

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

2 Annette M. Wilson*^a, Robin Raine^a, Hans D. Gerritsen^b, Konstadinos Kiriakoulakis^c, Sabena

3 Blackbird^d, A. Louise Allcock^a and Martin White^a

4 ^aSchool of Natural Sciences and Ryan Institute, National University of Ireland Galway, University

5 Road, Galway, Ireland

6 ^bMarine Institute, Rinvilla, Oranmore, Co. Galway, Ireland

7 ^cSchool of Natural Sciences and Psychology, Liverpool John Moores University, Liverpool L3 3AF, UK

8 ^dSchool of Environmental Sciences, University of Liverpool, Liverpool L69 3BX, UK

9

10 *Corresponding author:

11 E-mail: wilson.m.annette@gmail.com

12 Tel: +353 91 493921

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14 **Abstract**

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

26

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

28

29 1. Introduction

30 The steep sloping topography of submarine canyons promotes complex hydrographic and
31 sedimentary conditions and provides a preferential pathway for the transport of material from
32 continental shelves to the deep sea (Canals et al., 2013). Their conduit nature causes greater food
33 availability, attracting a wealth of benthic species and enhancing the burial of organic carbon.
34 Sediment gravity flows including nepheloid layers and other disturbance events can resuspend and
35 transport material to great depths (e.g. Hotchkiss and Wunsch, 1982; Gardner, 1989; Puig et al.,
36 2008;2014; de Stigter et al., 2007). Amplified energetic processes in submarine canyons support the
37 generation of benthic (BNL) and intermediate nepheloid layers (INL), which are significant
38 contributors to the shelf edge exchange of sediment (Amin and Huthnance, 1999; Puig et al., 2014).
39 These suspended layers contain higher amounts of suspended particulate matter (SPM) than the
40 surrounding clear-water minimum and are commonly observed along the NE Atlantic continental
41 margin (e.g. Thorpe and White, 1988; Mc Cave et al., 2001; Wilson et al., 2015).

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

55 Palanques et al., 2001; Durrieu de Madron et al., 2005) or provide additional dense elements to
56 trigger sediment gravity flows (Palanques et al., 2006; Puig et al., 2012; Martín et al., 2014). Accurate
57 estimates of the quantity of material being introduced to the water column are needed to better our
58 understanding of the broader environmental and ecological impacts of bottom trawling (O'Neill and
59 Summerbell, 2011). The elevated sediment transport rates and consequent impacts reported in the
60 NW Mediterranean during trawling periods (e.g. Palanques et al., 2014) are likely to be occurring in
61 other well trawled areas like the Celtic Sea. Since the 1980's the NE Atlantic and central European
62 margin have been heavily trawled due to the increase in fishing and industrialization of fleets (Puig
63 et al., 2012). In the northern Celtic Sea over two-thirds of the bottom area is impacted by trawling at
64 least once per year and some areas are impacted more than ten times per year (Gerristen et al.,
65 2013). At the edge of the continental shelf in the Celtic Sea, Whittard Canyon has been the focus of
66 much submarine canyon research in this area. Although there have been no direct studies of
67 trawling activity in the water column at Whittard, ROV footage and side scan sonar have shown
68 trawl marks on the spurs of the upper part of the canyon (Huvenne et al., 2011), while other studies
69 have detected inexplicably high peaks in turbidity deeper in the Whittard Channel (Amaro et al.,
70 2015).

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

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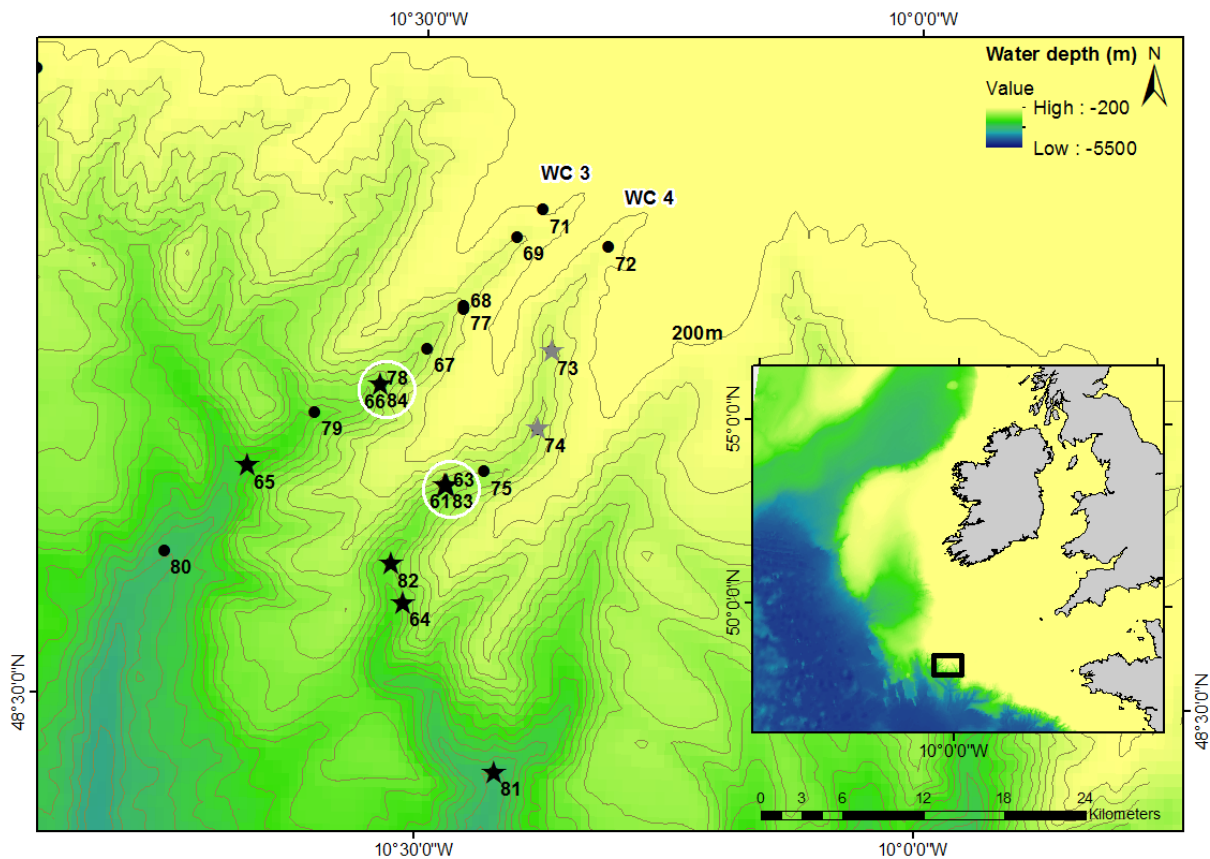
75 **2. Material and methods**

