



Near-bottom particulate matter dynamics in the Nazaré submarine canyon under calm and stormy conditions

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ABSTRACT

Two mooring lines equipped with near-bottom sediment traps were deployed in the axis of the Nazaré submarine canyon at ~1600 and ~3300 m depth, respectively. We studied time-series of particle flux, composition (biogenic silica, carbonates, organic matter and lithogenic fractions), granulometry, mineralogy and ²¹⁰Pb concentration of particulate matter over five sediment trap deployments between October 2002 and December 2004. Current meters equipped with turbidimeters were also deployed at trap depths to monitor the water flow, temperature, salinity and suspended particle concentration. The composition of the collected particles was fairly constant year-round, dominated by the lithogenic fraction and with OC/N ratios in the range 11–21, suggesting an important terrigenous influence inside the canyon. The results show contrasting dynamic environments in the upper (1600 m depth) and middle (3300 m depth) canyon. High current speeds (spring tides up to 80 cm s⁻¹) and high apparent mass fluxes of particulate matter (mean 65 g m⁻² d⁻¹; maximum 265 g m⁻² d⁻¹) are permanent at the shallowest station. At the deepest site, fluxes were below 10 g m⁻² d⁻¹ most of the time and the annual flux was governed by events of sharp flux increase. Storms affecting the continental shelf during autumn and winter are a major driver of down-canyon dispersal of sediments to the middle canyon and beyond. Important nepheloid activity developed inside the canyon in response to storms with significant wave heights between 4 and 6 m, as testified by turbidimeters deployed in midwater and near the seabed at 1600 m water depth. On three occasions during the study period, significant wave heights of incident storms surpassed 7 m, leading to notable episodes of down-canyon transport that were clearly observed in the middle canyon. During one of these stormy periods (January 2003) a sediment gravity flow transporting unusual quantities of sand and coastal plant debris was observed at 3200 m. However, a storm with significant wave heights as low as 5 m was apparently able to trigger a sediment gravity flow reaching beyond the middle canyon. The role of storms in the offshore dispersal of sediments is clearly relevant but seems to be modulated by synergic factors such as river flooding.

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1. Introduction

In comparison to non-dissected open margins, steep submarine canyons intersecting the continental shelf offer a faster route for the offshore export of bulk and organic material to the deep sea, with important consequences for issues including climate modulation through the sequestration of atmospheric carbon, the nourishment of deep-sea benthic ecosystems or the fate of pollutants (Pfannkuche, 1993; Puig et al., 1999; Canals et al., 2006). In spite of decreased sediment supply since the Holocene transgression, many contemporary submarine canyons are active sedimentary settings where significant concentration and off-

shelf export of particulate matter takes place (Hickey et al., 1986; Puig and Palanques, 1998; Palanques et al., 2006a; Canals et al., 2006; Martín et al., 2006, 2007). Some canyons remain active owing to their proximity or direct connection to fluvial systems (e.g. Walsh and Nittrouer, 2003; Khripounoff et al., 2003). However, proximity to river mouths is not a prerequisite for canyon activity. On narrow, tectonically active margins, canyon heads cross the continental shelf, intercepting and trapping the sediment transported by along-shore currents, which is delivered to the deep sea by the action of storms, earthquakes, spontaneous sediment destabilization and even human action (Lewis and Barnes, 1999; Mulder et al., 2001; Xu et al., 2004; Palanques et al., 2006a; Martín et al., 2008).

The role of submarine canyons as preferential repositories and offshore conduits of terrestrial particles was one of the main issues addressed by the EUROSTRATAFORM program, the general

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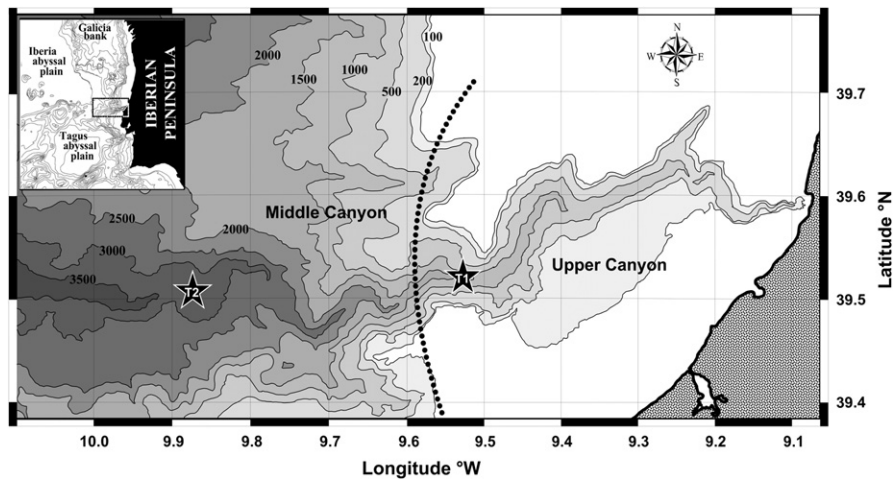


Fig. 1. Bathymetric chart of the Nazaré submarine canyon (modified after Vanney and Mougénot, 1993) and positions of the two moorings (stars). Each mooring carried a near-bottom PPS3/3 sediment trap coupled to a current meter (see text and Table 1 for details).

objective of which was to relate contemporary sedimentary processes to the preservation of sedimentary strata on European continental margins. The Nazaré Canyon, an impressive submarine incision that bisects the full width of the Western Iberian Margin, was selected as a suitable site to study the dynamic processes inside modern submarine canyons. The head of the Nazaré Canyon penetrates deep into the continental shelf, virtually reaching the coastline. As a consequence, and despite the absence of major rivers opening to the adjacent coast, the upper canyon acts as a sink for sediment particles transported by the general southward coastal drift (Oliveira et al., 2007). Evidence for sedimentary activity inside the canyon includes nepheloid layers hundreds of meters thick with particle loads up to 10 mg l^{-1} in the upper canyon (De Stigter et al., 2007) and accumulation rates of bulk and organic matter orders of magnitude higher than those on the open slopes of the West Iberian Margin at similar depths (Van Weering et al., 2002; Van Der Zee et al., 2002). Based on the activities of the short-lived radionuclide ^{234}Th in recent sediments, Schmidt et al. (2001) also confirmed the high contemporary activity of the Nazaré Canyon but were unable to distinguish continuous from pulsed sedimentary inputs. More recent studies have shown an event-driven sedimentary regime inside the canyon (De Stigter et al., 2007; Lastras et al., 2009). Storms have been invoked as a plausible triggering mechanism of major recent down-canyon transport events (Van Weering et al., 2002; Oliveira et al., 2007; De Stigter et al., 2007), although direct observations of such connection are still pending.

In the framework of EUROSTRATAFORM, two mooring lines equipped with near-bottom sediment traps, current meters and turbidimeters were deployed in the axis of the Nazaré Canyon, at 1600 and 3300 m nominal depths, respectively. In this work, we present and discuss results of the composition and apparent fluxes of settling particles collected by sediment traps and the hydrographical and hydrodynamic parameters recorded by current meters between October 2002 and December 2004. The temporal and spatial variability of near-bottom particle flux and composition at the study sites, as well as the role of shelf storms as driving mechanisms for the observed variability, are discussed.

2. Regional setting

2.1. The West Iberian Margin

The continental margin along the western side of the Iberian Peninsula is shaped by a relatively narrow shelf, indented by

several steep submarine canyons. Among them, the Nazaré Canyon (Fig. 1) is the largest and most deeply incised. The hydrography of the water column over the West Iberian Margin is complex (Van Aken, 2000). One of its most distinct features is a salinity maximum at 800–1400 m depth, corresponding to the Mediterranean Sea Outflow Water (MW) (Van Aken, 2000). A strong density gradient is formed between the core of MW and the overlying and underlying water masses, favouring the development of internal waves and the resuspension of fine sediments where these density discontinuities intersect the seafloor (McCave and Hall, 2002).

Over the continental slope, the water flow follows a seasonal pattern related to the Azores high pressure system (Wooster et al., 1976). During summer, the prevailing northern winds promote upwelling conditions along the west Iberian shelf (Fiúza et al., 1982). During winter, southern winds induce poleward flow over the upper slope (Frouin et al., 1990), which in turn promotes downwelling conditions along the Portuguese Margin and likewise in the Nazaré Canyon head. During most of the year, the wind and wave regimes are dominated by north-west swells with moderate significant wave heights between 1 and 4 m that nonetheless result in a significant southward sediment drift. Wave heights above 5 m are often linked to episodic west and southwesterly storms during autumn and winter. Return periods have been estimated as 0.3 years for typical storms and 10 years for major storms reaching significant wave heights $\geq 10 \text{ m}$ (Drago et al., 1998 and references therein; Vitorino et al., 2002a).

