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Article

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Anthropogenic influence on sediment transport in the Whittard Canyon, NE Atlantic.

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Abstract

Unusual peaks in turbidity were detected in two branches of the Whittard Canyon in June 2013. Concentrations of suspended matter exceeded those usually observed in benthic and intermediate nepheloid layers by at least an order of magnitude. These Enhanced Nepheloid Layers (ENLs) were defined as peaks in turbidity with suspended particulate matter concentrations exceeding ~1000 µg L^{-1} and the largest ENLs measuring between ~2000-8000 µg L^{-1}. The ENLs measured ~100-260 m in vertical height and were detected in water depths of ~640-2880 m. Vessel Monitoring System data showed high spatial and temporal activity of potential bottom trawling vessels coinciding with the occurrence of the ENLs. Molar C/N ratios of the suspended organic material from the ENLs showed a high degree of degradation. Regular occurrences of such events are likely to have implications for increased sediment fluxes, burial of organic carbon and alteration of benthic and canyon ecosystems.

Keywords: Trawling; SPM; Resuspension; turbidity; Enhanced nepheloid layers; Whittard Canyon

1. Introduction

The steep sloping topography of submarine canyons promotes complex hydrographic and sedimentary conditions and provides a preferential pathway for the transport of material from continental shelves to the deep sea (Canals et al., 2013). Their conduit nature causes greater food availability, attracting a wealth of benthic species and enhancing the burial of organic carbon. Sediment gravity flows including nepheloid layers and other disturbance events can resuspend and transport material to great depths (e.g. Hotchkiss and Wunsch, 1982; Gardner, 1989; Puig et al., 2008;2014; de Stigter et al., 2007). Amplified energetic processes in submarine canyons support the generation of benthic (BNL) and intermediate nepheloid layers (INL), which are significant contributors to the shelf edge exchange of sediment (Amin and Huthnance, 1999; Puig et al., 2014). These suspended layers contain higher amounts of suspended particulate matter (SPM) than the surrounding clear-water minimum and are commonly observed along the NE Atlantic continental margin (e.g. Thorpe and White, 1988; Mc Cave et al., 2001; Wilson et al., 2015).

The worlds' continental margins are constantly undergoing natural evolutionary change (Palanques et al., 2014). There is now evidence that fishing and bottom trawling significantly modify the ocean over large spatial scales (e.g. Sheppard, 2006). Bottom trawling involves towing large nets that are kept open by otter trawl boards (OTBs) or rigid metal bars and blades that dig into the seabed mobilising soft sediment and crushing harder substrates. Extensive reports on the physical disturbance of the seabed by towed bottom gear conclude that trawling has negative effects (see Gray et al., 2006). Continental shelves and deep seafloors have been homogenized, altering benthic habitats (e.g. Jennings and Kaiser, 1998; Watling and Norse, 1998; Roberts et al., 2006), smoothing topography (Puig et al., 2012) and impacting continental margin sediment transport dynamics (Martín et al. 2008; 2015). The interaction of towed fishing gear with the seabed and surrounding ambient water produces high velocity, bed shear stress and turbulence that entrain sediment, which disperses as a cloud of SPM settling out with turbulent decay (O'Neill and Summerbell, 2011). The excess material created in this manner can feed into thick nepheloid layers (Pilskaln et al., 1998;

Palanques et al., 2001; Durrieu de Madron et al., 2005) or provide additional dense elements to trigger sediment gravity flows (Palanques et al., 2006; Puig et al., 2012; Martín et al., 2014). Accurate estimates of the quantity of material being introduced to the water column are needed to better our understanding of the broader environmental and ecological impacts of bottom trawling (O'Neill and Summerbell, 2011). The elevated sediment transport rates and consequent impacts reported in the NW Mediterranean during trawling periods (e.g. Palanques et al., 2014) are likely to be occurring in other well trawled areas like the Celtic Sea. Since the 1980's the NE Atlantic and central European margin have been heavily trawled due to the increase in fishing and industrialization of fleets (Puig et al., 2012). In the northern Celtic Sea over two-thirds of the bottom area is impacted by trawling at least once per year and some areas are impacted more than ten times per year (Gerristen et al., 2013). At the edge of the continental shelf in the Celtic Sea, Whittard Canyon has been the focus of much submarine canyon research in this area. Although there have been no direct studies of trawling activity in the water column at Whittard, ROV footage and side scan sonar have shown trawl marks on the spurs of the upper part of the canyon (Huvenne et al., 2011), while other studies have detected inexplicably high peaks in turbidity deeper in the Whittard Channel (Amaro et al., 2015).

In this paper we report unusual peaks in turbidity detected in two tributaries of the Whittard Canyon. We investigate the possibility that these plumes are induced by bottom trawling and discuss the effect on sediment transport dynamics at the Whittard Canyon.

2. Material and methods

2.1 Study area

Whittard Canyon is a dendritic submarine canyon located at the edge of the continental shelf approximately 300 km off southwest Ireland with Goban spur to the west and Meriadzek Terrace to the south-east. The system cuts the continental margin with the head of the canyon connected to the Celtic Sea shelf at ~200 m water depth. The branches extend (100 km) from the upper slope and are characterized by steep vertical walls. Incised by numerous gullies, the branches converge into one deep channel at ~3800 m. The principal water masses comprise; Eastern North Atlantic Water (ENAW), Mediterranean Outflow Water (MOW), Labrador Sea Water and North Atlantic Deep Water (NADW) (Pollard et al., 1996; van Aken, 2000). The upper water column (150-700 m) is characterized by the boundary slope or Shelf Edge Current (SEC), with mean flows of 5 -10 cm s^{-1} (Pingree and Le Cann, 1990; Xu et al., 2015). Bottom currents display tidal frequencies with reports of maximum velocities varying between 16 and 40 cm s^{-1} (Reid and Hamilton, 1990; van Weering et al., 2000; Duros et al., 2011; Amaro et al., 2015). Nepheloid layers (NLs) are commonly observed throughout the water column and dominate distribution patterns of SPM (Johnson et al., 2013; Wilson et al., 2015). Pelagic material and reworked sediments from the outer shelf and canyon edges tend to be coarse in the upper canyon in contrast to the alterations of coarse and fine material found in the lower reaches (Duros et al., 2011). The Celtic Sea shelf break is characterized by high internal tidal energy fluxes (Vlasenko et al., 2014) that drive nutrient fluxes and fuel enhanced primary productivity (Sharples, 2007) in surface waters along the margin and in the Bay of Biscay (100-250 g C m^{-2} yr^{-1}, Wollast and Chou, 2001). High primary production promotes good fishing and the Celtic Sea shelf break is heavily fished by various fleets mainly from Spain, France and Ireland using bottom trawls, pelagic trawls and longlines (Gerritsen and Lordan, 2014).