76 *2.1 Study area*

77 Whittard Canyon is a dendritic submarine canyon located at the edge of the continental shelf
78 approximately 300 km off southwest Ireland with Goban spur to the west and Meriadzek Terrace to
79 the south-east. The system cuts the continental margin with the head of the canyon connected to
80 the Celtic Sea shelf at ~200 m water depth. The branches extend (100 km) from the upper slope and

81 are characterized by steep vertical walls. Incised by numerous gullies, the branches converge into
82 one deep channel at ~3800 m. The principal water masses comprise; Eastern North Atlantic Water
83 (ENAW), Mediterranean Outflow Water (MOW), Labrador Sea Water and North Atlantic Deep Water
84 (NADW) (Pollard et al., 1996; van Aken, 2000). The upper water column (150-700 m) is characterized
85 by the boundary slope or Shelf Edge Current (SEC), with mean flows of 5 -10 cm s⁻¹ (Pingree and Le
86 Cann, 1990; Xu et al., 2015). Bottom currents display tidal frequencies with reports of maximum
87 velocities varying between 16 and 40 cm s⁻¹ (Reid and Hamilton, 1990; van Weering et al., 2000;
88 Duros et al., 2011; Amaro et al., 2015). Nepheloid layers (NLs) are commonly observed throughout
89 the water column and dominate distribution patterns of SPM (Johnson et al., 2013; Wilson et al.,
90 2015). Pelagic material and reworked sediments from the outer shelf and canyon edges tend to be
91 coarse in the upper canyon in contrast to the alterations of coarse and fine material found in the
92 lower reaches (Duros et al., 2011). The Celtic Sea shelf break is characterized by high internal tidal
93 energy fluxes (Vlasenko et al., 2014) that drive nutrient fluxes and fuel enhanced primary
94 productivity (Sharples, 2007) in surface waters along the margin and in the Bay of Biscay (100-250 g
95 C m⁻² yr⁻¹, Wollast and Chou, 2001). High primary production promotes good fishing and the Celtic
96 Sea shelf break is heavily fished by various fleets mainly from Spain, France and Ireland using bottom
97 trawls, pelagic trawls and longlines (Gerritsen and Lordan, 2014).

98



99

100 **Figure 1.** Location and bathymetry of Whittard Canyon on the Celtic Sea Shelf, NE Atlantic. CTD
 101 stations from CE13008 are shown as black dots (●) and labeled with event numbers in black.
 102 Locations of enhanced nepheloid layers are shown as black stars ★(suspended particulate material
 103 >1300 $\mu\text{g L}^{-1}$) and grey stars ★ (600-1300 $\mu\text{g L}^{-1}$). Central stations where repeats profiles were made
 104 are marked with a white circle. **(Note: 2 column-fitting image)**

105

106 2.2 Sampling and analytical methods

107 Four branches of the Whittard Canyon system were surveyed between 2011 and 2013 on
 108 the RV *Celtic Explorer* with benthic and intermediate nepheloid layers observed in all four surveyed
 109 branches (see Figure 1 and Table 1; Wilson et al., 2015). Here we focus on unusual observations
 110 from two of those branches, WC3 and WC4 (Figure 1), during the 2013 survey (CE13008; 9-17th
 111 June), where enhanced nepheloid layers (ENLs) were observed repeatedly during a five day period
 112 (13-17th June). Transects and locations of sampling events where ENLs were detected are shown in
 113 Figure 1 and details of water samples used in this study are shown in Table 1.

114 Hydrographic measurements were carried out using a Seabird SBE 911 CTD and SBE32
 115 rosette system in transects along the branches with repeat profiles taken at key stations. Vertical

116 profiles of water turbidity were recorded by a 0.25 m path-length transmissometer (C-star, WET
117 Labs) operating at 650 nm. Transmission values were converted to beam attenuation coefficient
118 (BAC) which was correlated by linear regression with the mass of suspended particulate material
119 (SPM $\mu\text{g L}^{-1}$) obtained from filtered water samples collected during three surveys 2011-2013 as
120 described in Wilson et al. (2015); see Figure 2.

121 Samples for qualitative analysis (organic carbon and total nitrogen) of the SPM were
122 collected on two stacked pre-combusted (400°C, 4 hrs) 47 mm GF/F filters, using water samples (2-
123 10 L) collected from the CTD rosette. On recovery, each filter was folded in half (onto itself) and then
124 into quarters before wrapping in combusted foil and storing at -80 °C for the duration of the cruise.
125 Samples were analyzed according to the methods of Kiriakoulakis et al. (2009). Briefly, after freeze-
126 drying, punched circles ($\sim 7 \text{ mm}^2$) were taken from homogenous areas on the top filters of the stacks
127 (at the middle and edge of the filters) for measurement of particulate organic carbon and nitrogen
128 (POC, PN). POC values were obtained after de-carbonation of the filters and PN values were
129 determined before decarbonation on separate circles. The analyses were carried out using a
130 CEInstruments NC 2500 CHN analyzer in duplicate and the mean value was taken. Consistent
131 variability between circles from the edge and middle of the filter, a filtration artifact, were observed
132 and mean values were therefore taken to give a better approximation of the true value of the filter.
133 The bottom filters of the stacks were used to correct for overestimations of POC and PN due to
134 adsorption of dissolved organic matter (DOM) onto the filters (see Turnewitsch et al., 2007).

135 Data on the activity of fishing vessels are remotely collected by the Irish Naval Service
136 through Vessel Monitoring Systems (VMS). These systems transmit a vessel's position and speed at
137 intervals of 2h or less. VMS data for the study area quadrangle (48° 30' – 48° 55' N, 10° 35'– 10° 15'
138 W) for the month of June 2013 were extracted. The total records for the month of June (589) were
139 reduced to those fitting the criteria for trawling activity and recorded during the operational survey
140 period to Whittard Canyon (9-17th June 2013). To fit the criteria (likely) for trawling activity, vessels
141 must be equipped with bottom trawling gear and be operating at ≤ 5 knots, a suitable threshold to

142 denote fishing activity (Gerritsen and Lordan, 2011). Vessels meeting these criteria were selected
143 and plotted using ArcGIS 10.2 (ESRI). Data outside these criteria were discarded. VMS data in the
144 quad from 2011 and 2012 during the periods when two previous research surveys (CE11006: 24-26th
145 April & CE12006; 15-26th April) were also examined.

