightly consolidated sediment on the canyon floor. KI 20, KI 21, KI 22 and KI 32 (Fig. 4) show numerous fining-up beds interpreted as turbidites suggesting that turbidity currents are presently frequent in this canyon. This is consistent with the $^{210}Pb_{ex}$ activity in KI 32 (Fig. 4) that suggests that three turbidites are younger than 100 years. This is also consistent with the results of Mulder et al. (2001) and Chaillou et al. (2003) who demonstrated the high frequency of turbidity currents in the present Capbreton Canyon leading to the deposition of centimeter-thick preserved beds. The presence at the top of cores of a few centimeter-thick brown underconsolidated mud (KI 19, KI 20, KI 21 and KI 22; Fig. 4) suggests that recent hemipelagic deposits are preserved in most part of the canyon. These observations are consistent with the results of Gaudin (2006) who suggested that the Capbreton Canyon act as a sediment trap during Holocene. ^{14}C dating in core MD03-2693 provided age estimates of 775, 1445 and 2390 yrs BP respectively at 350, 1190 and 2280 cm suggesting sedimentation rates varying between 0.45 m/ka and 1.21 m/ka for the last 2390 yrs. Despite the frequency of turbidity currents, sediments are preserved from erosion on the terraces bordering the talweg.

5.2. Tidal activity in the three canyons

In the three canyons, time series of speed records show periodical upcanyon and downcanyon alternations (Fig. 6). Spectral analysis of pressure and current in the three canyons indicate the semi-diurnal M2 and S2 components. In the three canyons, the frequency of currents is correlated to the surface tide frequency. But the current speed is not perfectly associated with the amplitude of surface tides: even if the most intense currents are measured during spring tide periods, some peak current velocities are measured under neap tide conditions. This suggests that the alternative currents measured in the canyons are partially, but not completely, initiated by surface tides to explain the good correlation between cycle frequency but that other parameters are involved to explain the lesser fit for intensities. This difference with the interpretation of Reid and Hamilton (1990) is related to the longer duration of our record. In the Bay of Biscay, one of the hydrodynamic processes induced by surface tides is the generation of internal (baroclinal) tides (Pingree et al., 1986). Whereas tidal currents are generated directly by the surface pressure gradient (barotropic tide), internal tidal currents are generated via tide-topography interactions.

Recent exhaustive analysis of hydrographic data showed the activity of intense internal tidal currents in other submarine canyon, as the Gaoping canyon off southwestern Taiwan (Wang et al., 2008) and in Baltimore Canyon (Gardner, 1989). In the deep Bay of Biscay, Van Haren (2004) examined eleven-month current meter observations. They indicated that year-long current meter records can be insufficient to distinguish between barotropic and persistent or coherent baroclinic motions if the site is near the source of internal tidal wave generation as in the present study. Indeed, Van Haren (2004) showed that the vertical current structure clearly indicated baroclinic motions, despite their persistence with time. The high value of currents observed in this study are believed to be, at least partly, due to internal tides even if the authors agree that other mechanisms (e.g. wind-driven upwelling and downwelling, tidally rectified current (Lam et al., 2004)) may increase the velocity.

5.3. The exceptional event in Capbreton Canyon

The exceptional event recorded on the mooring located at 500 m water depth in Capbreton Canyon in December 3rd, 2007 correlates with bad weather conditions and increased amplitude of waves (from 1.5 m to 5.5 m; Fig. 7). This storm is moderate when compared to the Martin storm in 1999 (wave amplitude was 12 m). The significant wave height suggests that the exceptional event began 1.5 days after the beginning of a storm.

Prior to the event, the periodical upslope/downslope current variations related to internal tides are recorded. The water pressure starts to increase following this cyclic variation 2 h 30 min before the event and the velocities turned from upslope to downslope less than 2 h before the beginning of the event. This suggests that the recorded abrupt physical changes are superimposed to the cyclic upslope/downslope hydrodynamic processes that are recorded in the canyon. Consequently, a process adds to the cyclic variations in current velocities that we related to internal waves. This process is a downslope current because the downslope motion masks the cyclic upslope/downslope motion related to internal waves during more than 18 h. In addition, several parameters vary simultaneously, consistently with the triggering of a downslope gravity process. This downslope process recorded by the current meter is characterized by 1) a sudden increase of the pressure, 2), a change in current meter heading, 3) increased current speed and 4) a steady increase of the water temperature (Fig. 7).