2.2. The Nazaré submarine canyon

The Nazaré Canyon has been divided into several regions or domains on the basis of the succession of geomorphologic and dynamic features along the canyon's path, the exact criterion varying with the author. We will hereafter use the original description by Vanney and Mougénot (1993), who divided the Nazaré Canyon into three subunits: upper, middle and lower. The upper canyon stretches from the canyon head to approximately 1700 m depth ($\sim 47 \text{ km}$ offshore) along a sinuous path incised across the Portuguese margin (Fig. 1). The upper canyon axis is typically a V-shaped erosive valley with a mean axial gradient of 3.2%. In the middle canyon (1700–4000 m depth; approximately 50–100 km from the shoreline), entrenchment, slope and sinuosity of the canyon axis decrease downstream in proportion to its increasing width (Vanney and Mougénot, 1993). In the proximal part of the middle canyon course, the canyon axis is still markedly

V-shaped and axial gradients can reach up to 8.2% at some locations. Towards the distal limit of the middle canyon, the axis evolves slowly into a U-shaped valley with a mean bathymetric gradient $\sim 2.9\%$ (Vanne and Mougnot, 1993). Along the canyon lower course (> 4000 m depth), the canyon axis slope decreases progressively from 1.9% to 0.3% till the canyon merges with the Iberian Abyssal Plain at approximately 5000 m depth. More detailed descriptions of the canyon morphology are given by Lastras et al. (2009) and Masson et al. (2011).

The upper canyon has been identified as a temporary reservoir of particles that accumulate until sufficiently high energy conditions promote their transport down canyon (Oliveira et al., 2007). The dynamic setting near the bottom at the upper canyon is very energetic owing to intensified near-bottom tides and internal wave formation (Vitorino et al., 2005). It has been claimed that formation of density flows is the main process responsible for the redistribution of sediments along the canyon (De Stigter et al., 2007). According to De Stigter et al. (2007), only major sediment gravity flows with recurrence periods in the range of centuries can progress to the deepest reaches of the canyon, while the upper and middle canyon are swept by gravity flows at much higher, probably seasonal, frequencies.

3. Materials and methods

3.1. Experimental design and moored instruments

Two sediment traps were deployed 25 m above the bottom (mab) in moorings located at nominal water depths of 1600 m (M1) and 3300 m (M2), along the main axis of the Nazaré Canyon (Fig. 1). The study lasted from October 2002 to December 2004, separated into five consecutive deployments. Traps will be hereafter referred to as T1 (1600 m depth) and T2 (3300 m depth). Due to persistent overfilling, trap T1 was lifted to 50 mab from the third deployment onwards. Geographic positions, bottom depth, distance of traps above the seafloor and sampling dates for each deployment are given in Table 1. The Technicap PPS3/3 traps used in this study consist of cylindro-conical collectors with an aspect ratio = 2.5 (1.0/0.4 m) in its cylindrical part, and an un baffled aperture of 0.125 m². A set of 12 sampling cups filled with a buffered formalin solution (5%, v/v) are replaced at preset intervals by a programmable rotary mechanism.

It must be considered that sediment traps were originally conceived to sample the downward flux of particles at midwaters, and that flux measured by traps deployed near the seafloor may be heavily biased by particles laterally advected or uplifted from the seafloor underneath the trap (see Bonnin et al., 2008 and references therein). As a consequence, the mass fluxes here

reported should not be regarded strictly as a 'downward flux' but rather as the integration of a variety of sources including the settling flux from the water column, resuspension and rebounding (Walsh et al., 1988) from the seafloor, and advection of the bottom nepheloid layer by tides. The term 'apparent flux' rather than 'downward flux' is therefore used hereafter.

Mooring M1 included an Aanderaa current meter RCM-9 at 20 mab. Additional data from RCM-9 units deployed at 300 mab in line M1 were available discontinuously. An RCM-8 Aanderaa current meter was installed at 20 mab in Mooring M2 (Fig. 1). Together with current speed and direction, RCM units recorded pressure, temperature and conductivity. RCM-9s were also equipped with turbidimeters (optical back-scatter sensors), which were calibrated according to Guillén et al. (2000). Sampling interval of current meters/turbidimeters was set to 30 min.

3.2. Processing and analysis of sediment trap samples

Sediment trap samples were treated and subsampled following the procedures described by Heussner et al. (1990). Total mass flux (TMF) was calculated from the sample dry weight, the collecting area of the trap and the sampling interval. Total carbon and nitrogen were measured by high-temperature combustion and detection of the gaseous by-products in a LECO CN-2000 analyzer. For inorganic carbon the samples were decarbonated in a LECO CC-100 module coupled to the CN-2000 that consists of a stirred bath of 6 M HCl (digestion time = 1 min). The released CO₂ was analyzed by the CN-2000 and the inorganic carbon content of the sample back-calculated. Calcium carbonate content was then obtained from inorganic carbon using the molecular mass ratio 8.33, assuming that all inorganic carbon was in the form of calcium carbonate. Organic matter was assumed to be twice the organic carbon content (calculated as the difference between total and inorganic carbon). Biogenic silica was analyzed using a wet-alkaline extraction with Na₂CO₃ following the method by Mortlock and Froelich (1989). The lithogenic fraction was then calculated as the residue of the sample after discounting the contents of biogenic silica, carbonates and organic matter.

Grain-size analysis of sediment trap samples was performed after disaggregation and removal of the biogenic fraction with H₂O₂ (10% v/v) and dispersed using an ultrasonic bath. The grain-size distribution was measured using a laser forward-scattering particle sizer (MALVERN MicroP 2000). Bulk mineralogy of the samples was analyzed by X-ray diffraction (XRD) in non-oriented powders ($< 63 \mu\text{m}$ fraction). The scans were run between 2° and 60° 2 θ in a PANalytical diffractometer using CuK α radiation. For semi-quantitative determination, the criteria recommended by Schultz (1964), Thorez (1976) and Rocha (1993) and retaken by Oliveira et al. (2007) have been followed.

Table 1

Sampling dates, geographical locations and depths of sediment traps deployed in the Nazaré submarine canyon. 'mab' stands for distance of the traps above the seafloor. Mean and maximum current speed, measured by current meters installed 5 m below the traps, are also shown.

Deployment	Sampling dates	Latitude	Longitude	Sampling interval (d)	Depth (m)	mab (m)	Mean speed (cm s ⁻¹)	Max. speed (cm s ⁻¹)
I	09/11/2002–19/11/2002	39°31'22"N	9°31'51"W	10	1630	25	16.6	64.1
II	28/04/2003–22/05/2003	39°31'30"N	9°32'42"W	12	1604	25	25.5	75.3
III	–	39°31'06"N	9°32'52"W	12	1525	50	No data	No data
IV	20/05/2004–17/09/2004	39°31'22"N	9°32'48"W	10	1610	50	26.7	80.7
V	05/11/2004–04/01/2005	39°31'18"N	9°32'50"W	5	1600	50	No data	No data
I	09/11/2002–28/01/2003	39°30'24"N	9°51'44"W	10	3350	25	8.0	30.7
II	16/04/2003–26/08/2003	39°30'18"N	9°52'00"W	12	3270	25	7.4	27.3
III	10/10/2003–03/11/2003	39°30'02"N	9°52'19"W	12	3250	25	7.5	32.5
IV	20/05/2004–17/09/2004	39°30'04"N	9°52'05"W	10	3250	25	8.9	32.5
V	05/11/2004–04/01/2005	39°30'12"N	9°52'16"W	5	3270	25	No data	No data

^{210}Pb concentration of sediment trap samples was measured via its alpha-particle emitting grand-daughter isotope ^{210}Po , assuming secular equilibrium between ^{210}Pb and ^{210}Po . Aliquots of dried and ground trap samples were spiked with ^{209}Po as a yield tracer and then totally digested in a cocktail of HNO_3 and HF . After removal of the acids by evaporation, the polonium isotopes were collected by spontaneous deposition on a silver

disk and counted with a Passivated Implanted Planar Silicon (PIPS) Canberra detector.