146 **Table 1.** Geochemical data; date, time, co-ordinates, location, elemental; particulate nitrogen (PN), particulate organic carbon (POC) and suspended
 147 particulate matter concentrations (SPM) of samples from enhanced nepheloid layers (ENLs), small ENLs and water samples where no ENL was present.
 148

	Date (June '13)	Time (UTC)	Branch WC	Event #	Latitude N	Longitude W	Sample depth (m)	Bottom depth (m)	PN ($\mu\text{g L}^{-1}$)	POC ($\mu\text{g L}^{-1}$)	C/N (molar)	SPM ($\mu\text{g L}^{-1}$)
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

149 **3. Results**

150 *3.1 Distribution of SPM in the water column and peaks in turbidity*

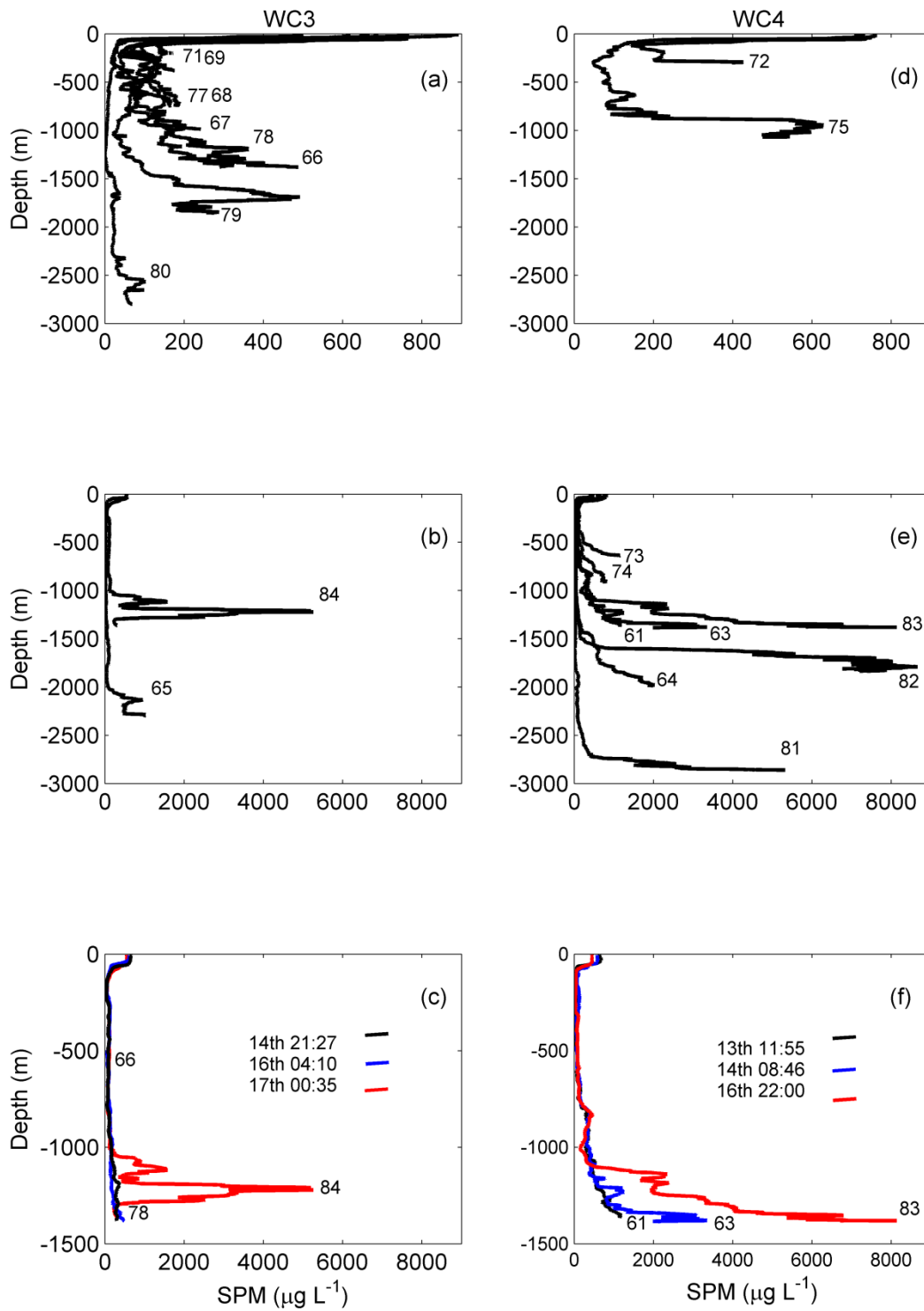
151 Increased SPM concentrations were commonly observed at benthic and various
152 intermediate mid-water depths with concentrations ranging between $>275\text{--}600\ \mu\text{g L}^{-1}$ (Figure 2a and
153 d and Wilson et al., 2015). Vertical profiles in WC3 (Figure 2a-c) and WC4 (Figure 2d-f) showed a
154 general increase in SPM towards the seabed in significant BNLs. Similarities in thickness and depth
155 ranges of occurrence were observed in both branches in comparison to the observations in these
156 and other branches (WC1 and WC2) during this and previous surveys (2011, 2012, see Wilson et al.,
157 2015). BNL thicknesses of 150-200 m were detected with INLs extending from the BNL at 250 m, 850
158 m, 1150 m and 1600 m (Figure 2a and d).

159 Unusual peaks in turbidity were observed in a number of profiles from the mid-lower
160 reaches (i.e. $> \sim 1150\text{m}$) WC3 and WC4 (Figure 2b and e). These observations were unexpected and
161 therefore measurements were restricted to a small number of isolated profiles. Concentrations of
162 SPM ranged from $\sim 1000\text{--}8000\ \mu\text{g L}^{-1}$; exceeding the highest values previously detected by at least
163 one order of magnitude. Typical BNL concentrations were observed up to $\sim 400\text{ m}$ above the seabed
164 (Figure 2c and f) with maximum SPM in the ENL just above the seabed with comparable thicknesses
165 of normal BNLs, ranging from $\sim 100\text{--}260\text{ m}$. The ENLs were detected in the upper reaches of WC4 at
166 $\sim 640\text{ m}$ and all along the axis down to $\sim 2875\text{ m}$, a distance of $\sim 24\text{ km}$, with two observations in the
167 middle of WC3 at 1363-2304 m.

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

175 L⁻¹ (Figure 2f; event 83). In the upper reaches of the branch (i.e. <1370 m), small ENLs (SPM values of
176 ~1000-2000 µg L⁻¹) were also detected (Figure 2e; event 73, 74) on June 15th. In the lower reaches
177 (i.e. >1370 m), large ENLs were detected at 1856 m (event 81) and again at 2875 m (event 82) on
178 June 16th, with maximum concentrations at both locations exceeding 4000 µg L⁻¹ and matching the
179 highest observations at the central station (white circle, Figure 1) of ≥8000 µg L⁻¹, 24 km further up
180 the branch. A smaller ENL between these two locations at 1992m was observed on 14th June with
181 maximum concentrations of ~1900 µg L⁻¹.