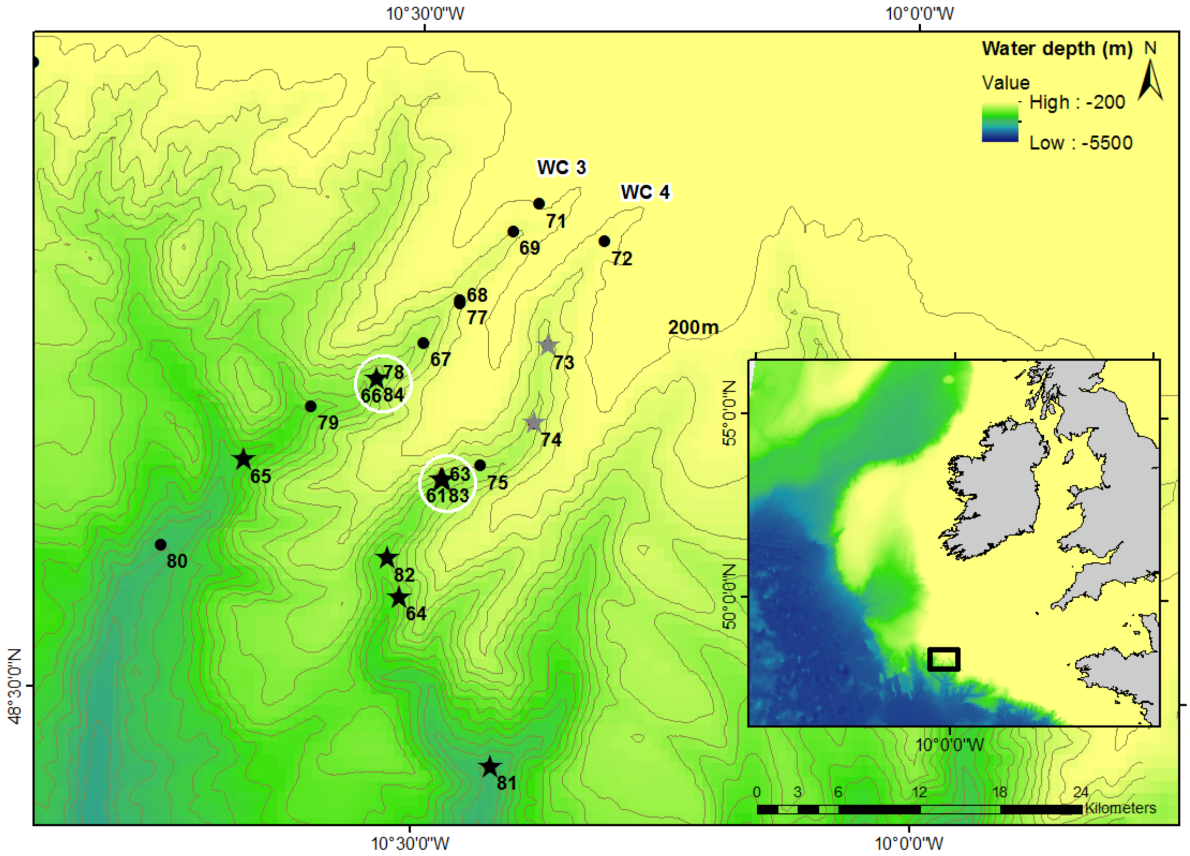

Figure 1. Location and bathymetry of Whittard Canyon on the Celtic Sea Shelf, NE Atlantic. CTD stations from CE13008 are shown as black dots (●) and labeled with event numbers in black. Locations of enhanced nepheloid layers are shown as black stars ★(suspended particulate material >1300 µg L^{-1}) and grey stars ★ (600-1300 µg L^{-1}). Central stations where repeats profiles were made are marked with a white circle. **(Note: 2 column-fitting image)**

2.2 *Sampling and analytical methods*

Four branches of the Whittard Canyon system were surveyed between 2011 and 2013 on the RV *Celtic Explorer* with benthic and intermediate nepheloid layers observed in all four surveyed branches (see Figure 1 and Table 1; Wilson et al., 2015). Here we focus on unusual observations from two of those branches, WC3 and WC4 (Figure 1), during the 2013 survey (CE13008; 9-17th June), where enhanced nepheloid layers (ENLs) were observed repeatedly during a five day period (13-17th June). Transects and locations of sampling events where ENLs were detected are shown in Figure 1 and details of water samples used in this study are shown in Table 1.

Hydrographic measurements were carried out using a Seabird SBE 911 CTD and SBE32 rosette system in transects along the branches with repeat profiles taken at key stations. Vertical profiles of water turbidity were recorded by a 0.25 m path-length transmissometer (C-star, WET Labs) operating at 650 nm. Transmission values were converted to beam attenuation coefficient (BAC) which was correlated by linear regression with the mass of suspended particulate material (SPM µg L^{-1}) obtained from filtered water samples collected during three surveys 2011-2013 as described in Wilson et al. (2015); see Figure 2.

Samples for qualitative analysis (organic carbon and total nitrogen) of the SPM were collected on two stacked pre-combusted (400°C, 4 hrs) 47 mm GF/F filters, using water samples (2-10 L) collected from the CTD rosette. On recovery, each filter was folded in half (onto itself) and then into quarters before wrapping in combusted foil and storing at -80 °C for the duration of the cruise. Samples were analyzed according to the methods of Kiriakoulakis et al. (2009). Briefly, after freeze-drying, punched circles (~7 mm^2) were taken from homogenous areas on the top filters of the stacks (at the middle and edge of the filters) for measurement of particulate organic carbon and nitrogen (POC, PN). POC values were obtained after de-carbonation of the filters and PN values were determined before decarbonation on separate circles. The analyses were carried out using a CEInstruments NC 2500 CHN analyzer in duplicate and the mean value was taken. Consistent variability between circles from the edge and middle of the filter, a filtration artifact, were observed and mean values were therefore taken to give a better approximation of the true value of the filter. The bottom filters of the stacks were used to correct for overestimations of POC and PN due to adsorption of dissolved organic matter (DOM) onto the filters (see Turnewitsch et al., 2007).

Data on the activity of fishing vessels are remotely collected by the Irish Naval Service through Vessel Monitoring Systems (VMS). These systems transmit a vessel's position and speed at intervals of 2h or less. VMS data for the study area quadrangle (48° 30' – 48° 55' N, 10° 35'– 10° 15' W) for the month of June 2013 were extracted. The total records for the month of June (589) were reduced to those fitting the criteria for trawling activity and recorded during the operational survey period to Whittard Canyon (9-17th June 2013). To fit the criteria (likely) for trawling activity, vessels must be equipped with bottom trawling gear and be operating at ≤5 knots, a suitable threshold to denote fishing activity (Gerritsen and Lordan, 2011). Vessels meeting these criteria were selected and plotted using ArcGIS 10.2 (ESRI). Data outside these criteria were discarded. VMS data in the quad from 2011 and 2012 during the periods when two previous research surveys (CE11006: 24-26th April & CE12006; 15-26th April) were also examined.

Table 1. Geochemical data; date, time, co-ordinates, location, elemental; particulate nitrogen (PN), particulate organic carbon (POC) and suspended particulate matter concentrations (SPM) of samples from enhanced nepheloid layers (ENLs), small ENLs and water samples where no ENL was present.

	Date (June ’13)	Time (UTC)	Branch WC	Event #	Latitude N	Longitude W	Sample depth (m)	Bottom depth (m)	PN (µg L^{-1})	POC (µg L^{-1})	C/N (molar)	SPM (µg L^{-1})
ENLs	14	13:50	4	64	48.5649	-10.5151	1972	1992	28.69	236.21	10	1937.60
	16	14:45	4	81	48.4532	-10.4209	2758	2875	62.81	365.37	7	2467.70
	16	14:45	4	81	48.4532	-10.4209	2858	2875	87.08	689.80	9	5324.50
	16	19:30	4	82	48.591	-10.5282	1831	1856	104.67	625.23	7	7480.60
	16	22:00	4	83	48.644	-10.4748	1148	1376	42.76	279.72	8	2274.40
	16	22:00	4	83	48.644	-10.4748	1380	1377	38.77	289.83	9	8139.80
	17	00:35	3	84	48.7102	-10.5421	1331	1363	NA	NA	NA	NA
Small ENLs	13	11:55	4	61	48.6441	-10.4757	1356	1371	47.08	190.98	5	1199.90
	13	11:55	4	61	48.6411	-10.4757	1356	1371	41.25	196.83	6	1199.90
	14	17:30	3	65	48.6545	-10.6736	2293	2304	49.69	271.29	6	1003.30
	15	09:30	4	73	48.7344	-10.3709	635	640	22.30	199.04	10	1139.20
	15	10:09	4	74	48.6826	-10.3826	860	922	14.43	337.94	27	730.04
No ENLs	15	00:25	3	67	48.7345	-10.4954	647	990	62.50	175.56	3	142.60
	15	08:45	4	72	48.8041	-10.3145	296	310	38.30	146.13	4	406.82
	16	06:55	3	79	48.6909	-10.6072	1708	1871	56.75	47.73	1	470.67
	16	10:45	3	80	48.5967	-10.7555	2583	2797	27.40	106.13	5	89.46
	16	10:45	3	80	48.5967	-10.7555	2800	2797	69.85	172.51	3	68.85
	15	04:45	3	69	48.8096	-10.4074	12	378	128.47	601.89	5	748.74