The increase in pressure (7 dbar) could be a technical problem though this is unlikely in the opinion of technical engineers (M. Outré, pers. Comm.). If related to a natural cause, the measured increase in pressure can be the result of three phenomena: (1) a 7 m increase of the water column above the current meter; (2) the deepening of the current meter because of its downslope motion along the seafloor; at this location, a deepening of 7 m in water depth would correspond to a downslope motion along 160 m; and (3) an increase of the mean water density. The increase of the thickness of the water column (process 1) could be related to an absolute increase of the water height but the generated excess pressure is completely attenuated at this water depth. Downslope motion of the current-meter (process 2) is possible because the mooring is light, particularly if taking into account the negative buoyancy due to the submersion. However, in-situ measurements of velocity structures within turbidity current suggest that the maximum flow velocity is at ~10 m above the seafloor (Xu et al., 2004; Xu, 2010). Using these results, velocities along seafloor during the peak conditions of the exceptional event were probably lower than 0.33 m/s. If the mooring has been dragged along the seafloor, the motion was probably steady and slow because during the event, both the pitch and the roll of the current meter remain stable (the maximum inclination during the event is 0.6°). However, if the 7 dbar is not related to the deepening of the mooring, the residual 0.5 dbar remaining after the event could be related to a sliding of the mooring down canyon. The 0.5 dbar increase suggests a slide along about 12 m which is a realistic value considering the low current speed.

The instantaneous 7 dbar increase in pressure measured by the current meter can thus be related either to an increase in water density or to dynamic pressure. As it is impossible to quantify the dynamic pressure effect, and to calculate the remaining effect of water densification resulting of the arrival of the sedimentary process, we compared our measured data to similar referenced events. For similar events, Xu et al. (2010) estimated SSC values between 0.73 and 2.25 g/l. De Stigter et al. (2011) provide SPM values in the same range (5 to 0.5 g/l from bottom to top, respectively) for turbidity currents measured in the Nazaré Canyon. Such values would provide an increase in pressure in the range of a dbar, depending of the flow thickness. Such concentrations are realistic to maintain flow concentrations high enough to sustain a downflow motion energetic enough to balance cyclic motion (and reversal-upslope) flows during 18 h. After 18 h, flow concentration and momentum decreased to allow reversal motion to occur.

This interpretation is also consistent with the change in heading value. The density current temporarily presses the mooring downward and tilted it causing a change in the heading, potentially generating a dynamic pressure increasing substantially the measured values. At this moment, the mooring may have been steadily dragged along the seafloor over a few meters. The slide of the mooring is also consistent with the permanent change in the heading of the current. The short duration of the phenomenon corresponds to the turbulent surge of Ravenne and Beghin (1983), i.e. a short duration unsteady turbulent flow leading to small or no deposition. The record of the event only at 500 m water depth (and not at 1500 m) is consistent with a very small magnitude event (surge rather than turbidity current) that corresponds to a densification of the nepheloid layer. The increase of temperature suggests that warm surface water was present in the density current and that the source of the event is located close to the canyon head (50 m water depth) consistently with plunging sediment-laden water because of the intensification of the longshore drift. The type of event recorded in Capbreton Canyon is very similar to the processes described in Nazaré Canyon (de Stigter et al., 2007), also located on the Atlantic margin with a canyon head located close to the shore. There, intensification of hydrodynamic processes during storms also favours sediment transfer through gravity flow processes.

This set of observations is also consistent with recent investigations on two submarine canyons in southern California (Xu et al., 2010). Turbidity currents were recorded through ADCP and CTD, showing similar abrupt changes in temperature, velocity and acoustic backscatter (related to suspended sediment concentration).

The process is interpreted as a low concentration turbulent surge meaning localized, short duration turbidity current. Following Normark and Piper (1991), this surge could be initiated by (1) a hyperpycnal flow; (2) a slide at canyon head and (3) hydrodynamic processes.

The present lack of connection between the Adour River and the head of the canyon suggests that no hyperpycnal-river-fed-hyperpycnal flow occurs. The presence of fresh abundant slump scars in the canyon head (Gaudin et al., 2006) suggests small slope failures, probably related to the small interstitial overpressure resulting from the increased wave height (wave-load liquefaction of Puig et al. (2004)). However, the increase of the sea-water temperature measured at the mooring site and the relatively low estimated sediment concentration are more consistent intensifications of hydrodynamic processes on the inner continental shelf rather than with a sediment failure. The triggering of the exceptional event with stormy condition, although a moderate storm is also consistent with a triggering related to the intensification of hydrodynamic processes. These processes include (1) the increase of the longshore drift and (2) the dissipation of the water bulge and the intensification of the nepheloid layer.