182 On the same day, 8.9 km to the west in the adjacent branch, WC3, a smaller intermediate
183 ENL (iENL) was observed with values of ~1000 µg L⁻¹ at 2200 m (Figure 2b; event 65). Further up the
184 branch at ~1370 m, no evidence of enhanced turbidity was detected until June 17th at 00:35 (Figure
185 2c). At 00:35, concentrations exceeded 5000 µg L⁻¹, with a thick iENL (~110 m) observed lying
186 between 1180-1290 m ~70 m above the seabed (event 84). Repeat vertical profiles at this station,
187 ~1370 m in WC3 (central station indicated with a white circle in Figure 1), capture the sudden
188 appearance of the ENLs within a ~20 hour period, while profiles in WC4 show the ongoing
189 appearance of the ENLs (Figure 2f). In WC4, concentrations increased by ~2000 µg L⁻¹ within 21
190 hours. iENLs were observed with peaks of the order of ~1200 µg L⁻¹ between 1100-1250 m. SPM
191 concentrations in these layers doubled (≥2400 µg L⁻¹) within 61 hours with iENLs detected at similar
192 depth ranges and thicknesses of ~125 m presenting as a continuum into the benthic ENL.



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 195
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Figure 2. Vertical profiles of suspended particulate material expressed in $\mu\text{g L}^{-1}$ 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

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

199

200 3.2 ENL categorization

201 ENLs were defined here as nepheloid layers with peaks in turbidity and elevated SPM
202 concentrations exceeding $\sim 1000 \mu\text{g L}^{-1}$. Plumes by this definition were detected on June 13th, 14th,
203 15th, 16th and 17th 2013 in two tributaries of the canyon at eight locations (Table 1). Measurements
204 from June 13th-15th inclusive had concentrations less than or equal to $\sim 2000 \mu\text{g L}^{-1}$ and were
205 categorized as smaller or remnant ENLs (light grey in Table 1). Measurements exceeding $\sim 2000 \mu\text{g L}^{-1}$
206 were classified as large ENLs (dark grey Table 1) and were observed mainly on June 16th and 17th, in
207 water depths of $\geq \sim 1150 \text{ m}$.

208 To differentiate whether the ENLs detected on June 17th in WC3 (event 84) were separate to
209 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
210 central station (white circle, Figure 1) of WC 4, density was measured as $\sigma_\theta = 27.74 \text{ kg m}^{-3}$ with
211 SPM = $8240 \mu\text{g L}^{-1}$ near the seabed at 1376 m depth (event 83). Two meters above this, SPM
212 concentrations were lower ($6970 \mu\text{g L}^{-1}$) and the density of ENL followed this trend: $\sigma_\theta = 27.67 \text{ kg m}^{-3}$.
213 Higher up in the water column, above the ENL, SPM values were $\sim 2080 \mu\text{g L}^{-1}$ and the density
214 remained constant at $\sigma_\theta = 27.67 \text{ kg m}^{-3}$. Benthic values at the central station (white circle, Figure 1) in
215 WC3 (event 84) had SPM concentrations of $\sim 300 \mu\text{g L}^{-1}$ and $\sigma_\theta = 27.74 \text{ kg m}^{-3}$ (4 m above the bottom),
216 while in the iENL observed in this profile between 1290-1180 m the concentration of SPM was 5030
217 $\mu\text{g L}^{-1}$ and $\sigma_\theta = 27.61 \text{ kg m}^{-3}$. In the smaller iENL above this at 1055-1159m, concentrations of SPM
218 were $\sim 1610 \mu\text{g L}^{-1}$ and $\sigma_\theta = 27.58 \text{ kg m}^{-3}$.

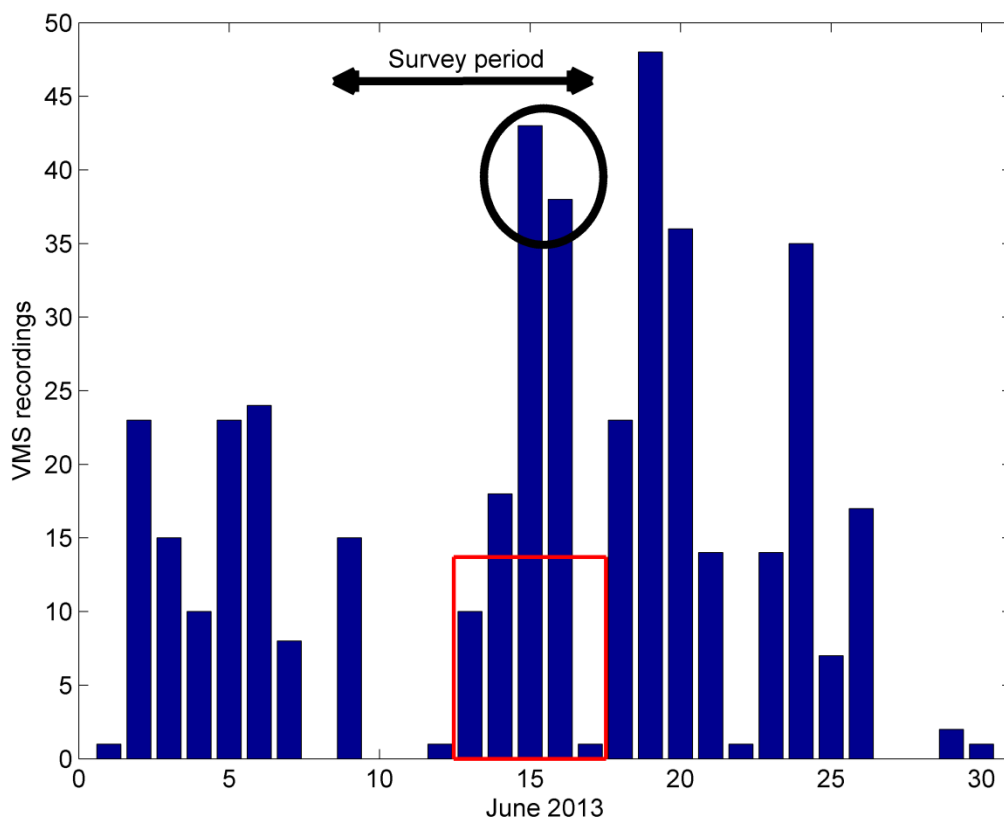
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220 3.3 Trawling activity on the spurs

221 VMS data showed 229 data points fitting the criteria for trawling activity (i.e. operating at
222 less than or equal to 5 knots and reporting the use of bottom trawls) during the survey in June 2013
223 for the quadrangle studied (Figure 3). The highest number of recordings for vessels that fitted the