3.3. Oceanographic and hydrographical data

Wave data were obtained from an oceanographic buoy maintained by Puertos del Estado (Ministerio de Fomento, Spain) at

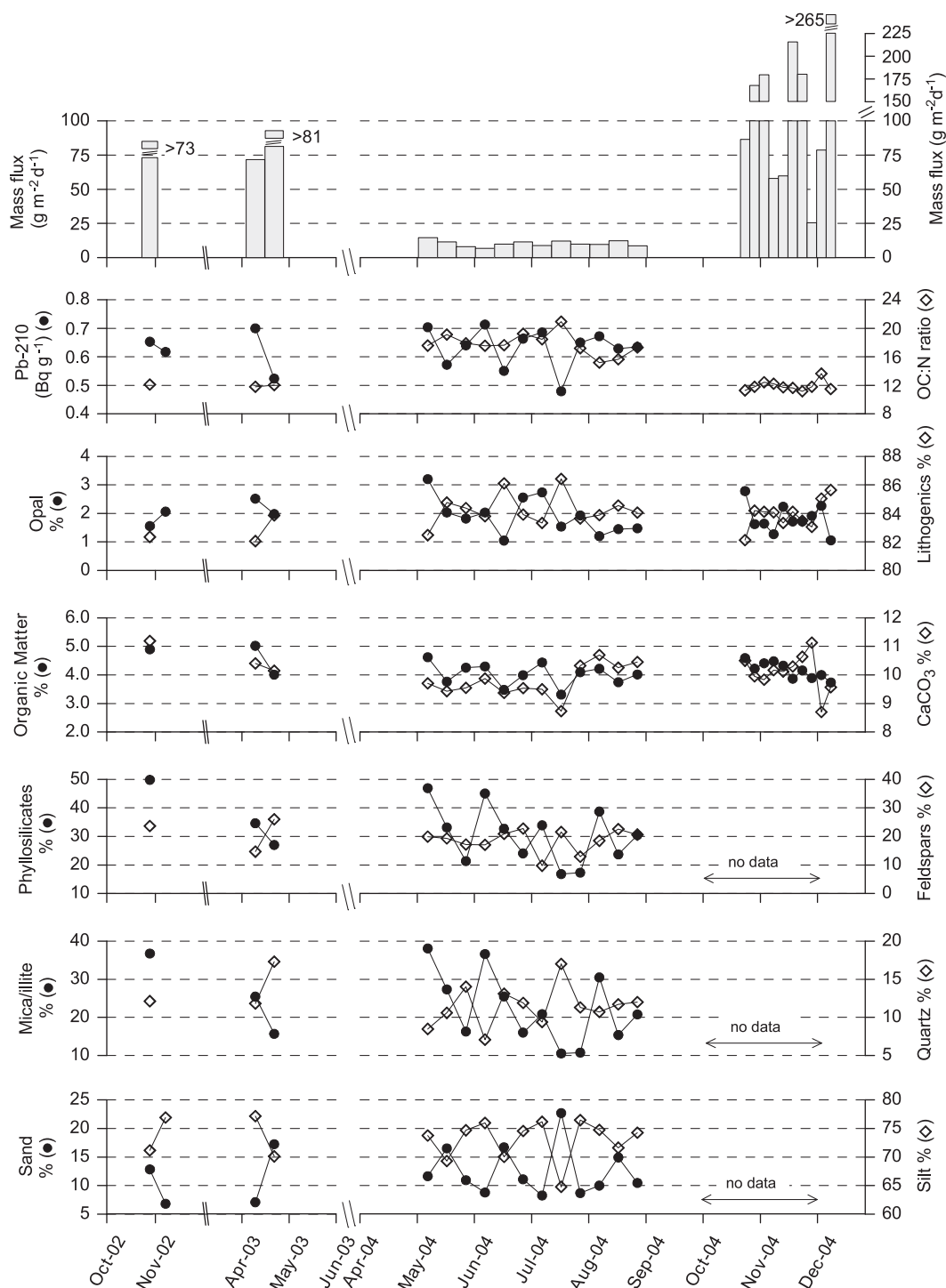


Fig. 2. Time-series of mass flux and major constituents (as percentage dry weight), ^{210}Pb total concentration, mineralogy and granulometry (sand and silt content) of sediment trap samples from trap T1 (1600 m depth). The width of the columns represents the time interval integrated by each sediment trap sample. Episodes of trap overfilling are indicated by broken bars and the minimum flux (the flux measured until the time of overfilling) is reported in $\text{g m}^{-2} \text{d}^{-1}$. The trap was installed at 25 mab during the first and second deployment periods and at 50 mab thereafter. Sampling intervals and other details are shown in Table 1. Feldspars are considered the sum of K-feldspars and plagioclase; the reported phyllosilicates are the sum of chlorite, kaolinite and mica/illite.

Silleiro (43°29.4'N, 9°12.6'W; 386 m bottom depth). Although this buoy is 200 km north from the study area, its records are considered representative of the storms that strike the Iberian Atlantic coast. Additional wave data were obtained from the forecast model Wavewatch III. Monthly discharge of Portuguese rivers was obtained from 'Sistema Nacional de Informação de Recursos Hídricos' (Ministerio do Ambiente, Portugal).

4. Results

Time-series of mass flux, major constituents, grain size and mineralogy of sediment trap samples collected at mooring locations T1 and T2, respectively, are shown in Figs. 2 and 3.

4.1. Bulk mass fluxes

4.1.1. T1 (~1600 m depth)

Although we expected strong active sediment movement in the Nazaré Canyon on the basis of its impressive topography and previously published papers, nonetheless we had underestimated the magnitude of the particle fluxes to be encountered. Sediment trap T1 was overfilled soon after it was put in operation in October 2002, yielding a minimum mass flux of $73.2 \text{ g m}^{-2} \text{ d}^{-1}$. Expecting weaker particle fluxes during spring–summer, the trap was installed again at the same height above the bottom (25 mab) in the second deployment starting on April 2003. To our surprise, the trap was again overfilled before finishing its second sampling period, measuring a (minimum) mass flux of $81.3 \text{ g m}^{-2} \text{ d}^{-1}$. To