This turbulent surge can be considered either as a simple increase of the concentration (or thus speed) of the nepheloid layer or as an intensification of the longshore drift and the plunging of sediment-laden water in the shallow canyon head. This increase could be due to the moderate storm that began the December 1st. The intensification of the nepheloid layer could then be related to the dissipation of the 0.7 m bulge that formed during this storm. Sediment might come either from canyon head or by reworking of shelf sediment (Xu et al., 2010) and by intensification of the longshore drift. The late between the surface process and the record of the hydrodynamic processes in the canyon is consistent with this interpretation. It suggests that at least 1.5 days are necessary to transfer energy in surface to hydrodynamic processes in the canyon. During its dissipation the bulge flows naturally by gravity through the Capbreton Canyon. It can intensify the speed of the nepheloid layer, erode and entrain soft, underconsolidated surface sediment or generate small-scale slumps that increase the suspended sediment concentration and increase the driving force and flow speed. The surge could also be related to the intensification of the longshore drift during the storm. It would product both acceleration and a densification of the nepheloid layer similar to what we described for bulge dissipation.

Such an exceptional event plays a key role of downslope transfer of sediment in the canyons. During most of the time (fair-weather conditions), sediments are trapped in the canyon and submitted to upward/downward motion related to internal tides. Sediments are transported downslope during gravity events. Because the event we record was too small to transfer sediment deeper than 1500 m water depth, we can assume that sediment purge from the canyon occurs only during large magnitude gravity events.

This kind of behaviour seems to be widespread and adds to the dataset already published on the Californian canyons: Eel Canyon (Puig et al., 2003, 2004) Monterey (Xu et al., 2004) and Hueneme and Mugu (Xu et al., 2010).

5.4. Comparison of Canyon sedimentation between northern and southern part of the Bay of Biscaye

For the two canyons located in the northern part of the Bay of Biscay, the location of canyon heads is presently far away from any sediment source. This suggests that probably a very little volume of sediments is supplied in canyons by downslope gravity processes. During the present highstand, only exceptional storms can affect and mobilize sediment located close to the continental shelf break, i.e. close to canyon heads to trigger turbidity current. The main sedimentation in canyons is presently the hemipelagic fall out. This small sediment supply might not even settle as it is remobilised by the strong cyclic currents initiated by internal waves that have a particular high energy in this open part of the Bay of Biscay. Main activity of these canyons probably occurs during relative sea-level lowstand, when the sediment supply from the outer shelf is increased and the Channel River is active. They are just relict structures during highstands.

The sedimentation in the Capbreton Canyon is drastically different. Because the head is located very close to the coastline, it is supplied by turbidity currents generated during storms, probably because of the intensification of the longshore drift and/or the dissipation of the coastal bulge. Because the canyon is located in the most protected part of the Bay of Biscay, the energy of internal wave is low and the sediment deposited both by turbidity currents and by the hemipelagic fall out is not remobilized. Sedimentation is preserved explaining the measured local high sedimentation rates in the most protected areas (terraces). The behaviour of this canyon seems to be very close to the behaviour of the Nazaré, Lisbon-Setubal and Cascais submarine canyons (De Stigter et al., 2007, 2011) located also along the Atlantic margin. Because of this incising head, these canyons maintain a sedimentary activity as a sediment trap during sea level high stand. However, the canyon activity during present is probably different from what it is during lowstand, in particular with a lesser turbidite activity.

This set of three examples suggests that canyon activity during highstands is dominated by deep sea hydrodynamic processes. Turbidite activity is only possible during highstand if the canyon head reaches the shallow water area close to the coast. The canyon can help them capture the particles supplied by rivers, longshore longshore drift or other shallow hydrodynamic process on the inner continental shelf.