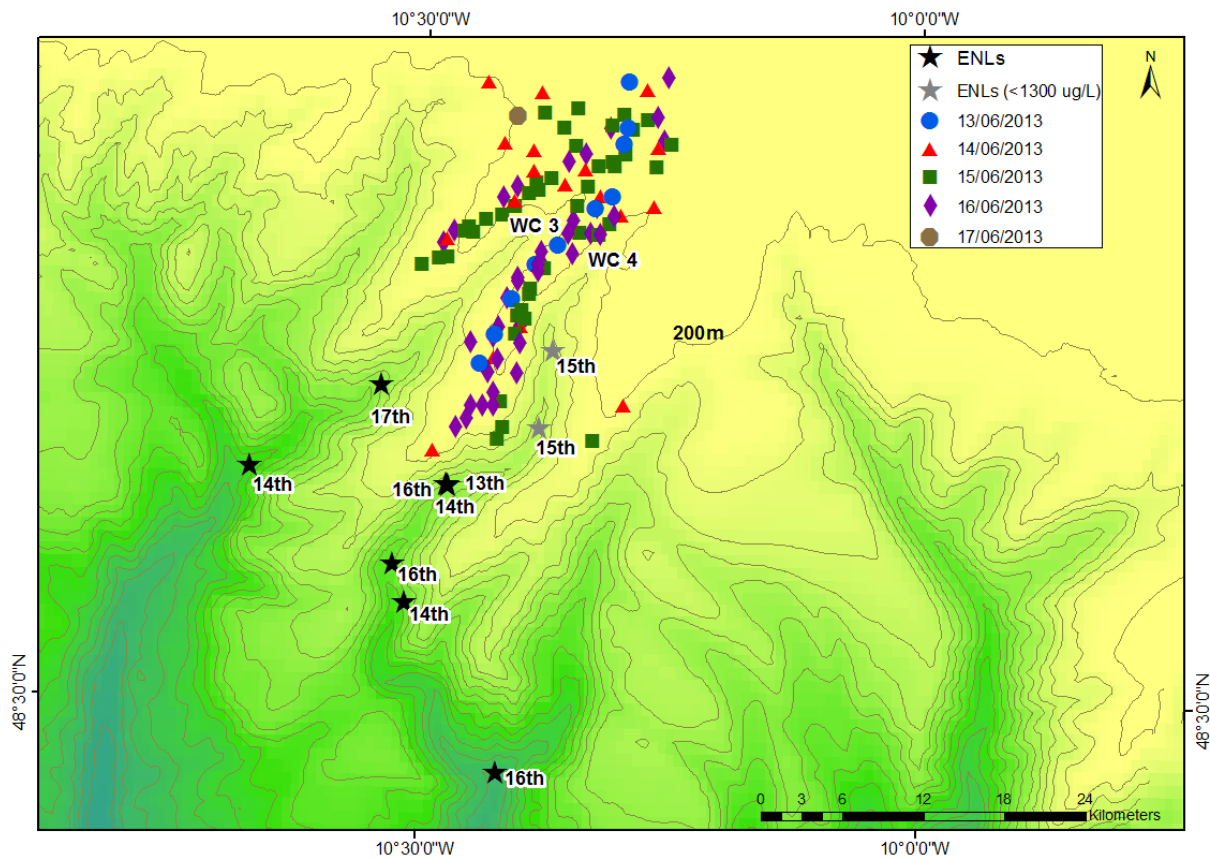
224 criteria during the survey period (June 9th-18th) occurred on June 15th (43 data points) and June 16th
225 (38 data points; Figure 3). Vessel positions recorded by VMS were linked to bathymetry of the area
226 and indicated that the majority of the activity took place in 200-300 m water depths. The data
227 revealed that trawling took place day and night regardless of time and was restricted to water
228 depths <1000m, with the shallowest recording at 122 m.

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



235 **Figure 3.** Vessel Monitoring System (VMS) recordings for bottom trawling in June 2013. Survey
236 period is marked with an arrow and dates when enhanced nepheloid layers were detected are
237 marked with a red box. The black circle highlights the highest frequency in VMS recordings and the
238

239 dates when maximum suspension particulate matter concentrations were detected. **(Note: 1**
 240 **column-fitting image)**
 241



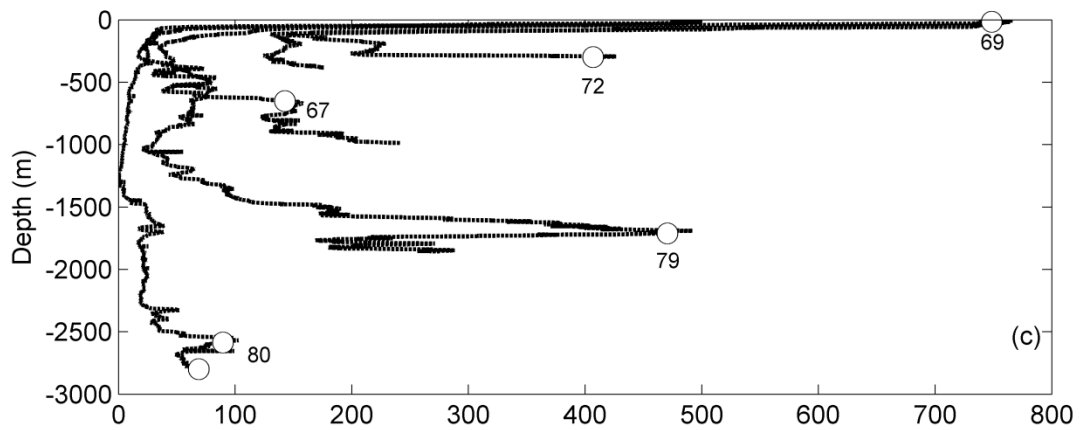
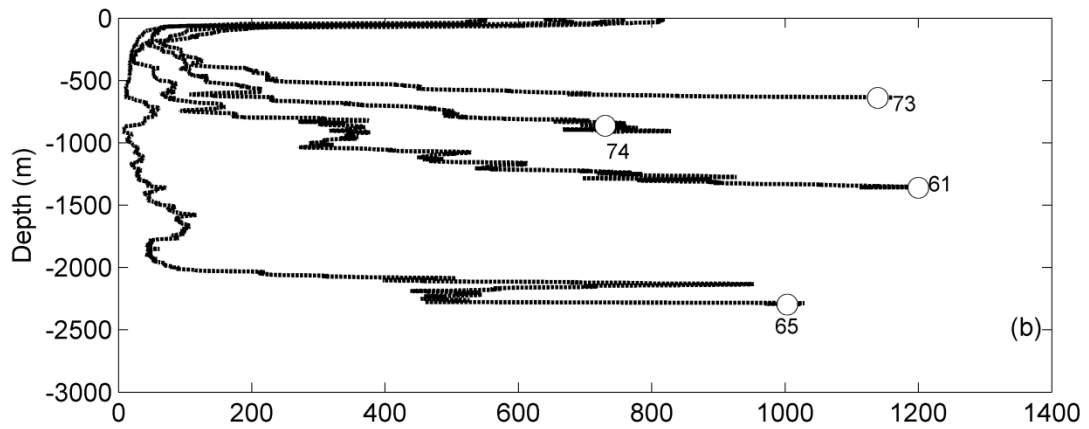
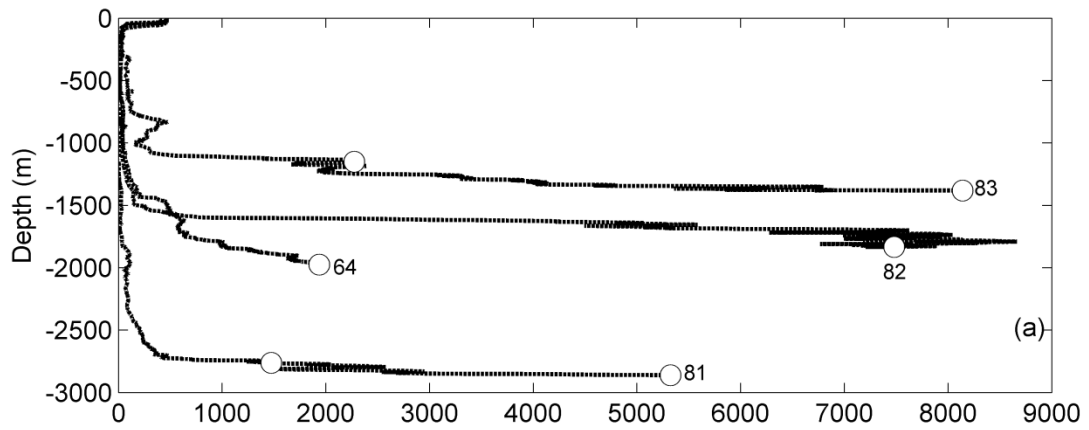
242
 243 **Figure 4.** Blue circles (●), red triangles (▲), green squares (■), purple diamonds (◆) and brown
 244 octagons (●) correspond to Vessel Monitoring System (VMS) positions of vessels fitting the criteria
 245 to be trawling for the period when the enhanced nepheloid layers were detected. The locations and
 246 dates of enhanced nepheloid layers are shown as black stars ★(suspended particulate material
 247 >1300 $\mu\text{g L}^{-1}$) and grey stars ★ (600-1300 $\mu\text{g L}^{-1}$). **(Note: 2 column-fitting image)**
 248