3. Results

3.1 Distribution of SPM in the water column and peaks in turbidity

Increased SPM concentrations were commonly observed at benthic and various intermediate mid-water depths with concentrations ranging between >275-600 µg L^{-1} (Figure 2a and d and Wilson et al., 2015). Vertical profiles in WC3 (Figure 2a-c) and WC4 (Figure 2d-f) showed a general increase in SPM towards the seabed in significant BNLs. Similarities in thickness and depth ranges of occurrence were observed in both branches in comparison to the observations in these and other branches (WC1 and WC2) during this and previous surveys (2011, 2012, see Wilson et al., 2015). BNL thicknesses of 150-200 m were detected with INLs extending from the BNL at 250 m, 850 m, 1150 m and 1600 m (Figure 2a and d).

Unusual peaks in turbidity were observed in a number of profiles from the mid-lower reaches (i.e. > ~1150m) WC3 and WC4 (Figure 2b and e). These observations were unexpected and therefore measurements were restricted to a small number of isolated profiles. Concentrations of SPM ranged from ~1000-8000 µg L^{-1}; exceeding the highest values previously detected by at least one order of magnitude. Typical BNL concentrations were observed up to ~400 m above the seabed (Figure 2c and f) with maximum SPM in the ENL just above the seabed with comparable thicknesses of normal BNLs, ranging from ~100-260 m. The ENLs were detected in the upper reaches of WC4 at ~640 m and all along the axis down to ~2875 m, a distance of ~24 km, with two observations in the middle of WC3 at 1363-2304 m.

The ENLs were initially detected by chance. They were first observed in the middle of branch WC4 (central station indicated with white circle in Figure 1) at ~1370 m (Figure 2e and f; event 61) on June 13th with concentrations of ~1200 µg L^{-1}. This relatively low value in comparison to what was to follow was still three times higher than typical maximum values (~400 µg L^{-1}) observed in BNLs and INLs in eastern and western branches during this and previous surveys (Wilson et al., 2015). Repeat measurements at this station less than 24 hours later, revealed ENLs with SPM concentrations reaching ~3000 µg L^{-1} (event 63). On June 16th SPM concentrations exceeded 8000 µg

L^{-1} (Figure 2f; event 83). In the upper reaches of the branch (i.e. <1370 m), small ENLs (SPM values of ~1000-2000 µg L^{-1}) were also detected (Figure 2e; event 73, 74) on June 15th. In the lower reaches (i.e. >1370 m), large ENLs were detected at 1856 m (event 81) and again at 2875 m (event 82) on June 16th, with maximum concentrations at both locations exceeding 4000 µg L^{-1} and matching the highest observations at the central station (white circle, Figure 1) of ≥8000 µg L^{-1}, 24 km further up the branch. A smaller ENL between these two locations at 1992m was observed on 14th June with maximum concentrations of ~1900 µg L^{-1}.

On the same day, 8.9 km to the west in the adjacent branch, WC3, a smaller intermediate ENL (iENL) was observed with values of ~1000 µg L^{-1} at 2200 m (Figure 2b; event 65). Further up the branch at ~1370 m, no evidence of enhanced turbidity was detected until June 17th at 00:35 (Figure 2c). At 00:35, concentrations exceeded 5000 µg L^{-1}, with a thick iENL (~110 m) observed lying between 1180-1290 m ~70 m above the seabed (event 84). Repeat vertical profiles at this station, ~1370 m in WC3 (central station indicated with a white circle in Figure 1), capture the sudden appearance of the ENLs within a ~20 hour period, while profiles in WC4 show the ongoing appearance of the ENLs (Figure 2f). In WC4, concentrations increased by ~2000 µg L^{-1} within 21 hours. iENLs were observed with peaks of the order of ~1200 µg L^{-1} between 1100-1250 m. SPM concentrations in these layers doubled (≥2400 µg L^{-1}) within 61 hours with iENLs detected at similar depth ranges and thicknesses of ~125 m presenting as a continuum into the benthic ENL.