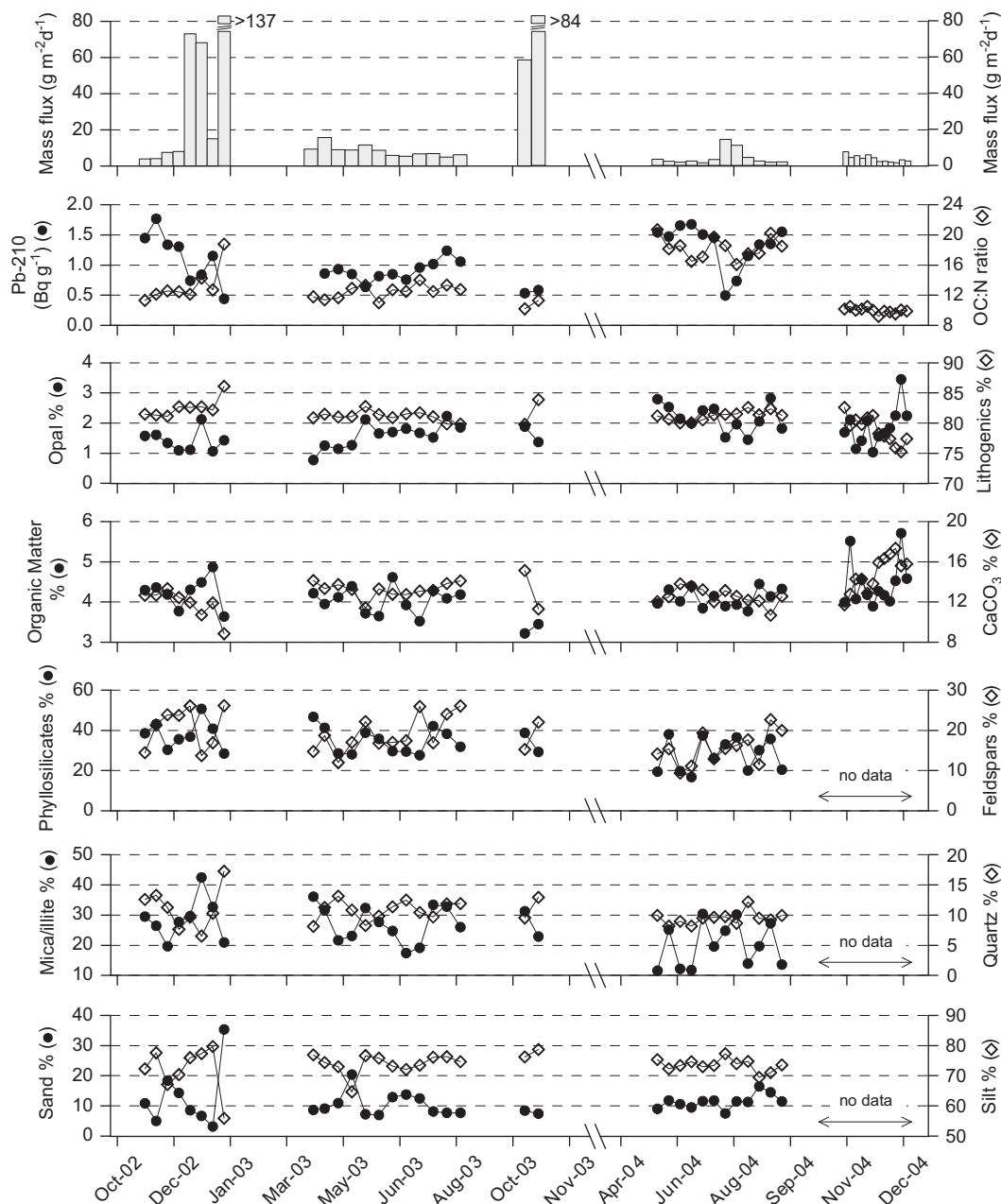


Fig. 3. Time-series of bulk mass flux, major constituents (as percentage dry weight), ^{210}Pb total concentration, selected minerals and sand and silt contents of trap T2 samples (3300 m depth; 25 mab). Trap overfilling episodes are indicated by a broken bar and the minimum flux is reported in units of $\text{g m}^{-2} \text{ d}^{-1}$. Feldspars are considered the sum of K-feldspars and plagioclase; the reported phyllosilicates are the sum of chlorite, kaolinite and mica/illite.

overcome these problems, the trap was lifted from 25 to 50 mab in subsequent deployments. A technical failure prevented the trap from sampling during the third deployment period, but it performed satisfactorily during the fourth and fifth deployments. A range of mass flux from 6.8 to 14.6 g m⁻² d⁻¹ (mean value 10.3 g m⁻² d⁻¹) was measured during the fourth deployment, corresponding to spring–summer 2004. In the fifth deployment (November–December 2004), traps were programmed with higher resolution (5 d interval), in an attempt to catch a glimpse of winter sedimentary dynamics while preventing premature interruptions of the sampling. Fluxes during this last deployment period were notably high, ranging from 30 to more than 250 g m⁻² d⁻¹.

4.1.2. T2 (~3300 m depth)

Mass fluxes at the deepest site were in general lower than at T1 and below 10 g m⁻² d⁻¹ during 75% of the total sampled time. Episodes of sharp increase in particle flux were also recorded at T2 and in two occasions (January and October–November 2003) led to trap overfilling (Fig. 3). The minimum mass fluxes recorded during these two extreme events were 137.4 and 83.9 g m⁻² d⁻¹, respectively. Excluding extreme flux values > 50 g m⁻² d⁻¹, mean settling fluxes were 7.7, 8.2, 4.3 and 4.1 g m⁻² d⁻¹ for the deployments I, II, IV and V, respectively.

4.2. Particulate matter composition

The relative concentrations of the main particulate matter components were fairly homogeneous at both sampling sites over time (Figs. 2 and 3) and thus no seasonal trends were identifiable in the composition of the material collected. The lithogenic fraction dominated the composition, accounting for ~84% and ~82% of the total flux in traps T1 and T2, respectively. Organic matter content of the samples was most of the time below 5% and always below 6%. The time-weighted mean organic matter content was remarkably similar at both traps and equal to 4.2%. It must be noted that organic contents could have been underestimated since all non-disaggregable particles with size > 1 mm were routinely removed from sediment trap samples before organic carbon was analyzed. Organic matter included fragments of coalified wood, as well as plant material (apparently fragments of eelgrass blades) which were relatively abundant in trap samples, particularly in the first overfilled sample of trap T2 (January 2003, Fig. 3). The organic matter present in the analyzed samples had a clear refractory and/or terrigenous imprint as indicated by the high OC/N (atomic) ratios, which ranged from 11.8 to 20.9 at site T1 and from 11.3 to 20.7 at T2. Carbonate contents were remarkably stable in the ranges 8.7–11.2% and 8.8–15.1% for T1 and T2, respectively. Biogenic silica contents were very low during all the deployments at both depths, and in fact close to the reliability limit (~3%) of the analytical method (Mortlock and Froelich, 1989).

4.3. ²¹⁰Pb concentration in settling particles

²¹⁰Pb total concentrations of sediment trap samples are available for deployments I–IV and shown in Figs. 2 and 3 for traps T1 and T2, respectively. A relatively narrow range of ²¹⁰Pb concentrations (479–713 Bq kg⁻¹) was found at T1 (weighed mean = 615 Bq kg⁻¹). At T2, ²¹⁰Pb concentrations ranged from 290 to 1768 Bq kg⁻¹ (weighed mean 1021 mBq g⁻¹). While ²¹⁰Pb at the shallower trap T1 is rather stable with increasing mass flux, at T2 it exhibits a clear decreasing trend that can be adjusted to a power fit (Fig. 4). For settling fluxes below 5 g m⁻² d⁻¹, ²¹⁰Pb concentrations at T2 were higher than 1200 Bq kg⁻¹. Taking into

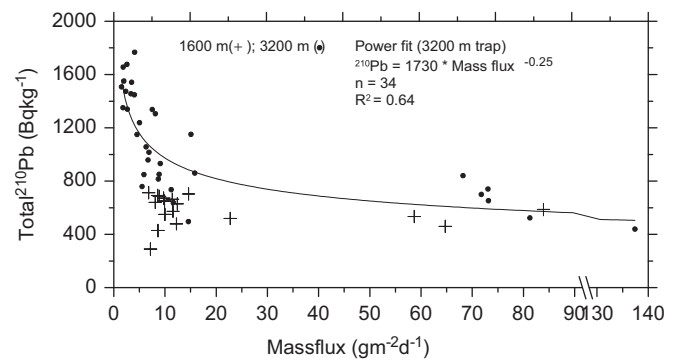


Fig. 4. Relationship between ²¹⁰Pb specific activity and settling particle flux in sediment trap samples from the Nazaré Canyon.

account that total activity of ²¹⁰Pb in surface sediments of the Nazaré Canyon ranges between 200 and 1200 Bq kg⁻¹ (De Stigter et al., 2007), values above 1200 Bq kg⁻¹ suggest a contribution of ²¹⁰Pb produced in the overlying water column from dissolved ²²⁶Ra. On the contrary, for mass fluxes higher than 5 g m⁻² d⁻¹, ²¹⁰Pb concentrations at T2 decline rapidly with increasing mass to a rather stable value ~600 Bq kg⁻¹, similar to the values typical of the shallower trap T1 and indicative of resuspended or reworked old sediments (Fig. 4). There is a potential overestimation of ²¹⁰Pb concentration in the samples from autumn 2004, given that only three ²¹⁰Po half-lives had passed between sampling and analysis. Being a weak beta emitter, the radionuclide ²¹⁰Pb is usually measured by analysis of its gamma-emission or indirectly by alpha-counting its grand-daughter radionuclide ²¹⁰Po. The last approach, used in this study, is valid as long as secular equilibrium between ²¹⁰Pb and ²¹⁰Po has been reached. However, it seems that excess ²¹⁰Po does not pose an important bias to the measurements, based on the fact that ²¹⁰Pb concentrations measured in October 2002 (in secular equilibrium with ²¹⁰Po), were similar to those measured in Autumn 2004 (see Figs. 2 and 3), under similar mass flux.

4.4. Mineralogy and granulometry of sediment trap samples

Mineralogy and grain size data are available for deployments I–IV (Figs. 2 and 3). Silt and clayey silt dominated the grain size distribution of sediment trap samples at both depths throughout the study, although sandy silt and silty sands were also apparent during certain periods. The sandiest sample (35% sand) was collected in January 2003 during the overfilling of trap T2. The fine sediment fraction mineralogy was rather monotonous with the same mineral types recorded during the four useful mooring deployment periods. The particles collected by the sediment traps showed higher mica/illite contents (mean 22%) and lower calcite contents (including calcite Mg), quartz and feldspars than bottom samples collected at nearby locations (Oliveira et al., 2007). There is a clear relationship between the mineralogy of the sediment trap samples and that of shelf sediments, although with increased importance of phyllosilicate minerals, as also found in suspended particulate matter near the seafloor (Oliveira et al., 2007).