249 **3.4 Molar C/N analysis of suspended organic particulate matter (sPOM)**

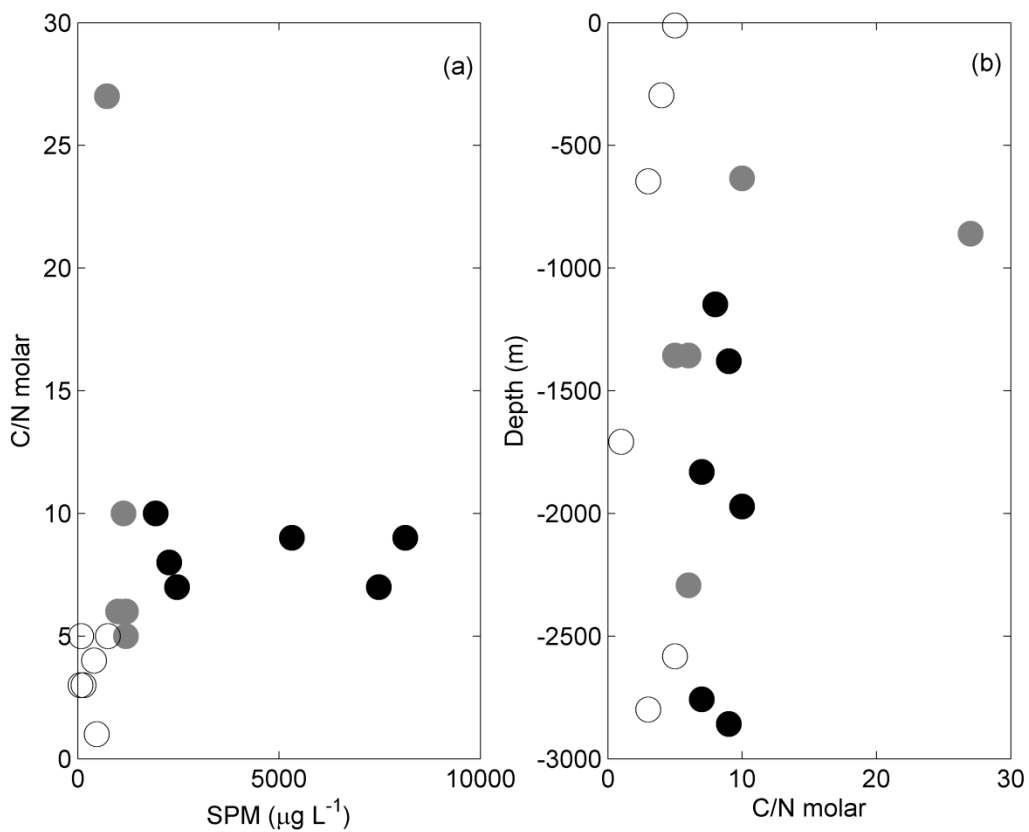
250 Water samples for elemental analysis of the organic components of SPM were collected at a
 251 range of water depths, from normal and profiles indicating ENLs (Figure 5 and Table 1). Two distinct
 252 groupings were observed in the dataset corresponding to samples from ENLs and other samples
 253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

254 Generally, molar C/N ratios of sPOM increase with water depth, with ratios of 6-9 in surface
 255 waters indicating that the organic material is mainly sourced from phytoplankton with higher values
 256 implying that sPOM may have terrestrial contributions (unlikely thus far from land) or is more likely
 257 degraded (Kiriakoulakis et al., 2011 and references therein). A general trend of increasing molar C/N

258 ratios with concentration of sPOM was seen in all samples (Figure 6 and Table 1). Molar C/N of
259 surface waters had a value of 5 (event 69; SPM=750 $\mu\text{g L}^{-1}$). A sample in the upper reaches of the
260 canyon (event 72; ~300 m) had a similar value of 4. Samples from typical to small NLs were taken
261 from a range of depths (650-2800 m) and C/N ratios ranged between 1 and 4 (SPM \approx 100-500 $\mu\text{g L}^{-1}$).
262 Samples from the largest ENLs (i.e. > ~2000 $\mu\text{g L}^{-1}$) had high molar C/N ratios ranging from 7-10 (SPM
263 = 1938-8140 $\mu\text{g L}^{-1}$), while samples from smaller ENLs with lower SPM concentrations (i.e. < 2000 μg
264 L^{-1}) had C/N ratios ranging from 5 to 27 (SPM= ~730-1200 $\mu\text{g L}^{-1}$).