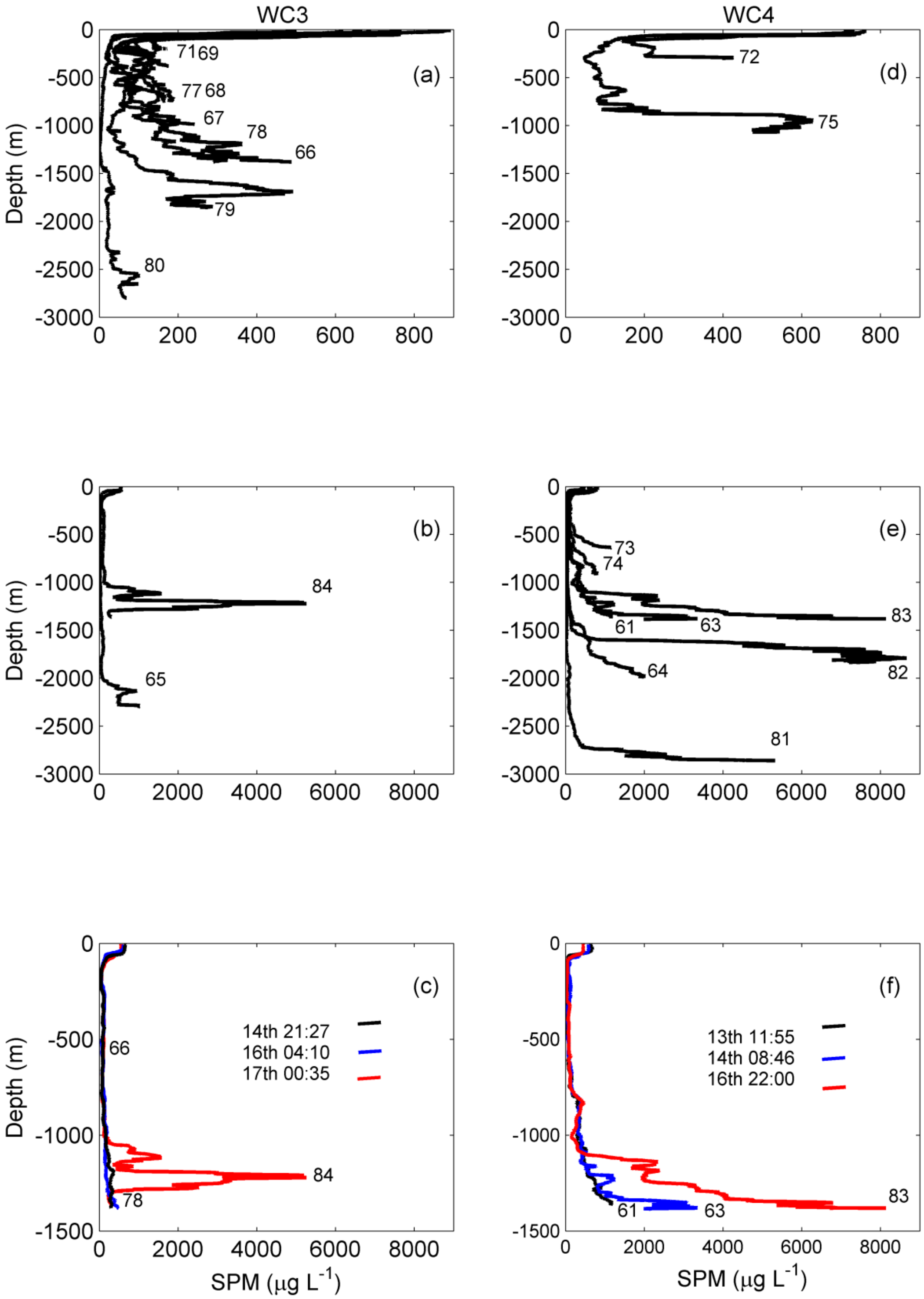

Figure 2. Vertical profiles of suspended particulate material expressed in µg L^{-1} along the axis of WC3 (a-c) and WC4 (d-f). Panels show normal profiles (a and d); enhanced nepheloid layers (b and e); repeat profiles at central location ~1350 m (c and f). Profiles are labeled by event numbers. Note

change in scale between normal and enhanced nepheloid layers profiles. **(Note: 2 column-fitting image)**

3.2 ENL categorization

ENLs were defined here as nepheloid layers with peaks in turbidity and elevated SPM concentrations exceeding ~1000 µg L^{-1}. Plumes by this definition were detected on June 13th, 14th, 15th, 16th and 17th 2013 in two tributaries of the canyon at eight locations (Table 1). Measurements from June 13th-15th inclusive had concentrations less than or equal to ~2000 µg L^{-1} and were categorized as smaller or remnant ENLs (light grey in Table 1). Measurements exceeding ~2000 µg L^{-1} were classified as large ENLs (dark grey Table 1) and were observed mainly on June 16th and 17th, in water depths of ≥ ~1150 m.

To differentiate whether the ENLs detected on June 17th in WC3 (event 84) were separate to those 8.8 km to the west in WC4 (event 83) the density (σ_{θ}, kg m^{-3}) of the ENLs was examined. At the central station (white circle, Figure 1) of WC 4, density was measured as σ_{θ}=27.74 kg m^{-3} with SPM=8240 µg L^{-1} near the seabed at 1376 m depth (event 83). Two meters above this, SPM concentrations were lower (6970 µg L^{-1}) and the density of ENL followed this trend: σ_{θ}=27.67 kg m^{-3}. Higher up in the water column, above the ENL, SPM values were ~2080 µg L^{-1} and the density remained constant at σ_{θ}=27.67 kg m^{-3}. Benthic values at the central station (white circle, Figure 1) in WC3 (event 84) had SPM concentrations of ~300 µg L^{-1} and σ_{θ}=27.74 kg m^{-3} (4 m above the bottom), while in the iENL observed in this profile between 1290-1180 m the concentration of SPM was 5030 µg L^{-1} and σ_{θ}=27.61 kg m^{-3}. In the smaller iENL above this at 1055-1159m, concentrations of SPM were ~ 1610 µg L^{-1} and σ_{θ}=27.58 kg m^{-3}.

3.3 Trawling activity on the spurs

VMS data showed 229 data points fitting the criteria for trawling activity (i.e. operating at less than or equal to 5 knots and reporting the use of bottom trawls) during the survey in June 2013 for the quadrangle studied (Figure 3). The highest number of recordings for vessels that fitted the criteria during the survey period (June 9th-18th) occurred on June 15th (43 data points) and June 16th (38 data points; Figure 3). Vessel positions recorded by VMS were linked to bathymetry of the area and indicated that the majority of the activity took place in 200-300 m water depths. The data revealed that trawling took place day and night regardless of time and was restricted to water depths <1000m, with the shallowest recording at 122 m.

Temporal activity of the vessels in lines or fishing tracks along the two spurs adjacent to WC3 and WC4 was revealed by VMS data (Figure 4). The times when the ENLs were observed coincided with or occurred immediately after a period of fishing, with the largest ENLs occurring after the highest trawling activity recorded. Recordings for June 13th, 15th and 16th, particularly June 15th (green squares) and June 16th (purple diamonds), emphasized the close proximity of trawling activity to locations where ENLs were observed.

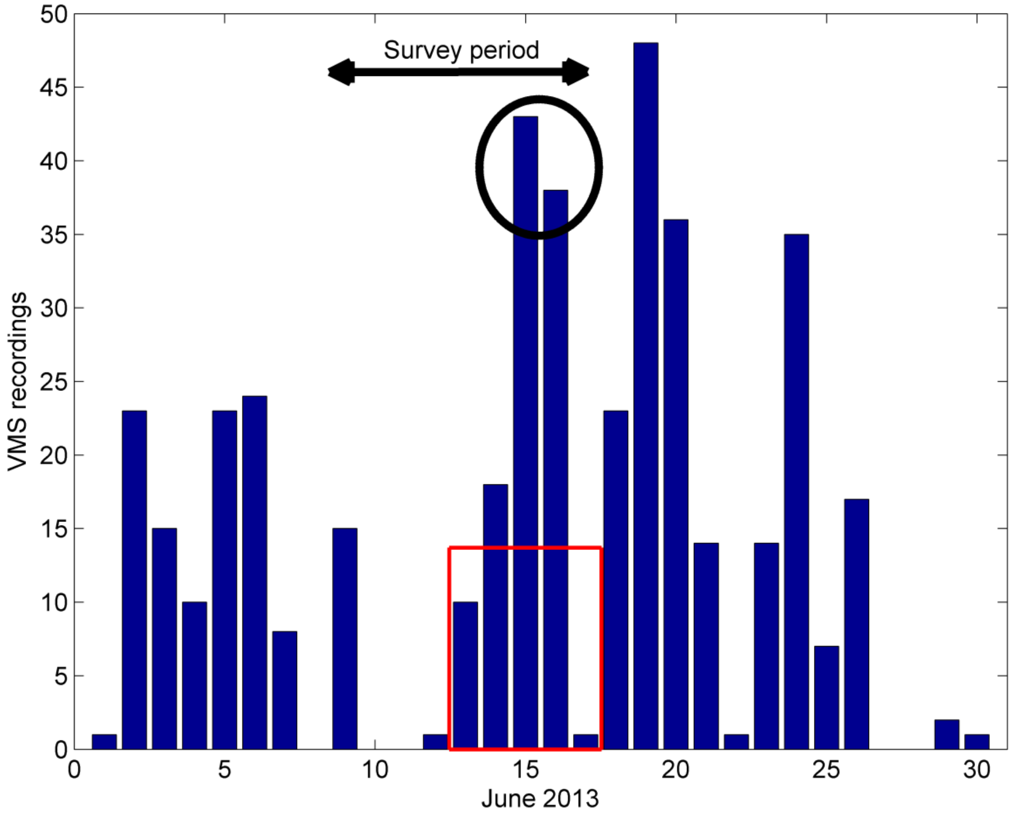

Figure 3. Vessel Monitoring System (VMS) recordings for bottom trawling in June 2013. Survey period is marked with an arrow and dates when enhanced nepheloid layers were detected are marked with a red box. The black circle highlights the highest frequency in VMS recordings and the

dates when maximum suspension particulate matter concentrations were detected. **(Note: 1 column-fitting image)**