4.5. Mean near-bottom currents

Time-series of 30 min-averaged near-bottom currents (rotated to fit the approximate direction of the canyon axis at each location) and temperature during two periods representative of calm conditions (i.e. in the absence of stormy weather or gravity flows) at the two mooring sites are shown in Fig. 5. At M1, this figure also shows suspended sediment concentration (SSC). The

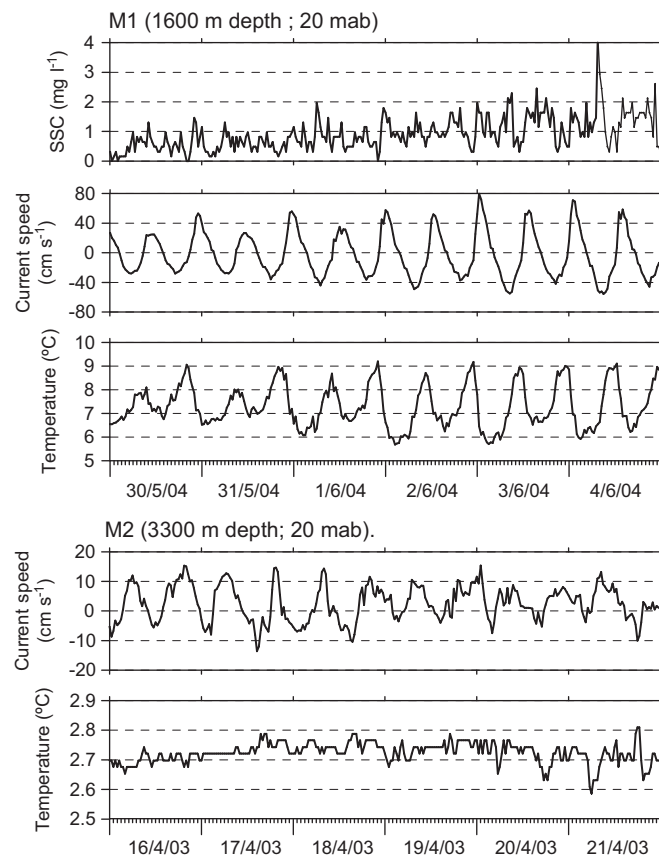


Fig. 5. Time-series of salinity, temperature and current speed recorded 20 m above bottom at sites M1 (top) and M2 (bottom). Suspended sediment concentration is also shown at M1. Two short representative periods have been selected in each case.

physical environment at the site M1 is characterized by strong tidal oscillations resulting in instantaneous current speeds up to 80 cm s^{-1} during spring tides. Near-bottom tides were weaker at M2, with instantaneous current speeds up to 32 cm s^{-1} . Over the entire studied period, current speeds averaged 22.9 and 7.7 cm s^{-1} , at M1 and M2, respectively.

4.6. Episodes of down-canyon sediment transport associated to shelf storms

4.6.1. Winter 2002–2003

Time-series of wave parameters, near-bottom hydrology, turbidity, current speed and sediment trap data were collected from December 2002 to February 2003 at both sites, in addition to turbidity at 20 and 300 mab in mooring M1 (Fig. 6). Several storms with significant wave heights (H_s) from 4 to more than 8 m affected the continental shelf from December 2002 to February 2003. The impact of these storms at M1 can be analyzed only from the current meter/turbidimeter data, since the sediment trap was already overfilled before this stormy period. Four consecutive marked increases in turbidity were registered near the bottom at M1 (Fig. 6). These high-turbidity events increased SSC near the bottom and 300 m above bottom and were also associated with temperature increases and some salinity decrease (Fig. 6). The near-bottom turbidity sensor (range 0–20 NTU) went off scale in each of these four episodes. The trend of low-pass filtered temperature at M1 (Fig. 6) mimics that of turbidity increasing during the four high-turbidity events. Two of these four turbidity increases coincided with storms with $H_s > 6 \text{ m}$, while the relationship is not so clear in the other two episodes. However, during the two events associated with major shelf

storms (late December 2002 and late January 2003), the settling flux of the deepest trap (T2) increased very notably, suggesting a link between the continental shelf and the distal middle canyon under severe stormy conditions. Special attention merits the third turbid event (January 2003) corresponding to the most dramatic storm of that winter (H_s up to 8.5 m). A marked increase of the mass flux was noticed at T2 (3200 m depth) during that episode, to the point of overflowing the trap. Before it became inoperative, the trap had collected a mass equivalent to a flux of $137 \text{ g m}^{-2} \text{ d}^{-1}$. Both the quantity and characteristics of the trapped particles were remarkable since the overfilled sample was the sandiest of all sampled material (35% of bulk sample $> 62.5 \mu\text{m}$) and vegetal debris (mainly wood chunks and fragments of leaves from vascular plants) were also notably more abundant than the average. On March 11, 2003, another gravity flow was detected at a location close to M2 (De Stigter et al., 2007) concomitant with a storm with $H_s > 8 \text{ m}$ (data are not shown).

4.6.2. Autumn–winter 2003

Time-series of wave parameters and selected variables collected during the stormy period of autumn–winter 2003 are shown in Fig. 7. Particle flux and current data were available only for the deepest M2 site and turbidity data at midwaters only from the end of November. Trap M2 overfilled in coincidence with a storm with H_s close to 9 m that struck the Iberian Atlantic Margin between 30 October and 2 November. Unlike the previous winter, the current meter data did not suggest a sediment gravity flow (Fig. 7), and the grain size of the material that overfilled the trap was remarkably finer than in the case of January 2003. The high mass flux observed during the first trap sample interval before the