6. Conclusions

These combined core and current meter records in three canyons of the Bay of Biscay show that:

1) Canyons located in the North Part of the Bay of Biscay (Blackmud and Audierne) have no recent sedimentary deposit suggesting present erosion of by-passing. Conversely, Capbreton Canyon, located in the southern part, show a significant recent sedimentary record.
2) The three canyons of the Bay of Biscay show a permanent current activity (low-intensity currents). These currents show a periodical alternation between a downcanyon and upcanyon motion.
3) Current intensity is highly variable between canyons located in the North of the Bay of Biscay (Audierne and Blackmud canyons) and in the South (Capbreton Canyon). Audierne and Blackmud canyons show high-speed currents explaining why no recent

sediments are trapped on the canyon floor. Conversely, current velocities measured along Capbreton Canyon floor are low. This is consistent with the fact that this canyon acts as a trap for sediments during Holocene. Sediments are mainly accumulated on terraces acting as nested levees as suggested by the high sedimentation rate (1 m/ky) published by Gaudin et al. (2006).

4) Currents measured in the three canyons show periodically variations related to the semi-diurnal periods M2 and S2.
5) The intensity of currents is not perfectly correlated to surface tide. It seems to be correlated to internal tides that are only related in part to surface tides. The transfer of motion from surface to canyon needs 1.5–2 days. The influence of internal tide is more intense in the north part of the Bay of Biscay, open on the ocean, rather than in the most restricted southern part of the Bay of Biscay.
6) The motion related to permanent, low intensity currents can be oriented either downcanyon or upcanyon. This suggests that sediment particles should be trapped in theses canyons if no exceptional hydrodynamic or sedimentary events occur.
7) An exceptional hydrodynamic and sedimentary event has been recorded in Capbreton canyon along the recording period. It is related to a low-density turbulent surge triggered either by a small slope failure in the canyon head or more probably by the dissipation of a water bulge and/or the intensification of the longshore drift formed after a moderate storm that began 1.5 days earlier, and the concomitant acceleration and density increase of the nepheloid layer. However, such a low magnitude event is unlikely to generate substantial deposit preserved in the sedimentary series. This suggests that this kind of event is frequent in Capbreton Canyon and this is consistent with the numerous recent turbidite beds collected in the interface cores. It is consistent with the frequency of such turbulent surge (1 event every 10 years) extrapolated after the 1999 in the canyon. It also explains both the rapid growth of the terraces and the permanence of the freshness of the canyon walls during the present sea level highstand.
8) The behaviour of the canyon is different according to their connection to the coast. Canyon with no connection during present Holocene highstand (Blackmud, Audierne) show little sediment accumulation while canyons with a direct connection to shallow coastal water have a larger sediment flux and accumulation during Holocene.

Acknowledgements

Authors thank the SHOM/GOA hydrographers, the Captain and the crew members of the Sedymane cruise on the RV Pourquoi-Pas?. UMR 5805 EPOC contribution number 1748. The authors also thank an anonymous reviewer and Dr. Joshu Mountjoy for their constructive comments during the review process.

References

Apprioual, R., 2001. Conception d'un carottier interface. Rapport Ifremer DRO/GM. (22 pp.).

Auffret, G., Zaragosi, S., Voisset, M., Droz, L., Loubrieu, B., Pelleau, P., Savoye, B., Bourillet, J.-F., Baltzer, A., Bourquin, S., Unterseh, S., Dennielou, B., Coutelle, A., Weber, N., Floch, G., 2000. Premières observations sur la morphologie et les processus sédimentaires récents de l'Eventail celtique. Oceanologica Acta 23 (1), 109–116.

Babonneau, N., Savoye, B., Cremer, M., Bez, M., 2004. Multiple terraces within the deep incised Zaire Valley (ZaiAngo Project): are they confined levees? In: Lomas, S., Joseph, P. (Eds.), Confined Turbidite Systems: Geol. Soc., London, Spec. Publ., 222, pp. 91–114.

Berthois, L., Brenot, R., 1960. La morphologie sous-marine du talus et du plateau continental entre le sud de l'Irlande et le Cap Ortegal (Espagne). Journal du Conseil International pour l'Exploration de la Mer 25 (2), 111–114.

Boillot, G., Dupeuble, P.A., Hennequin-Marchand, I., Lamboy, M., Leprêtre, J.-P., 1973. Carte géologique du plateau continental nord-espagnol entre le canyon de Capbreton et le canyon d'Aviles. Bulletin de la Société Géologique de France 7, 367–391.

Boillot, G., Dupeuble, P.A., Hennequin-Marchand, I., Lamboy, M., Leprêtre, J.-P., Musellec, P., 1974. Le rôle des décrochements "tardi-hercyniens" dans l'évolution structurale de la marge continentale et dans la localisation des grands canyons sous-marins à l'ouest et au nord de la péninsule ibérique. Revue de Géographie Physique et de Géologie Dynamique XVI (2), 75–86.