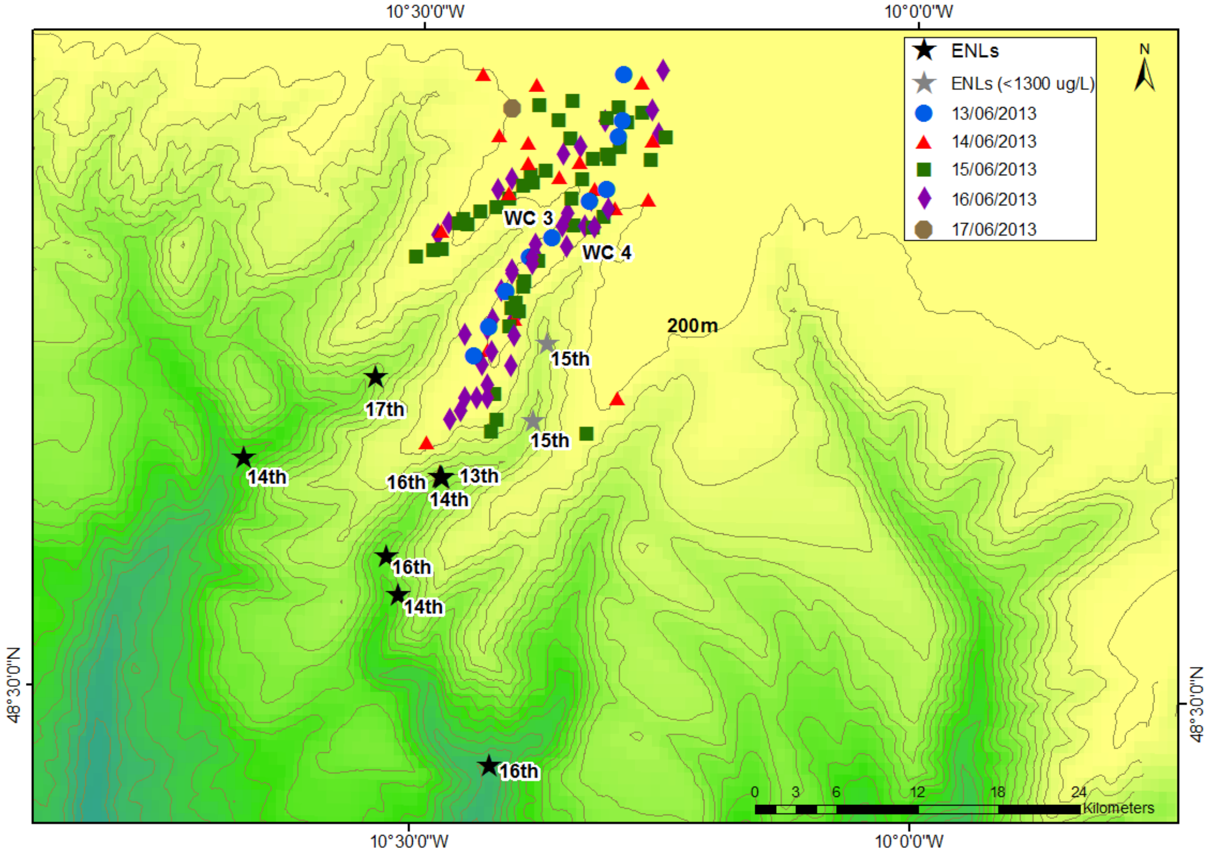

Figure 4. Blue circles (●), red triangles (▲), green squares (■), purple diamonds (◆) and brown octagons (⬢) correspond to Vessel Monitoring System (VMS) positions of vessels fitting the criteria to be trawling for the period when the enhanced nepheloid layers were detected. The locations and dates of enhanced nepheloid layers are shown as black stars ★(suspended particulate material >1300 µg L^{-1}) and grey stars ★ (600-1300 µg L^{-1}). **(Note: 2 column-fitting image)**

3.4 Molar C/N analysis of suspended organic particulate matter (sPOM)

Water samples for elemental analysis of the organic components of SPM were collected at a range of water depths, from normal and profiles indicating ENLs (Figure 5 and Table 1). Two distinct groupings were observed in the dataset corresponding to samples from ENLs and other samples from typical to small BNLs and INLs and the surface (Figure 6).

Generally, molar C/N ratios of sPOM increase with water depth, with ratios of 6-9 in surface waters indicating that the organic material is mainly sourced from phytoplankton with higher values implying that sPOM may have terrestrial contributions (unlikely thus far from land) or is more likely degraded (Kiriakoulakis et al., 2011 and references therein). A general trend of increasing molar C/N ratios with concentration of sPOM was seen in all samples (Figure 6 and Table 1). Molar C/N of surface waters had a value of 5 (event 69; SPM=750 µg L^{-1}). A sample in the upper reaches of the canyon (event 72; ~300 m) had a similar value of 4. Samples from typical to small NLs were taken from a range of depths (650-2800 m) and C/N ratios ranged between 1 and 4 (SPM≈100-500 µg L^{-1}). Samples from the largest ENLs (i.e. > ~2000 µg L^{-1}) had high molar C/N ratios ranging from 7-10 (SPM = 1938-8140 µg L^{-1}), while samples from smaller ENLs with lower SPM concentrations (i.e. < 2000 µg L^{-1}) had C/N ratios ranging from 5 to 27 (SPM= ~730-1200 µg L^{-1}).