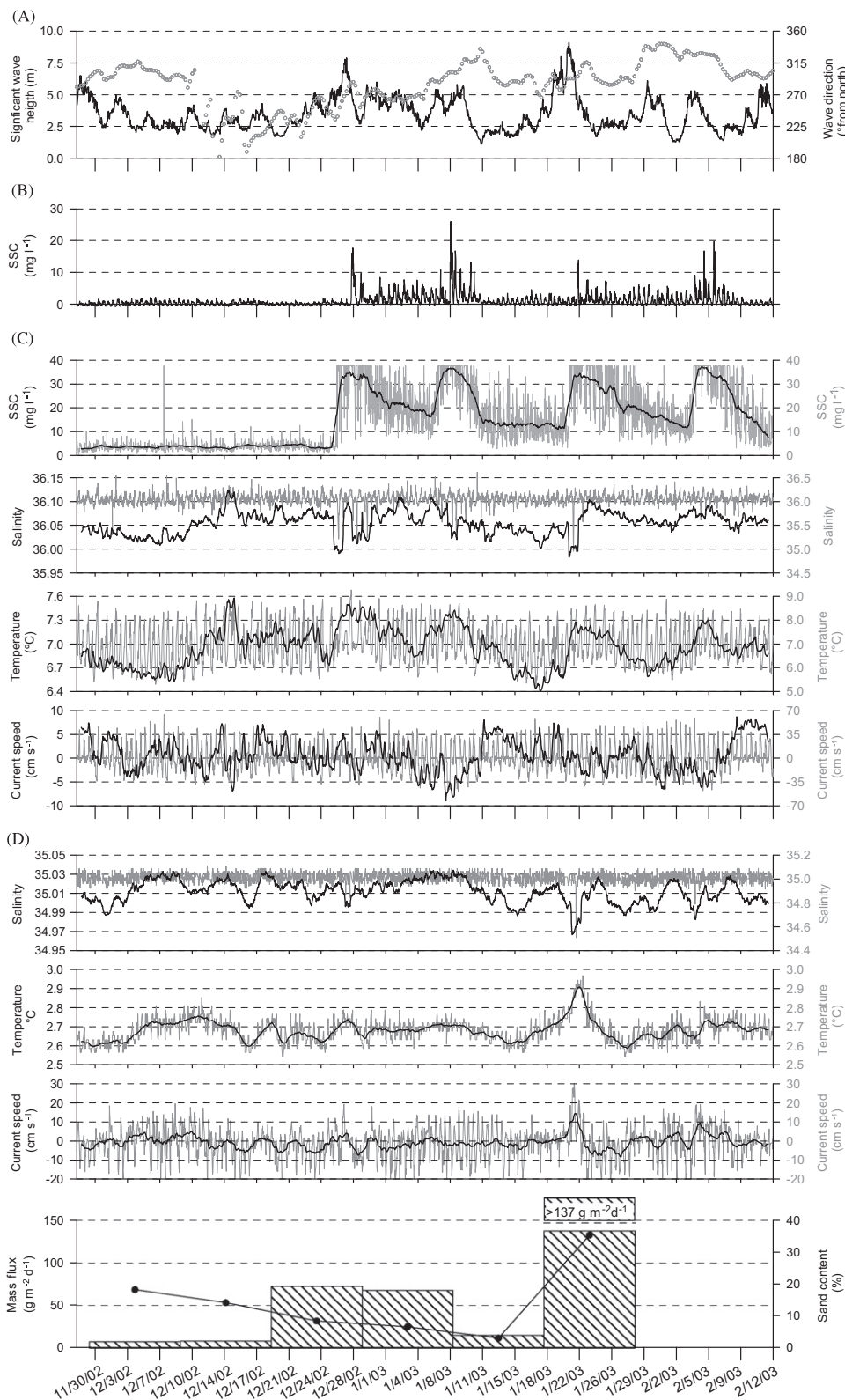


Fig. 6. Time-series of available oceanographic, hydrodynamic, nephelometric and mass flux measurements during late autumn 2002–winter 2003: (A) significant wave height (line) from the oceanographic buoy and wave direction (open circles) measured in degrees from north, obtained from the Wavewatch 3 model; (B) water turbidity at 300 mab in 1600 m total water depth; (C) suspended sediment concentration, salinity, temperature and current speed near the bottom at 1600 m depth; (D) salinity, temperature, current speed and apparent mass flux near the bottom at 3300 m depth. A low pass filter (window=25 h) was applied to near-bottom hydrodynamic, hydrographic and turbidity data in order to filter supradiurnal (mainly tidal) oscillations (black line). The original data (sampling rate=30 min) is shown by the gray line. Current speed corresponds to the along-canyon component after rotating the velocity vector to fit the approximate direction of the canyon axis at each station (positive values are down-canyon).

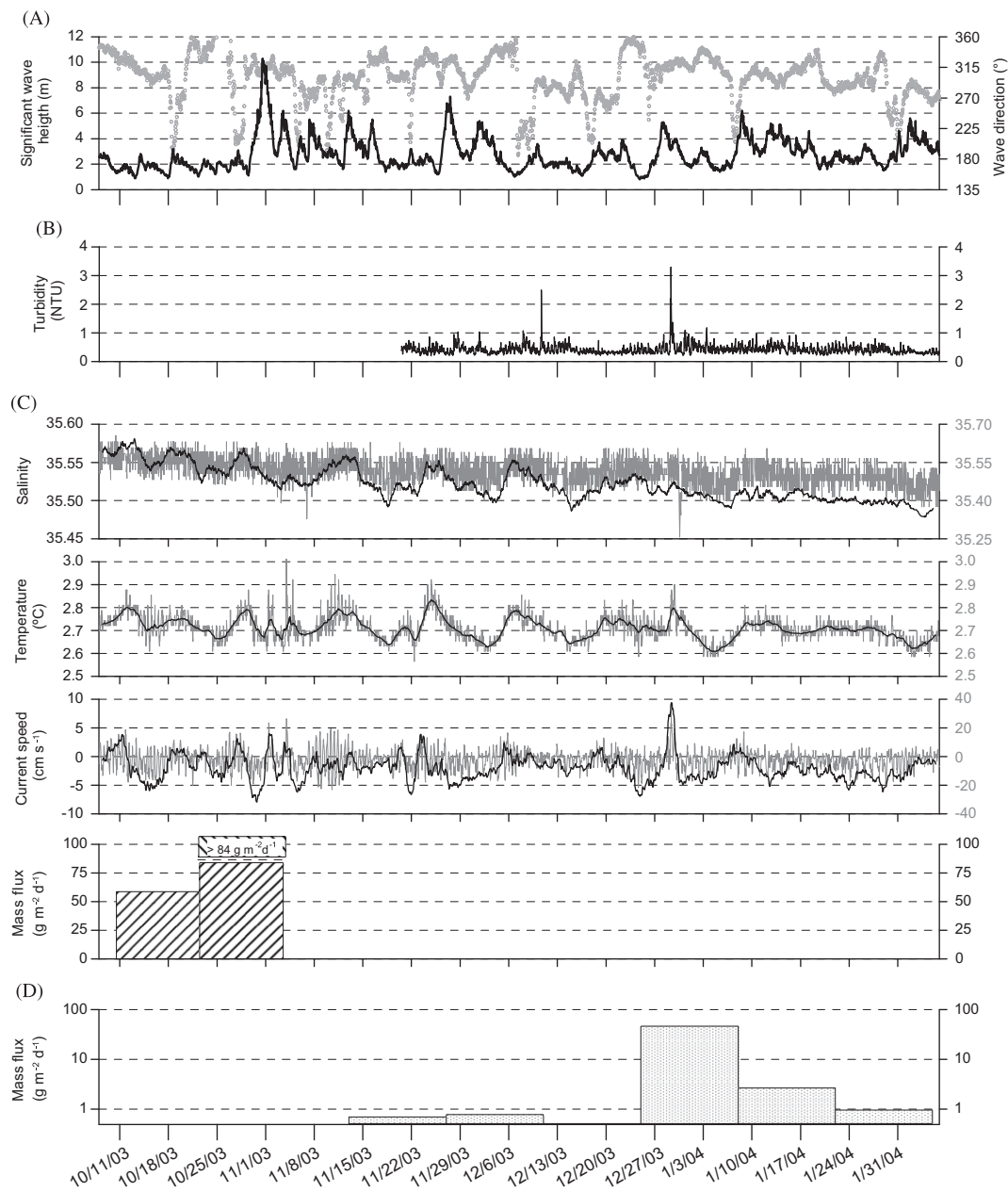


Fig. 7. Time-series of oceanographic, hydrodynamic, nephelometric and mass flux measurements available for autumn–winter 2003: (A) Significant wave height (line) and mean wave direction (open circles) from the Silleiro oceanographic buoy. (B) Water turbidity at 300 mab in 1600 m total water depth. (C) Current speed, temperature, salinity and apparent mass flux near the bottom at 3300 m depth. For near-bottom RCM data, the right axis relates to the original data (resolution 30 min) and left axis for low-pass filtered (25 h) data. (D) Mass flux measured by a near-bottom trap deployed in the lower canyon axis (4300 m depth, see De Stigter et al., 2007 for details). Note the logarithmic scale for the deepest trap.

storm is attributed to resuspension caused by the mooring hitting the seafloor, as observed in other occasions. Two increases of SSC were observed at mid- and late-December 2003 in midwaters (Fig. 7), in connection to relatively weak increases of wave energy. In particular, a storm during late-December with H_s around 5 m was apparently associated to both SSC enhancement at midwaters in the upper canyon and an increase of the down-canyon current speed at 3300 m. This event was simultaneously detected by another sediment trap deployed at 4300 m depth and identified as a gravity flow (De Stigter et al., 2007, Fig. 7).

4.6.3. Autumn–winter 2004

Time-series of wave parameters and particle flux measured during October–December 2004 are shown in Fig. 8. Current and water turbidity data were not available for this period. The high

resolution (5 d) of sediment trap sampling during this deployment allowed observation of particle fluxes at T1 under relatively energetic conditions while preventing rapid overfilling the trap. In fact, the effect of at least two storms at T1 can in this case be discerned from the background of very high particle fluxes derived from tidal resuspension and the bottom nepheloid layer. The time-series show three consecutive events of high particle flux at T1 (approximately 10–19 November, 1–10 December and 19–29 December) and at least on two occasions they seemed connected to increases in wave energy over the continental shelf. The first event (first half of November) was characterized by mass fluxes around $170 \text{ g m}^{-2} \text{ d}^{-1}$ and relatively weak H_s up to 4 m. The second event showed higher mass fluxes (up to $210 \text{ g m}^{-2} \text{ d}^{-1}$) and correlative H_s surpassing 5 m. During the third event, the sediment trap overfilled (minimum mass flux