Boillot, G., Dupeuple, P.A., Malod, J., 1979. Subduction and tectonics on the continental margin off northern Spain. Marine Geology 32, 53–70.

Bourgoin, J., Reyre, D., Magloire, P., Krichewsky, M., 1963. Les canyons sous-marins du Cap Lopez (Gabon). Cahiers Oceanographiques 6, 372–387.

Bourillet, J.-F., Lericolais, G., 2003. Feeder systems of the fans. Morphology and seismic stratigraphy of the Manche Paleoriver system, Western approaches. In: Mienert, J., Weaver, P.P.E. (Eds.), European Margin Sediment Dynamics, Side-Scan Sonar and Seismic Images. Springer Verlag, New York, pp. 229–238.

Bourillet, J.-F., Zaragosi, S., Mulder, T., 2005. The French Atlantic margin and the deep sea submarine systems. Deep-sea turbidite systems on French margin. In: Mulder, T. (Ed.), Deep-Sea Turbidite Systems on French Margins: Geo-Marine Lett., Spec. Issue, 26(6), pp. 311–316.

Canals, M., Puig P., Durrieu de Madron, X, Heussner, S., Palanques, A., Fabres, J., 2006. Flushing submarine canyons. Nature, 444, 354–357.Chaillou, G., 2003. La dynamique biogéochimique des espèces rédox dans les sédiments modernes du Golfe de Gascogne. PhD thesis, Univ. Bordeaux 1, 281 pp.

Canals, M., Danovaro, R., Heussner, S., Lykousis, V., Puig, P., Trincardi, F., Calafat, A.M., Durrieu de Madron, X., Palanques, A., Sánchez-Vidal, A., 2009. Cascades in Mediterranean submarine grand canyons. Oceanography 22 (1), 26–43.

Chaillou, G., Schäfer, J., Anschutz, P., Lavaux, G., Blanc, G., 2003. The behaviour of Arsenic in the muddy sediments of the Bay of Biscay (France). Geochimica et Cosmochimica Acta 67, 2993–3003.

Chaillou, G., Schäfer, J., Blanc, G., Anschutz, P., 2008. Mobility of Mo, U, As, and Sb within modern turbidites. Marine Geology 254, 171–179.

Cirac, P., Bourillet, J.-F., Griboulard, R., Normand, A., 2001. Le canyon de Capbreton: nouvelles approches morphostructurales et morphosédimentaires. Premiers résultats de la campagne Itsas: Canyon of Capbreton: New morphostructural and morphosedimentary approaches. First results of the ITSAS cruise. Comptes Rendus de l' Academie des Sciences, Paris Series IIA E332, 447–455.

Cremer, M., 1983. Approches sédimentologiques et géophysiques des accumulations turbiditiques. L'éventail profond du Cap-Ferret (Golfe de Gascogne), La série des grès d'Annot (Alpes de Haute Provence). Thèse d'état, Univ. Bordeaux 1, 344 pp.

Cunningham, M.J., Hodgson, S., Masson, D.G., Parson, L.M., 2005. An evaluation of along- and down-slope sediment transport processes between Goban Spur and Brenot Spur on the Celtic Margin of the Bay of Biscay. Sedimentary Geology 179, 99–116.

De Stigter, H.C., Boer, W., de Jesus Mendes, P.A., Jesus, C.C., Thomsen, L., van den Bergh, G.D., van Weering, T.C.E., 2007. Recent sediment transport and deposition in the Nazaré Canyon, Portuguese continental margin. Marine Geology 246, 144–164.

De Stigter, H.C., Jesus, C.C., Boer, W., de Jesus Mendes, Richter, T.O., Costa, A., van Weering, T.C.E., 2011. Recent sediment transport and deposition in the Lisbon-Setubal and Cascais submarine canyons, Portuguese continental margin. Deep Sea Research Part II: Topical Studies in Oceanography 58 (23–24), 2321–2344.

Durrieu de Madron, X., Castaing, P., Nyffeler, F., Courp, T., 1999. Slope transport of suspended particulate matter on the Aquitanian margin of the Bay of Biscay. Deep Sea Research 2 (46), 2003–2027.