265
 266 **Figure 5.** Vertical profiles of suspended particulate material ($\mu\text{g L}^{-1}$) with depths of water samples in
 267 figure 6 are indicated with open circles (O) for (a) enhanced nepheloid layers; (b) small enhanced
 268 nepheloid layers; (c) no enhanced nepheloid layers. **(Note: 1 column-fitting image)**

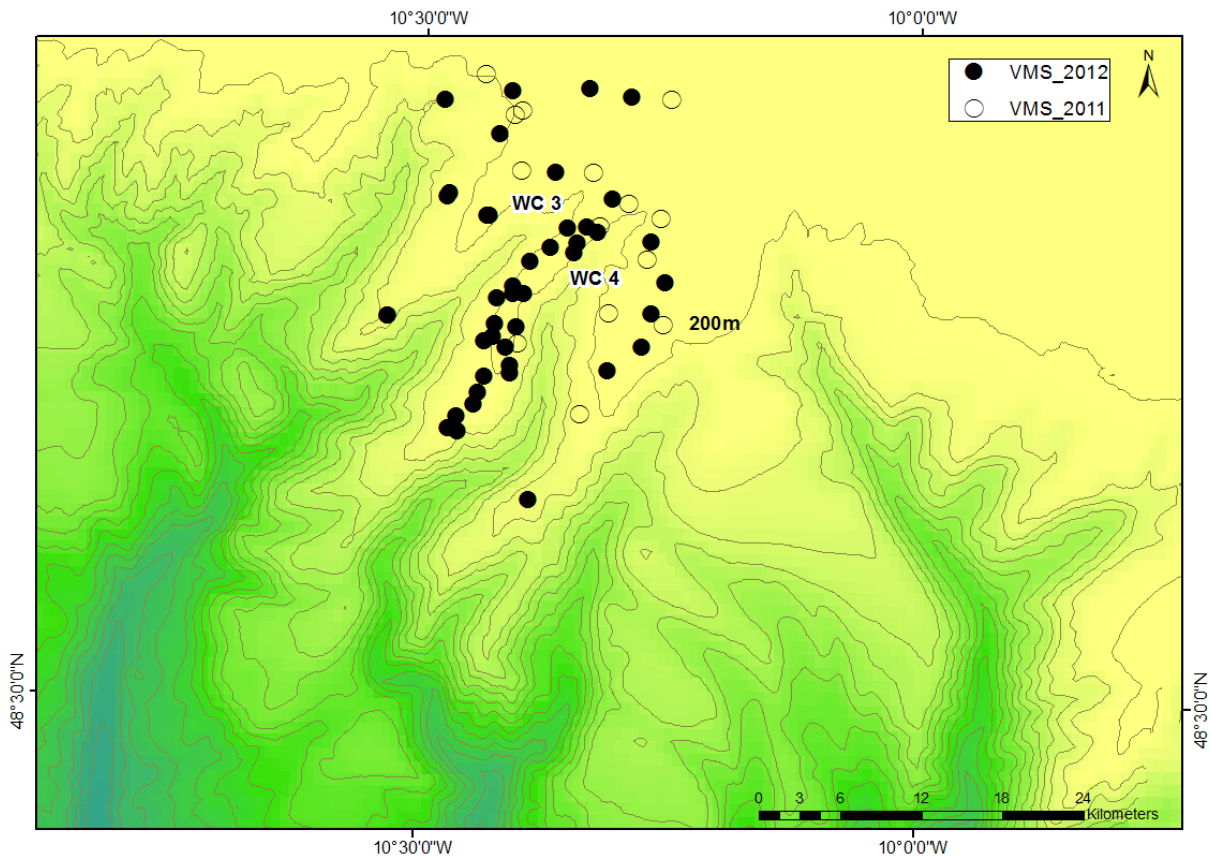


269
270 **Figure 6.** (a) Molar C/N versus concentration of suspended particulate material (SPM) measured in
271 $\mu\text{g L}^{-1}$ and (b) Molar C/N versus depth (m). Samples are from bottom mid and surface water depths.
272 Data from enhanced nepheloid layers are shown with black circles (●); grey circles show small
273 enhanced nepheloid layers (●) and open circles (○) show data from samples where there were no
274 enhanced nepheloid layers. Corresponding geochemical data is shown in table 2. **(Note: 1 column-
275 fitting image)**

276 **4. Discussion**

277 *4.1 Evidence for trawl-induced ENLs*

278 The evidence presented here suggests that trawling activity is likely responsible for the ENLs
279 detected at the Whittard Canyon, although a natural mechanism for the mobilisation of sediments
280 cannot be entirely ruled out. Visually, more trawlers were noted during the survey in 2013 than in
281 2012 or 2011. As a control, VMS data from the same area of the Whittard Canyon for the periods
282 surveyed in (24-26th April) 2011 and (15-26th April) 2012 were also examined (Figure 7). There was no
283 evidence of any unusual peaks in turbidity during either of these earlier surveys. VMS data fitting the
284 criteria for trawling during the 2011 survey were limited to 14 recordings randomly scattered in the
285 quadrangle during the survey period. During the 2012 survey, 43 recordings were measured and the
286 locations and the times of the points suggested ~three fishing tracks along the spur between WC3
287 and WC4 and one to the west of WC4 between April 19-21st 2012 (Figure 7). However, CTD profiles
288 recorded during this period were limited to mid-lower reaches of WC3. In comparison 299
289 recordings were measured during the survey period in 2013, with 43 recordings on the 15th of June
290 alone and followed by a further 38 data points on the 16th of June. The increased trawling activity on
291 the spurs during the 2013 survey period in comparison to 2011 and 2012 and advantageous CTD
292 deployments in branches adjacent to these spurs during this time frame allowed for the chance
293 detection of these events, with the timelines of fishing tracks and the appearance of ENLs matching
294 as shown in Table 2. The highest number of trawl recordings on June 15th and 16th June coincide with
295 the largest peaks in turbidity occurring on June 16th and 17th. It is likely that the peaks in turbidity
296 reported here are not unique observations and are likely occurring more often than recorded.
297 Indeed, it seems likely that another peak in turbidity would have been observed on June 19th when
298 recordings of vessels reached 48 but unfortunately the survey was complete at this time.



299
 300 **Figure 7.** Vessel Monitoring System (VMS) recordings for bottom trawling during CE11006 survey
 301 (○) and CE12006 survey (●) periods. **(Note: 1 column-fitting image)**
 302

303 The dislodgment and mobilization of SPM in the concentrations detected here could be
 304 induced by meteorologically driven events (e.g. storms or dense shelf water cascading (Gardner,
 305 1989; Palanques et al., 2006) or tectonic activity. Relative to conditions during the 2012 survey when
 306 maximum wind speeds of 59 m s^{-1} and a mean speed of 30 m s^{-1} was measured during two
 307 significant storms (significant wave heights of 8-9 m), weather conditions were calmer during the
 308 2013 survey. Winds were in a predominantly SSW-WSW direction with daily means varying between
 309 $7\text{-}24 \text{ m s}^{-1}$. Hull mounted ADCP data recorded underway during the survey revealed no unusual flow
 310 patterns down to 800 m water depth. Although the UK seismology network only detect earthquakes
 311 with magnitudes >2 , USGS public seismic records confirmed that no there were no earthquakes
 312 within a 500 km radius of Whittard during the 2013 survey period (British Geological Survey
 313 earthquake database, 2015; U.S. Geological Survey, 2015). USGS records did show activity in the
 314 North Atlantic Ocean ~ 750 km to the south west ($43^\circ 48.18' \text{ N } 17^\circ 8.1' \text{ W}$ at depth 14.8 m) before

315 the survey on May 28th (magnitude 4.7). Therefore, a natural mechanism for the mobilization of
316 sediment forming ENLs cannot be disregarded. However, figure 2f would suggest that the ENLs were
317 being generated during the 2013 survey and not before.