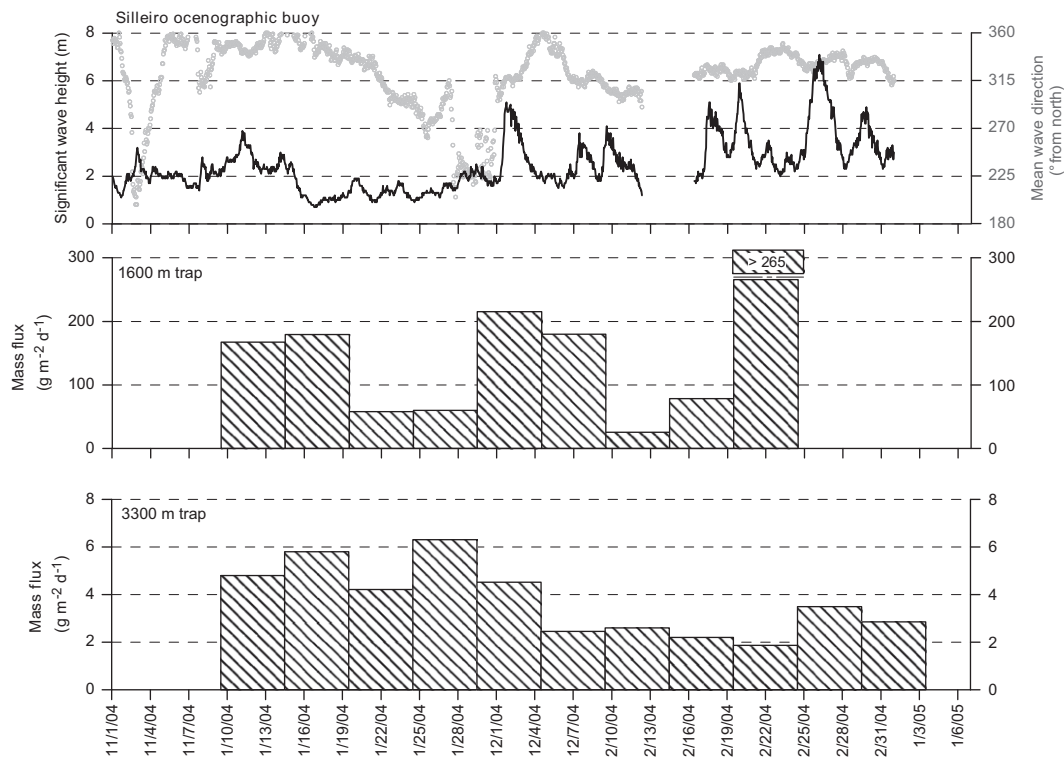


Fig. 8. Time-series of wave data and downward particle fluxes in the Nazaré submarine canyon during autumn–winter 2004.

$265 \text{ g m}^{-2} \text{ d}^{-1}$) in coincidence with a storm with H_s of 6 m. It is worth noting that none of the flux increases at 1600 m were observed simultaneously at 3200 m depth, and that a storm with H_s close to 7 m during late December also had no discernible effect at this depth (Fig. 8).

5. Discussion

5.1. Sedimentary conditions at the upper and middle canyon sites

5.1.1. Site M1 (upper canyon: 1500–1600 m depth)

The extremely high apparent fluxes measured by the near-bottom trap at M1 testify to the intense sedimentary activity taking place in this part of the canyon. The Nazaré Canyon at 1500–1600 m is characterized by permanent conditions of very high current speed (Fig. 5). Under these conditions, fine unconsolidated sediments are continuously resuspended by tidal currents (De Stigter et al., 2007). Apart from tidal currents, other processes may contribute to enhanced particle resuspension and transport in the upper canyon. Significant internal wave formations, as well as bottom-intensified tides have been identified between the MW lower limit and the canyon bed (Vitorino et al., 2005). Oceanographic cruises conducted during 2002 and 2004 repeatedly found maxima of turbidity at the upper (500–800 m) and lower (1100–1400 m) limits of the MW core (Oliveira et al., 2007). In particular, a very turbid and recurrent bottom nepheloid layer has been observed between 1200 and 1400 m depth, at the approximate lower contact of the Mediterranean water with the seafloor (De Stigter et al., 2007). It is also seen that the stable and low values of ^{210}Pb at M1 (close to the activity of surface sediments) reinforces the idea that this part of the canyon is subject to permanent high fluxes from a dominant homogeneous source, consisting of sediments resuspended from the adjacent shelf and transported into the canyon where they may undergo

many resuspension/redeposition cycles until all excess ^{210}Pb is depleted.

5.1.2. Site M2 (middle canyon: 3200–3300 m depth)

Time-series of mass fluxes at M2 (~ 3300 m depth) were longer than at M1 and were not affected by high current speeds. Mass fluxes were in general lower at this site, although the particle composition was remarkably homogeneous between both stations, suggesting a common origin of the bulk flux (Heussner et al., 2006).

Two contrasting situations can be distinguished in the annual dynamics of apparent mass flux at M2: during spring–summer, fluxes are relatively steady and lower than $8 \text{ g m}^{-2} \text{ d}^{-1}$; in autumn–winter, total fluxes are notably higher as a consequence of sharp flux increase events up to more than $130 \text{ g m}^{-2} \text{ d}^{-1}$. To account for the sediment accumulation rates $8\text{--}33 \text{ g m}^{-2} \text{ d}^{-1}$ obtained at similar depths (De Stigter et al., 2007), and taking into account that trap fluxes are probably overestimated, it must be acknowledged that pulsed inputs of sediment, rather than steady sedimentation, make up the bulk of the sediment accretion in the middle canyon.

5.2. Storms as drivers of pulsed sediment transport through the canyon

Increases of SSC both near the bottom and at intermediate waters at M1 (upper canyon) occurred in conjunction with storms with H_s between 4 and 6 m. This suggests either the formation of bottom nepheloid layers (BNL) hundreds of meters thick or detachments of intermediate nepheloid layers together with discrete BNLs. Major storms with H_s above 7 m occurred in January and October 2003 and correspond to strong increases in particle flux in the middle canyon to the point of overflowing trap M2. However, the effects of these two major storms at M2

differed both in the transport mechanisms and the properties of the particles involved. In January 2003, a gravity flow was observed at the deepest site carrying relatively coarse particles. During the overfilling of the trap at M2 an increase of down-canyon near-bottom current speed occurred simultaneously with an increase of near-bottom temperature and a decrease of salinity (Fig. 6). Similar signatures have been observed for the passage of sediment gravity flows (Palanques et al., 2006b; Khrifounoff et al., 2009). At M1, SSC and temperature also increased and salinity decreased simultaneously with overfilling of the deepest trap at M2. However, no related increase of current speed was observed at M1, and therefore the gravity flow observed at T2 had to originate in an intermediate location down-canyon from T1, but ultimately related to the enhancement of sediment transport observed at T1 during the January storm. In fact, T1 is located just up-canyon from the area of maximum bathymetric gradient of the canyon axis (Vannay and Mougenot, 1993), which is therefore a good candidate as an area in which gravity flows might be generated. In addition, nepheloid layers advancing offshore from the upper course along the middle canyon could have also contributed to the downward particle flux increases at T2.

Unlike the storm of January 2003, the October 2003 storm (Fig. 7) was not accompanied by an increase of the near-bottom residual current and temperature at M2. Furthermore, sand and plant debris were present in much smaller amounts. This suggests that in this case, the trap was filled as a consequence only of nepheloid layers generated by the storm, without the interplay of near-bottom gravity transport. The major autumn storm could have generated a turbidity current that did not reach M2, but generated bottom and intermediate nepheloid layers that impacted this deep site. It has been observed in the past that bottom nepheloid layers at the canyon head extend into the upper and middle canyon as intermediate nepheloid layers (Van Weering et al., 2002). The strong changes in slope along

the canyon axis likely favor the detachment of these turbid layers.

As shown in Fig. 7, storms with H_s as low as 5 m are apparently able to trigger density currents that traverse the entire middle canyon. Although shelf storms clearly have an impact on deep fluxes in the canyon, wave height alone cannot justify the intense down-canyon transport events observed, and other concurrent or modulating factors must be invoked.