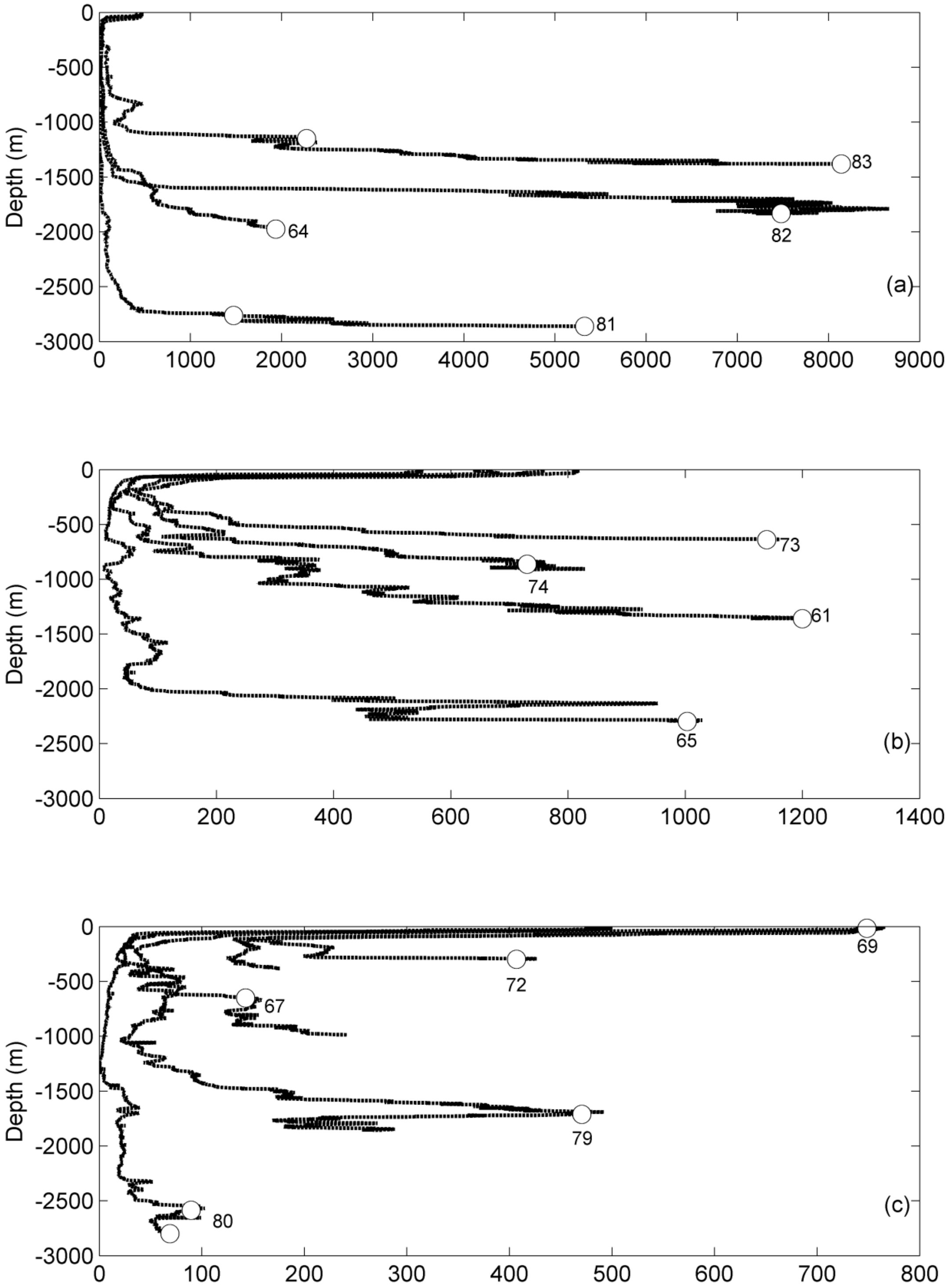

Figure 5. Vertical profiles of suspended particulate material (μg L^{-1}) with depths of water samples in figure 6 are indicated with open circles (○) for (a) enhanced nepheloid layers; (b) small enhanced nepheloid layers; (c) no enhanced nepheloid layers. **(Note: 1 column-fitting image)**

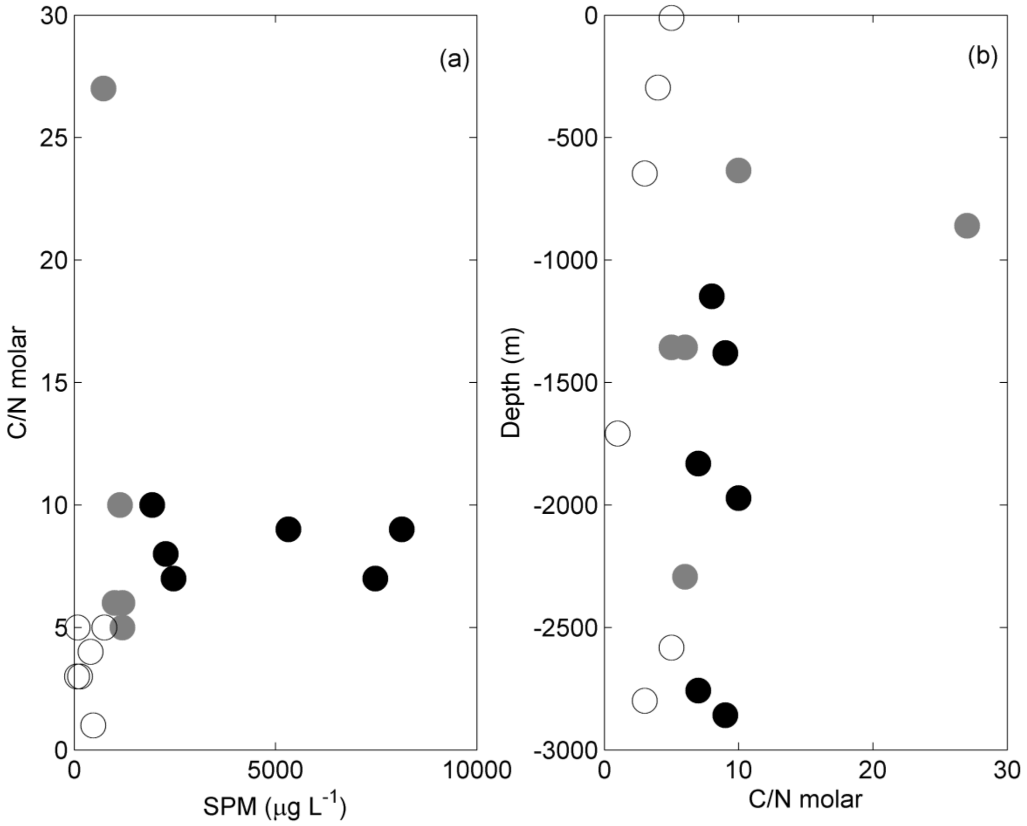

Figure 6. (a) Molar C/N versus concentration of suspended particulate material (SPM) measured in μg L^{-1} and (b) Molar C/N versus depth (m). Samples are from bottom mid and surface water depths. Data from enhanced nepheloid layers are shown with black circles (●); grey circles show small enhanced nepheloid layers (●) and open circles (○) show data from samples where there were no enhanced nepheloid layers. Corresponding geochemical data is shown in table 2. **(Note: 1 column-fitting image)**

4. Discussion

4.1 Evidence for trawl-induced ENLs

The evidence presented here suggests that trawling activity is likely responsible for the ENLs detected at the Whittard Canyon, although a natural mechanism for the mobilisation of sediments cannot be entirely ruled out. Visually, more trawlers were noted during the survey in 2013 than in 2012 or 2011. As a control, VMS data from the same area of the Whittard Canyon for the periods surveyed in (24-26th April) 2011 and (15-26th April) 2012 were also examined (Figure 7). There was no evidence of any unusual peaks in turbidity during either of these earlier surveys. VMS data fitting the criteria for trawling during the 2011 survey were limited to 14 recordings randomly scattered in the quadrangle during the survey period. During the 2012 survey, 43 recordings were measured and the locations and the times of the points suggested ~three fishing tracks along the spur between WC3 and WC4 and one to the west of WC4 between April 19-21st 2012 (Figure 7). However, CTD profiles recorded during this period were limited to mid-lower reaches of WC3. In comparison 299 recordings were measured during the survey period in 2013, with 43 recordings on the 15th of June alone and followed by a further 38 data points on the 16th of June. The increased trawling activity on the spurs during the 2013 survey period in comparison to 2011 and 2012 and advantageous CTD deployments in branches adjacent to these spurs during this time frame allowed for the chance detection of these events, with the timelines of fishing tracks and the appearance of ENLs matching as shown in Table 2. The highest number of trawl recordings on June 15th and 16th June coincide with the largest peaks in turbidity occurring on June 16th and 17th. It is likely that the peaks in turbidity reported here are not unique observations and are likely occurring more often than recorded. Indeed, it seems likely that another peak in turbidity would have been observed on June 19th when recordings of vessels reached 48 but unfortunately the survey was complete at this time.