Froidefond, J.-M., Castaing, P., Weber, O., 1983. Evolution morpho-sédimentaire de la tête du canyon de Capbreton d'après les cartes de 1860 et de 1963, utilisation des méthodes informatiques. Bulletin de la Société Géologique de France XXV, 705–714.

Gardner, W.D., 1989. Periodic resuspension in Baltimore Canyonby focusing of internal waves. Journal of Geophysical Research 94 (C12), 18185–18194.

Garlan, T., 2004. Apports de la modélisation dans l'étude de la sédimentation marine récente HDR thesis, Université d'Angers, 175 pp, 7 annexes.

Gaudin, M., 2006. Processus et enregistrements sédimentaires dans les canyons sous-marins Bourcart et de Capbreton durant le dernier cycle climatique. PhD thesis, Univ. Bordeaux 1, no 3322, 296 pp.

Gaudin, M., Mulder, T., Cirac, P., Berné, S., Imbert, P., 2006. Past and present sedimentary activity in the Capbreton Canyon, southern Bay of Biscay. In: Mulder, T. (Ed.), Deep-Sea Turbidite Systems on French Margins: Geo-Marine Lett., Spec. Issue, 26(6), pp. 331–346.

Gennesseaux, M., Guibout, P., Lacombe, H., 1971. Enregistrement de courants de turbidité dans la vallée sous-marine du Var (Alpes-Maritimes). Comptes Rendus de l' Academie des Sciences, Paris 273, 2456–2459.

Gennesseaux, M., Mauffret, A., Pautot, G., 1980. Les glissements sous-marins de la pente continentales niçoise et la rupture de câbles en mer Ligure (Méditerranée occidentale). Comptes Rendus de l' Academie des Sciences, Paris 290, 959–962.

Gouleau, D., Jouanneau, J.-M., Weber, O., Sauriau, P.G., 2000. Short term, long term sedimentation on Montportail-Brouage intertidal mudflat, Western side of Marennes Oléron Bay (France). Continental Shelf Research 20, 1513–1530.

Heezen, B.C., Ewing, M., 1952. Turbidity currents and submarine slumps, and the 1929 Grand Banks earthquake. Am. J. Sci. 250, 849–873.

Hughes-Clarke, J.E., Shor, A.N., Piper, D.J.W., Mayer, L.A., 1990. Large-scale current-induced erosion and deposition in the path of the 1929 Grand Banks turbidity current. Sedimentology 37, 613–629.

Hughes-Clarke, J.E., O'Leary, D., Piper, D.J.W., 1992. The relative importance of mass wasting and deep boundary current activity on the continental rise off western Nova Scotia. In: Poag, C.W., de Graciansky, P.C. (Eds.), Geologic Evolution of Atlantic Continental rises. Van Nostrand Reinhold, New York, pp. 266–281.

Inman, D.L., 1970. Strong currents in submarine canyons. Abstracts, Transactions of the American Geophysical Union 51, 319.

Jézéquel, N., Mazé, R., Pichon, A., 2002. Interaction of semidiurnal tide with a continental slope in a continuously stratified ocean. Deep Sea Research 49, 707–734.

Jouanneau, J.-M., Garcia, C., Oliveira, A., Rodrigues, A., Dias, J.A., Weber, O., 1988. Dispersal and deposition of suspended sediment on the shelf off the Tagus and Sado estuaries, SW Portugal. Progress in Oceanography 42 (1–4), 233–257.

Kenyon, N.H., Belderson, R.H., Stride, A.H., 1978. Channels, canyons and slump folds on the continental slope between South-West Ireland and Spain. Oceanologica Acta 3, 369–380.

Khripounoff, A., Vangriesheim, A., Babonneau, N., Crassous, P., Dennielou, B., Savoye, B., 2003. Direct observation of intense turbidity current activity in the Zaire submarine valley at 4000 m water depth. Marine Geology 194, 151–158.

Kuenen, P.H., 1952. Estimated size of the Grand Banks turbidity current. American Journal of Science 250, 849–873.

Lam, F.P.A., Maas, L.R.M., Gerkema, T., 2004. Spatial structure of tidal and residual currents as observed over the shelf break in the Bay of Biscay. Deep-Sea Research I 51, 1075–1096.

Le Cann, B., 1990. Barotropic tidal dynamics of the Bay of Biscay shelf: observations, numerical modelling and physical interpretation. Continental Shelf Research 10 (8), 723–758.

Le Suavé, R., 2000. Synthèse Bathymétrique et Imagerie Acoustique. Zone économique exclusive (ZEE). Brest, Editions IFREMER, Atlantique Nord-Est.