5.3. Role of river discharge on sediment flows in the canyon?

Although the Nazaré Canyon is usually considered unconnected to fluvial systems, the potential nourishment of the canyon head with sediments delivered by rivers discharging north from the canyon should not be neglected, taking into account the fact that the mean sedimentary drift is markedly southward. In addition, the contribution of several small (but undammed) streams southwards from Nazaré has been signaled as a probable source of sediments to the shelf and the canyon mouth in winter (Oliveira et al., 2007). In particular, the Mondego River has a watershed of 6644 km² and opens to the sea about 50 km north of the canyon head. In spite of considerable regulation of the Mondego flow, substantial flooding still occurs (up to 1900 m³ s⁻¹ measured at Coimbra in January 2001; Proença Cunha, 2003). Monthly discharge of the Mondego and Agueda (tributary to the Vouga, which opens to the sea 100 km north of the canyon head) rivers during the study period are shown in Fig. 9. Unusually heavy rainfall and river flow rates were registered in the Atlantic side of the Iberian Peninsula both in December 2002 and January 2003 (Rodrigues et al., 2003, Fig. 9), corresponding to the two major mass flux pulses in trap T2 (Fig. 6). In particular, the overfilling of the trap coincided with the period of maximum river discharge, more than five times higher than the interannual mean (1990–2009) for the month of

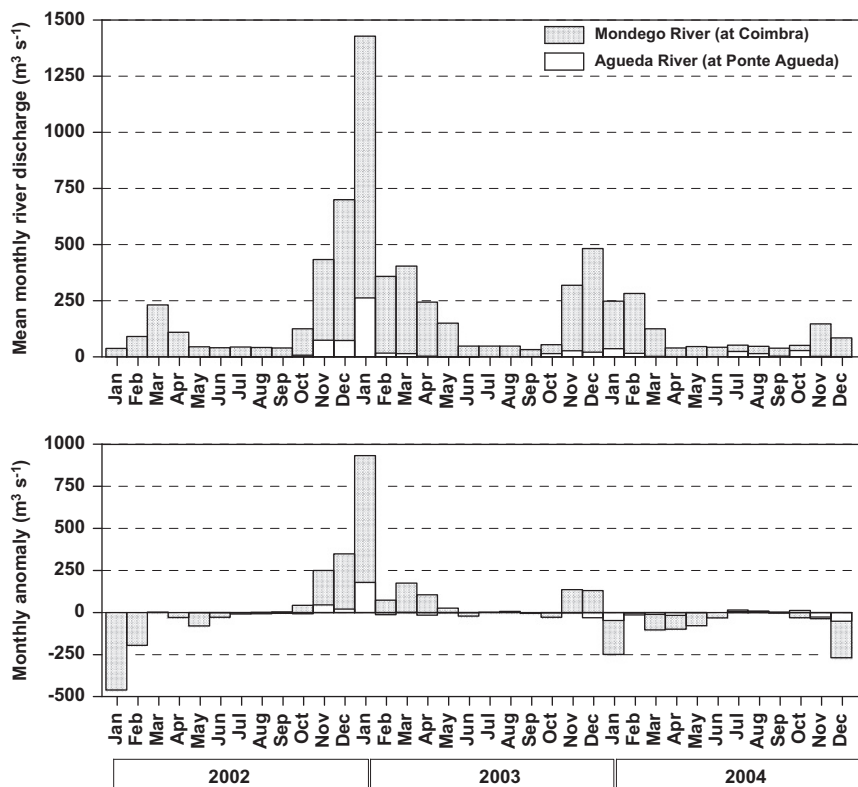


Fig. 9. Top: mean monthly water discharge of the Mondego and Agueda rivers during the study period. Bottom: monthly anomalies with respect to the interannual mean (1990–2009 for the Mondego River; 2001–2009 for the Agueda River).

January (Fig. 9). This suggests that storms are able to trigger sediment transport events that reach the deep mooring site at the end of the rainy season, following the accumulation of sufficient material on the shelf. Also at 4200 m depth (Fig. 7) an important increase of the mass flux occurred in December–January 2003 just after the peak of the rainy period (Fig. 9). Furthermore, during the relatively dry winter of 2004, the effect of storms was documented at M1 but did not reach M2 even when H_s reached ~ 7 m (Fig. 7). An exception to this rule is the storm of 30 October–1 November 2003, which enhanced sediment transport at M2 during the first rains of autumn, but it must be taken into account that this storm was the strongest recorded (H_s up to 10.3 m).

5.4. Other factors potentially relevant in the triggering of deep sediment transport

Since the Iberian Margin is seismically active (Alves et al., 2003), we also investigated the occurrence of earthquakes during the periods of operation of the sediment traps and their eventual impact on offshore sediment transport. The largest seismic events during the sampled period took place on July 29, 2003 and December 14, 2004 SW of Cape Sao Vicente with a similar intensity of 5.4 in the Richter scale (Carrilho, 2005). No effect of these earthquakes on sediment transport was discernable in our dataset.

More likely drivers for down-canyon sediment transport are downwelling at the canyon head and the associated enhancement of internal waves. During winter, south and east winds promote downwelling over the Iberian Shelf, implying net offshore transport in the bottom Ekman layer (Vitorino et al., 2002a, b). It has been suggested that detaching of nepheloid layers from the upper canyon is favoured during downwelling conditions at the Nazaré Canyon head (Oliveira et al., 2007). As a consequence of downwelling in the canyon head, warm oceanic water is displaced towards the coast, thus enhancing the vertical density gradient and the scope for internal waves to develop (Vitorino et al., 2002a, b). Near the bottom, the density gradient is further enhanced by the presence of dense nepheloid layers, a process that may be amplified following wave-induced resuspension on the continental shelf and the subsequent transport of particles into the canyon. Hence, storms that are not able to trigger significant down-canyon transport directly may however favor far-reaching down-canyon density currents generated in synergy with downwelling conditions and internal waves.

5.5. Origin of particles trapped in the middle canyon

Given the relative temporal and spatial homogeneity of the four main particle components (opal, carbonate, organic matter and lithogenics) during this study, it is difficult to discriminate between recent supply of shelf and coastal material and resuspension of past supply, accumulated temporarily on the canyon bed. Mica/illite percentage was higher and calcite, quartz and feldspars percentages lower in sediment trap samples than in bottom samples collected at nearby locations (Oliveira et al., 2007). This can be an indication of preferential transport in nepheloid layers, since suspended particulate matter show higher values of mica/illite ($> 60\%$) than bottom samples (Oliveira et al., 2007). The CaCO_3 contents of sediment trap samples were remarkably stable at both traps and close to those reported by Alt-Epping et al. (2007) in the continental shelf adjacent to the Nazaré canyon head (12–15%), and by Van Weering et al. (2002) in surface sediments of the middle Nazaré Canyon (8–12%). This uniformity reflects intense mixing of sediments during repeated episodes of resuspension, but it could also suggest that most of the particles reaching the upper and middle canyon have a

common origin in a temporary reservoir near the canyon head, from where they are redistributed down-canyon, whether slowly by the action of tides and internal waves (Quaresma et al., 2007) or in fast pulses when gravity currents develop. An exception can be found in the overfilling of T2 trap in January 2003 when the minimum CaCO_3 content of the time-series (8%, see Fig. 3) was found. This can indicate a shallower, coastal origin since Alt-Epping et al. (2007) reported CaCO_3 contents of 12–15% in sediments adjacent to the Nazaré canyon head but only 5% closer to the coast. During the rest of the study carbonates were rather stable at $13.2 \pm 1.6\%$ in the deepest trap T2, suggesting contributions from the main sedimentary source in the shelf surrounding the canyon head. Concomitantly with the decrease of carbonate at T2 during the overfilling of January 2003, organic carbon decreased drastically whereas the sand fraction and terrigenous constituents such as quartz and dolomite increased. This could be indicative of coastal transport, although the increase of dolomite inside the canyon could also be an indication of a different source region, richer in dolomite, in the northern outer shelf (Oliveira et al., 2007).

OC/N ratios in sediment trap samples (range 11–21) were well in excess of both the Redfield ratio and the range 4–9 reported by Alt-Epping et al. (2007) in sediments of mainly marine origin on the continental shelf north of the canyon head. The high OC/N values of trap samples are indicative of terrestrial organic matter and/or old reworked sediments, where labile organic matter has been remineralized after successive resuspension-deposition cycles. The frequent presence of continental vegetal debris and wood chunks in the samples at both depths, and particularly during the extreme flux pulse of January 2003 at the deep mooring site, confirms the relevance of terrestrial inputs into the canyon.

6. Summary

The observation of near-bottom particle fluxes at 1600 and 3300 m depth in the Nazaré submarine canyon has revealed some contrasting features. The shallowest site (1600 m) is an extremely dynamic environment with permanent conditions of high particle fluxes year-round. Seasonal variability of fluxes is more evident at the deepest site (3300 m), where periods of relatively low and steady mass flux in spring–summer and in the absence of major shelf storms are followed by a more variable regime during autumn–winter. In the latter case, sharp increases of the apparent particle flux occur related to shelf storms and overall govern the annually integrated mass flux. Storms impinging in the continental shelf enhanced sedimentary activity in the upper and middle canyon, causing apparent near-bottom fluxes exceeding $230 \text{ g m}^{-2} \text{ d}^{-1}$ at 1600 m in the upper canyon axis and $130 \text{ g m}^{-2} \text{ d}^{-1}$ at 3200 m depth in the middle canyon axis. In addition to, or more likely in synergy with the action of storms, flooding of rivers north of the canyon head apparently contributes to triggering the observed increases in particle flux to the middle canyon. The composition of trapped particles was rather uniform at both sites, and suggests an important terrigenous contribution.

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