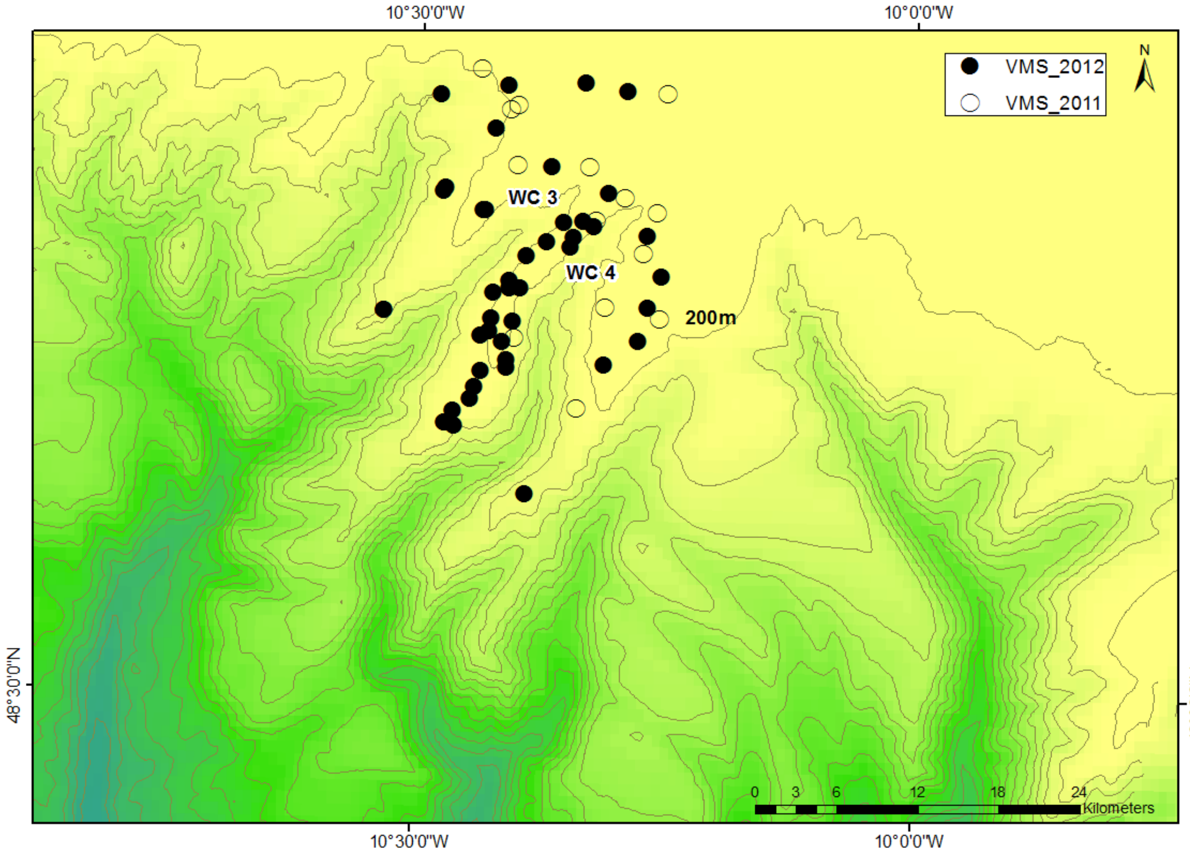

Figure 7. Vessel Monitoring System (VMS) recordings for bottom trawling during CE11006 survey (○) and CE12006 survey (●) periods. **(Note: 1 column-fitting image)**

The dislodgment and mobilization of SPM in the concentrations detected here could be induced by meteorologically driven events (e.g. storms or dense shelf water cascading (Gardner, 1989; Palanques et al., 2006) or tectonic activity. Relative to conditions during the 2012 survey when maximum wind speeds of 59 m s^{-1} and a mean speed of 30 m s^{-1} was measured during two significant storms (significant wave heights of 8-9 m), weather conditions were calmer during the 2013 survey. Winds were in a predominantly SSW-WSW direction with daily means varying between 7-24 m s^{-1}. Hull mounted ADCP data recorded underway during the survey revealed no unusual flow patterns down to 800 m water depth. Although the UK seismology network only detect earthquakes with magnitudes >2, USGS public seismic records confirmed that no there were no earthquakes within a 500 km radius of Whittard during the 2013 survey period (British Geological Survey earthquake database, 2015; U.S. Geological Survey, 2015). USGS records did show activity in the North Atlantic Ocean ~750 km to the south west (43° 48.18’ N 17° 8.1’ W at depth 14.8 m) before the survey on May 28th (magnitude 4.7). Therefore, a natural mechanism for the mobilization of sediment forming ENLs cannot be disregarded. However, figure 2f would suggest that the ENLs were being generated during the 2013 survey and not before.

The branches of the Whittard Canyon are incised with many tributaries that run from the top of the walls on the spurs into the canyon axis, providing ducts for trawl induced resuspended material. At La Fonera Canyon, the occurrence of gravity flows in the canyon axis matched with the timing of local fisherman passing a tributary of the canyon (Palaques et al., 2006). Many other studies have reported similar observations of material from sediment gravity flows or resuspension events induced by trawling being incorporated into nepheloid layers (Pilskaln et al., 1998; Palanques et al., 2001, 2014; Durrieu de Madron et al., 2005; Zúñiga et al., 2009; Martín et al., 2014). Observations here showed the ENLs dominating the SPM distribution of the water column, diminishing any natural nepheloid structure in the water column. Material suspended by critical internal waves that generate the nepheloid layers here is presumably mixed with the newly introduced sediment. When the plume settles out after a number of hours (Martín et al., 2014), lighter material may form intermediate nepheloid layers at another resuspension point.

4.2 C/N ratios of sPOM in ENLs

The categorization of SPM based on molar C/N ratios of sPOM showed that material from the ENLs was degraded in comparison to material taken from areas where there were no ENLs. As expected, a general trend of increasing C/N ratios from the surface to depth was observed due to the natural break down of sinking organic matter. C/N ratios higher than the Redfield ratio (~6), often reflect the preferential loss of nitrogen-rich organic compounds (e.g. amino acids) during transport (Redfield et al., 1963; Kiriakoulakis et al., 2001). Samples from ENLs had higher C/N values than samples not from ENLs (i.e. typical NLs; see Figure 5c) within the same depth range, indicating that sPOM from ENLs have undergone further degradation than that which is naturally observed with depth (see also Kiriakoulakis et al., 2001). These results would suggest the trawling activity was resuspending degraded superficial sediment and lithogenic material from the shelf that had been in the system for some time.

sPOM from smaller ENLs also showed high C/N ratios, but with generally higher values observed in conjunction with higher SPM concentrations. Greater amounts of material in suspension were detected primarily on the dates of highest trawling activity, indicating that perhaps greater fishing effort mobilized and entrained deeper sub-surface sediment. The very small ENL (event 74) with a very high C/N ratio may be the remnant of a larger event. Lighter material from the initial event may remaining in suspension for a longer time and thus allowing for degradation of this order, indicative of microbial activity. Sampling procedure errors due to filter rinsing and heterogeneous subsamples of water from the CTD rosette are likely responsible for the scatter of values observed between repeat samples (event 61).

Surface samples had high SPM and corresponding C/N ratios of 5 (event 69) indicating fresh phytoplankton-rich material. A sample in the upper reaches of the canyon (event 72; 310 m) had a similar C/N ratio of 4 and much the same as results in Portuguese submarine canyons (Kiriakoulakis et al., 2011). Nitrogen-enriched fine grained material (Keil et al., 1994) may be responsible for very low C/N values (1–3) detected in some of these samples (event 79, 67, 80).

4.3 iENLs and reoccurring events

Other studies have observed the detachment of nepheloid layers from canyon spurs at the depth ranges exploited by trawling (Zúñiga et al. 2009; Martín et al., 2014) but there were no similar observations here. While iENLs were observed in WC3 between 1055 – 1290 m (event 84), VMS logs show that trawling activity took place in mean water depths ~200m. These iENLs are likely density induced detachments, composed of lighter material that has remained in suspension for longer. The iENL detected in WC3 (event 84) was observed two hours after a large ENL in WC4 (event 83). If the iENL detected in WC3 and ENL in WC4 were both sourced from the same event, with the iENL generated from lighter material, it would be expected that the iENL is less dense. However, similar values of σ_θ of the ENLs in the two tributaries would suggest that they are not of the same origin. Considering the VMS data shows activity on both spurs adjacent to both branches, it is more reasonable that material is coming down as sedimentary gravity flows from the sides of both branches and suggests recurring events. Organic geochemical analysis of the material from both events would have provided valuable information on the material composition and duration of suspension but no samples were available from the iENL. The detection of smaller ENLs prior to the big events would suggest a link with a build up before the larger ENLs in the lower reaches of the branch. Alternatively, smaller ENLs (e.g. event 65 at 2293 m in WC3) may possibly be the remnant of a previous plume. The sporadic sampling regime may be responsible for the detection of the plume in WC3 two hours after the event in WC4, while this event may have been happening instantaneously as has been seen in other studies (Palanques et al., 2006). Due to the limited data set it is not possible to conclude whether the ENLs were sourced by one event or a number of recurring events, but the time lines of VMS and appearance of the ENLs would indicate that these were ongoing processes (Table 2) and it is likely that not all events were captured.