Lee, I.-H., Lien, R.C., Liu, J.T., Chuang, W., 2009. Turbulent mixing and internal tides in Gaoping (Kaoping) submarine canyon, Taiwan. Journal of Marine Systems 76, 383–396.

Migeon, S., Weber, O., Faugères, J.-C., Saint-Paul, J., 1999. SCOPIX: a new X-ray imaging system for core analysis. Geo-Marine Letters 18, 251–255.

Mulder, T., Weber, O., Anschutz, P., Jorissen, F.J., Jouanneau, J.-M., 2001. A few months-old storm generated turbidite deposited in the Capbreton Canyon (Bay of Biscay, SW France). Geo-Marine Letters 21, 149–156.

Mulder, T., Cirac, P., Gaudin, M., Bourillet, J.-F., Tranier, J., Normand, A., Weber, O., Griboulard, R., Jouanneau, J.-M., Anschutz, P., Jorissen, F.J., 2004. Understanding continent-ocean sediment transfer. Eos, Transactions of the American Geophysical Union 85 (27), 261–262 (257).

Normark, W.R., Piper, D.J.W., 1991. Initiation processes and flow evolution of turbidity currents: implications for the depositional record. SEPM Special Publication 46, 207–229.

Pairaud, I.L., Lyard, F., Auclair, F., Letellier, T., Marsaleix, P., 2008. Dynamics of the semi-diurnal and quarter-diurnal internal tides in the Bay of Biscay. Continental Shelf Research 28 (10–11), 1294–1315.

Palanques, A., Durrieu de Madron, X., Puig, P., Fabres, J., Guillen, J., Calafat, A., et al., 2006. Suspended sediment fluxes and transport processes in the Gulf of Lions submarine canyons. The role of storms and dense water cascading. Marine Geology 234, 43–61.

Palanques, A., Puig, P., Latasa, M., Scharek, R., 2009. Deep sediment transport induced by storms and dense shelf-water cascading in the northwestern Mediterranean basin. Deep Sea Research Part I: Oceanographic Research Papers 56, 425–434.

Pichon, A., Correard, S., 2006. Internal tides modelling in the Bay of Biscay. Comparisons with observations. Oceanography of the Bay of Biscay 70S1 (Suppl. 1), 65–88.

Pingree, R.D., Mardell, G.T., New, A.L., 1986. Propagation of internal tides from the upper slopes of the Bay of Biscay. Nature 321, 154–158.

Pratson, L.F., Ryan, W.B.F., Mountain, G.S., Twichell, D.C., 1994. Submarine canyon initiation by downslope-eroding sediment flows: evidence in late Cenozoic strata on the New Jersey continental slope. Geological Society of America Bulletin 106, 395–412.

Puig, P., Ogston, A.S., Mullenbach, B.L., Nittrouer, C.A., Sternberg, R.W., 2003. Shelf-to-canyon sediment-transport processes on the Eel continental margin (northern California). Marine Geology 193, 129–149.

Puig, P., Ogston, A.S., Mullenbach, B.L., Nittrouer, C.A., Parsons, J.D., Sternberg, R.W., 2004. Storm-induced sediment gravity flows at the head of the Eel submarine canyon, northern California margin. Journal of Geophysical Research 109, C03019. doi:10.1029/2003JC001918.

Ravenne, C., Beghin, P., 1983. Apport des expériences en canal à l'interprétation sédimentologique des dépôts de cônes détritiques sous-marines. Revue. Institut Français du Pétrole 38, 279–297.

Reading, H.G., Richard, M.T., 1994. The classification of deep-water siliciclastic depositional systems by grain size and feeder systems. AAPG Bulletin 78, 792–822.

Reid, G.S., Hamilton, D., 1990. A reconnaissance survey of the Whittard Sea Fan, South-western Approaches, British Isles. Marine Geology 69–86.

Salles, T., 2006. Modélisation numérique du remplissage sédimentaire des canyons et chenaux sous-marins par approche génétique. Unpubl. Ph.D. thesis, Univ. Bordeaux 1, no. 3254, 215 pp.

Salles, T., Mulder, T., Gaudin, M., Cacas, M.C., Lopez, S., Cirac, P., 2008. Simulating the 1999 Capbreton canyon turbidity current with a Cellular Automata model. Geomorphology 97, 516–537.