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

330

331 4.2 *C/N ratios of sPOM in ENLs*

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

341 resuspending degraded superficial sediment and lithogenic material from the shelf that had been in
342 the system for some time.

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

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

357

358 4.3 *iENLs and reoccurring events*

359 Other studies have observed the detachment of nepheloid layers from canyon spurs at the
360 depth ranges exploited by trawling (Zúñiga et al. 2009; Martín et al., 2014) but there were no similar
361 observations here. While iENLs were observed in WC3 between 1055 – 1290 m (event 84), VMS logs
362 show that trawling activity took place in mean water depths ~200m. These iENLs are likely density
363 induced detachments, composed of lighter material that has remained in suspension for longer. The
364 iENL detected in WC3 (event 84) was observed two hours after a large ENL in WC4 (event 83). If the
365 iENL detected in WC3 and ENL in WC4 were both sourced from the same event, with the iENL
366 generated from lighter material, it would be expected that the iENL is less dense. However, similar

367 values of σ_θ of the ENLs in the two tributaries would suggest that they are not of the same origin.
368 Considering the VMS data shows activity on both spurs adjacent to both branches, it is more
369 reasonable that material is coming down as sedimentary gravity flows from the sides of both
370 branches and suggests recurring events. Organic geochemical analysis of the material from both
371 events would have provided valuable information on the material composition and duration of
372 suspension but no samples were available from the IENL. The detection of smaller ENLs prior to the
373 big events would suggest a link with a build up before the larger ENLs in the lower reaches of the
374 branch. Alternatively, smaller ENLs (e.g. event 65 at 2293 m in WC3) may possibly be the remnant of
375 a previous plume. The sporadic sampling regime may be responsible for the detection of the plume
376 in WC3 two hours after the event in WC4, while this event may have been happening
377 instantaneously as has been seen in other studies (Palanques et al., 2006). Due to the limited data
378 set it is not possible to conclude whether the ENLs were sourced by one event or a number of
379 recurring events, but the time lines of VMS and appearance of the ENLs would indicate that these
380 were ongoing processes (Table 2) and it is likely that not all events were captured.

381 **Table 2.** Timeline of trawling activity and enhanced nepheloid layers occurrence. Date, number of VMS recordings, estimated number of vessels (based on
 382 country of origin) and average water depth fished (based on position and local bathymetry) with locations of fishing tracks and corresponding enhanced
 383 nepheloid layers (ENLs); location, depth and details.
 384

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 side WC4, 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+further 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)	

385 4.4 *Impacts and implications of bottom trawling transporting sediment*

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

401 The physical changes made to grain sizes and deposition rates by trawling activity are also
402 likely to influence carbon fluxes and sequestration. As discussed by Martín et al. (2015), if bottom
403 trawling influences, and in most cases enhances lateral transport of sediments, then local and
404 regional carbon budgets will be affected as will the export of material to the deep ocean. Excess
405 turbidity can clog the respiratory surfaces of fauna, while smoothing of topographic features may
406 disturb larval settlement and affect the unique canyon ecosystems (e.g. Watling and Norse, 1998).
407 The vertical walls of Whittard Canyon harbor unique assemblages (Johnson et al., 2013). Although
408 the ENLs were not detected in the upper water column where these walls are found, these density
409 laden flows are likely to impinge on the lower parts of the wall and with repeated activity could alter
410 the morphology and habitats found on this feature. It would be reasonable to presume that trawling

411 is causing more resuspension events than those reported here. Previous studies have found evidence
412 of trawling marks at the Whittard Canyon (Huvenne et al., 2011); while others have suggested the
413 possibility that trawling causes large peaks in turbidity (Amaro et al., 2015). Although most studies
414 have seen background values of suspended sediment return after a number of hours (e.g. Martín et
415 al., 2014), the processes induced by the repeated action of trawling appear to pose the great threat
416 to the ocean/benthic ecosystems and margin shaping (Puig et al., 2012). Effects of these events and
417 maximum resuspension are not localized to the fishing sites. As demonstrated by O'Neill and
418 Summerbell (2011), the mass of sediment entrained is directly related to the hydrodynamic drag of
419 the gear components and the type of sediment over which it is towed. Direct impacts can therefore
420 extend great distances and depths depending on; gear, equipment add-ons (e.g. tickler chains),
421 substrate type and operational methods (Martín et al., 2015 and references therein). Most studies
422 on trawling resuspension have taken place in coastal and continental shelf environments but the
423 effects of trawling are likely to be more profound at slope depths (Martín et al., 2015). The steep
424 bathymetry of submarine canyons, naturally focusing excess sediment from shallower trawling
425 locations, is therefore likely to increase their vulnerability to the impacts of trawl induced
426 resuspension.

427

428 **5. Conclusions**

429 Sediment transport processes from productive shelf seas carry material for consumption by
430 benthic ecosystems and for deposition to the deep sea. Many of these processes are enhanced by
431 the steep bathymetry of conducting submarine canyons. Anthropogenic activity in the form of
432 bottom trawling is now known to cause excess resuspension of sediments, inducing sediment gravity
433 events and accelerating the export and deposition of material. Here we have detected unusual peaks
434 in turbidity with high concentrations of SPM at the Whittard Canyon over a five day period. Although
435 concentrated nepheloid layers are commonly observed in Whittard, the layers detected here had
436 concentrations of SPM an order of magnitude higher than maximum values typically found in NLs at

437 this site. The locations and presence of bottom trawlers in the area provides persuasive evidence for
438 the relationship between trawling activity on the adjacent spurs and the occurrence of ENLs. The
439 ENLs appear to be induced by the excess density of the addition sediment. The molar C/N ratios of
440 sPOM were highly heterogeneous and suggested that material from the ENLs is degraded more than
441 passively sinking or recently deposited particles on the sea floor, indicating its long residence times
442 in the system. VMS logs and the data presented here would suggest that this is a recurring event,
443 with sufficient activity inducing small and larger plumes. Our study only provides a snapshot of the
444 full story and more extensive study is required to fully explain these and other unusual peaks that
445 have been detected in this region (Amaro et al., 2015). Sediment dating and knowledge of the
446 sedimentation and accumulations rates would greatly increase our understanding. The deep sea is a
447 fragile environment vulnerable to alterations and takes a long time to recover from negative
448 impacts. It is likely that recurrence of plumes like those described here would have similar effects on
449 sediment transport rates and dynamics to those reported in the Mediterranean. As suggested by
450 Martín et al. (2015), perhaps bottom trawling needs to be considered and measured as another
451 process governing deep sea sediment dynamics.

452

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461

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