Table 2. Timeline of trawling activity and enhanced nepheloid layers occurrence. Date, number of VMS recordings, estimated number of vessels (based on country of origin) and average water depth fished (based on position and local bathymetry) with locations of fishing tracks and corresponding enhanced nepheloid layers (ENLs); location, depth and details.

Date (June 2013)	# recordings	# vessels	Av. Water depth(m)	Track period	Track details	ENLs	Location	Bottom depth (m)	EV	ENL details
13th	10	1	181	**02:24-11:24**	Down and up spur between WC3 & 4	**11:55**	WC 4	1371	61	Small ENL (benthic)
14th	18	3	196	**06:24-11:24**	Shelf edge top of canyon head, down E side WC3	**08:46**	WC 4	1387	63	ENL (benthic)
				11:35-21:13	E sideWC4, down spur between WC3& 4	**13:50**	WC4	1992	64	Small ENL (benthic)
15th	43	3	198	**15:28-23:06**	Shelf edge, head of WC3&4, W side WC3	**17:30**	WC 3	2304	65	Small ENL (benthic & intermediate)
				19:06-23:06	From W-E across shelf edge, down W side WC3					
				00:06-19:06	Head WC3, up + down E of WC3 (x3)	**09:30**	WC4	640	73	Small ENL (benthic)
				00:24-23:23	Head WC3+futher E, down spur between WC3&4.	**10:09**	WC4	922	74	Small ENL (benthic)
16th	38	3	196	**00:03-23:30**	Up + down spur between WC3&4.	**14:45**	WC4	2875	81	ENL (benthic)
				00:06-06:06	Down +up spur W side WC3+onto shelf edge	**19:30**	WC4	1856	82	ENL (benthic)
				01:01-22:09	Up + down spur between WC3&4 (x6)	**22:00**	WC4	1376	83	ENL (benthic)
17th	1	1	198	**22:45**	Isolated recording	**00:35**	WC3	1363	84	ENL (benthic & intermediate)

4.4 Impacts and implications of bottom trawling transporting sediment

Trawling is now widely recognised as a significant driver of sediment transport dynamics (Palanques et al., 2006; Puig et al., 2012; 2014; Martín al., 2014; 2015). The effects of trawling vary widely with physical impacts ranging from changes in sediment characteristics, water quality and sediment transport dynamics to alterations in seabed morphology (e.g. Martín et al., 2008; Puig et al., 2012). In the Mediterranean, the industrialisation of the fishing fleet has been held accountable for accelerated sedimentation and accumulation rates in sediment cores there (Martín et al., 2008) and it is likely that intensive fishing at the Celtic margin is having a similar affect. One third of the sediment exported from the Gulf of Lions shelf is estimated to be brought about by trawling induced resuspension (Ferré et al., 2008), while export at the shelf of Ebro increased by 5-9 times during trawling periods (Palanques et al., 2014) and 5.4 x 10^3 tons of sediment was estimated to be exported from fishing grounds in 136 days at La Fonera Canyon (Puig et al., 2012). The ENLs observed here incorporate any naturally present nepheloid layers present before the event into one large gravity flow after the trigger as similarly observed by e.g. Palanques et al. (2006) and, with concentrations of SPM at least an order of magnitude higher than previously observed in typical NLs, are likely to have similar effects on sediment transport rates, deposition and transfer fluxes.

The physical changes made to grain sizes and deposition rates by trawling activity are also likely to influence carbon fluxes and sequestration. As discussed by Martín et al. (2015), if bottom trawling influences, and in most cases enhances lateral transport of sediments, then local and regional carbon budgets will be affected as will the export of material to the deep ocean. Excess turbidity can clog the respiratory surfaces of fauna, while smoothing of topographic features may disturb larval settlement and affect the unique canyon ecosystems (e.g. Watling and Norse, 1998). The vertical walls of Whittard Canyon harbor unique assemblages (Johnson et al., 2013). Although the ENLs were not detected in the upper water column where these walls are found, these density laden flows are likely to impinge on the lower parts of the wall and with repeated activity could alter the morphology and habitats found on this feature. It would be reasonable to presume that trawling is causing more resuspension events that those reported here. Previous studies have found evidence of trawling marks at the Whittard Canyon (Huvenne et al., 2011); while others have suggested the possibility that trawling causes large peaks in turbidity (Amaro et al., 2015). Although most studies have seen background values of suspended sediment return after a number of hours (e.g. Martín et al., 2014), the processes induced by the repeated action of trawling appear to pose the great threat to the ocean/benthic ecosystems and margin shaping (Puig et al., 2012). Effects of these events and maximum resuspension are not localized to the fishing sites. As demonstrated by O'Neill and Summerbell (2011), the mass of sediment entrained is directly related to the hydrodynamic drag of the gear components and the type of sediment over which it is towed. Direct impacts can therefore extend great distances and depths depending on; gear, equipment add-ons (e.g. tickler chains), substrate type and operational methods (Martín et al., 2015 and references therein). Most studies on trawling resuspension have taken place in coastal and continental shelf environments but the effects of trawling are likely be more profound at slope depths (Martín et al., 2015). The steep bathymetry of submarine canyons, naturally focusing excess sediment from shallower trawling locations, is therefore likely to increase their vulnerability to the impacts of trawl induced resuspension.

5. Conclusions

Sediment transport processes from productive shelf seas carry material for consumption by benthic ecosystems and for deposition to the deep sea. Many of these processes are enhanced by the steep bathymetry of conduiting submarine canyons. Anthropogenic activity in the form of bottom trawling is now known to cause excess resuspension of sediments, inducing sediment gravity events and accelerating the export and deposition of material. Here we have detected unusual peaks in turbidity with high concentrations of SPM at the Whittard Canyon over a five day period. Although concentrated nepheloid layers are commonly observed in Whittard, the layers detected here had concentrations of SPM an order of magnitude higher than maximum values typically found in NLs at this site. The locations and presence of bottom trawlers in the area provides persuasive evidence for the relationship between trawling activity on the adjacent spurs and the occurrence of ENLs. The ENLs appear to be induced by the excess density of the addition sediment. The molar C/N ratios of sPOM were highly heterogeneous and suggested that material from the ENLs is degraded more than passively sinking or recently deposited particles on the sea floor, indicating its long residence times in the system. VMS logs and the data presented here would suggest that this is a recurring event, with sufficient activity inducing small and larger plumes. Our study only provides a snapshot of the full story and more extensive study is required to fully explain these and other unusual peaks that have been detected in this region (Amaro et al., 2015). Sediment dating and knowledge of the sedimentation and accumulations rates would greatly increase our understanding. The deep sea is a fragile environment vulnerable to alterations and takes a long time to recover from negative impacts. It is likely that recurrence of plumes like those described here would have similar effects on sediment transport rates and dynamics to those reported in the Mediterranean. As suggested by Martín et al. (2015), perhaps bottom trawling needs to be considered and measured as another process governing deep sea sediment dynamics.

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