Serpette, A., Le Cann, B., Colas, F., 2006. Lagrangian circulation of the North Atlantic Central Water over the abyssal plain and continental slopes of the Bay of Biscay: description of selected features. Oceanography of the Bay of Biscay 70S1 (Suppl. 1), 27–42.

Shanmugam, G., 2003. Deep-marine bottom currents and their reworked sans in modern and ancient submarine canyons. Marine and Petroleum Geology 20, 471–491.

Shepard, F.P., 1981. Submarine canyons: multiple causes and long-time persistence. AAPG Bulletin 65 (6), 1062–1077.

Shepard, F.P., Dill, R.F., 1966. Submarine Canyons and Other Sea Valleys. Rand McNally Comp, Chicago. (381 pp.).

Shepard, F.P., Marshall, N., McLoughlin, P.A., 1974. “Internal waves” advancing along submarine canyons. Science 183 (4121), 195–198. doi:10.1126/science.183.4121.195.

Shepard, F.P., McLoughlin, P.A., Marshall, N.F., Sullivan, G.G., 1977. Current-meter recordings of low-speed turbidity currents. Geology 5, 297–301.

Sverdrup, H.U., 1942. Oceanography for Meteorologists. Prentice Hall, New York. (246 pp.).

Thinon, I., 1999. Structure profonde de la Marge Nord-Gascogne et du Bassin Armoricain. Thèse $3^{\text{ème}}$ cycle, Université de Bretagne Occidentale, Brest.

Toucanne, S., 2008. Reconstruction des transferts sédimentaires en provenance du système glaciaire de Mer d'Irlande et du paléo-fleuve Manche au cours des derniers cycles climatiques. PhD thesis, Univ. Bordeaux 1, 340 pp.

Toucanne, S., Zaragosi, S., Bourillet, J.F., Cremer, M., Eynaud, F., Van Vliet-Lanoë, B., et al., 2009. Timing of massive ‘fleuve Manche’ discharges over the last 350 kyr: insights into the European ice-sheet oscillations and the European drainage network from MIS 10 to 2. Quaternary Science Reviews 28 (13–14), 1238–1256.

Twichell, D.C., Roberts, D.G., 1982. Morphology, distribution, and development of submarine canyons on the United States Atlantic continental slope between Hudson and Baltimore canyons. Geology 10, 408–412.

Van Haren, H., 2004. Incoherent internal tidal currents in the deep ocean. Ocean Dynamics 54, 66–76.

Wang, Y.H., Lee, I.H., Liu, J.T., 2008. Observation of internal tidal currents in the Kaoping Canyon off southwestern Taiwan. Estuarine, Coastal and Shelf Science 80, 153–160.

Xu, J.P., 2010. Normalized velocity profiles of field-measured turbidity currents. Geology 38 (6), 563–566.

Xu, J.P., Noble, M.A., Rosenfield, L.K., 2004. In-situ measurements of velocity structure within turbidity currents. Geophysical Research Letters 31, L09311. doi:10.1029/2004GL019718.

Xu, J.P., Swarzenski, P.W., Noble, M.A., Li, A.C., 2010. Event-driven flux in Hueneme and Mugu submarine canyons, southern California. Marine Geology 269, 7488.

Zaragosi, S., 2001. Les systèmes turbiditiques profonds de la marge celtique–armoricaine (Golfe de Gascogne): physiographie et évolution au cours des derniers 30 000 ans. Unpubl. PhD thesis, Univ. Bordeaux 1, n° 2264, 291pp.

Zaragosi, S., Auffret, G.A., Faugères, J.-C., Garlan, T., Pujol, C., Cortijo, E., 2000. Physiography and recent sediment distribution of the Celtic Deep-sea Fan, Bay of Biscay. Marine Geology 169, 207–237.

Zaragosi, S., Le Suavé, R., Bourillet, J.F., Auffret, G.A., Faugères, J.-C., Pujol, C., Garlan, T., 2001. The deep-sea Armorican depositional system (Bay of Biscay), a multiple source, ramp model. Geo-Marine Letters 20, 219–232.

Zaragosi, S., Auffret, G.A., Voisset, M., Garlan, T., 2003. Morphology and depositional processes of Celtic Fan, Bay of Biscay. In: Mienert, J., Weaver, P.P.E. (Eds.), European Margin Sediment Dynamics, Side-Scan Sonar and Seismic Images. Springer Verlag, New York, pp. 239–243.