

1 **Sediment and organic carbon transport and deposition driven by internal tides**  
2 **along Monterey Canyon, offshore California**

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29 **ABSTRACT**

30 Submarine canyons are globally important conduits for sediment and organic carbon  
31 transport into the deep sea. Using a novel dataset from Monterey Canyon, offshore  
32 central California, that includes an extensive array of water column sampling devices, we  
33 address how fine-grained sediment and organic carbon are transported, mixed,  
34 fractionated, and buried along a submarine canyon. Anderson-type sediment traps were  
35 deployed 10 to 300 meters above the seafloor on a suite of moorings anchored between  
36 278–1849 m water depths along the axial channel of Monterey Canyon during three  
37 consecutive 6-month deployments (2015–2017). Tidal currents within the canyon  
38 suspended and transported fine-grained sediment and organic carbon that were captured  
39 in sediment traps, which record the composition of sediment and organic carbon transport  
40 along the canyon. High sediment accumulation rates in traps increased up-canyon and  
41 near the seafloor, where fine-scale (<1 cm) layering was increasingly distinctive in CT  
42 scans. There was no along-canyon trend in the organic carbon composition (percent  
43 modern carbon and isotopic signatures) among trap locations, suggesting effective  
44 mixing. Organic carbon content (weight percent total organic carbon) and excess  $^{210}\text{Pb}$   
45 activities (dpm/g) increased down-canyon, reflecting reduced flux of sediment and  
46 organic carbon into deeper water, more distal traps. Differing organic carbon signatures  
47 in traps compared with previous measurements of seabed deposits along Monterey  
48 Canyon suggest that organic carbon transported through the canyon with internal tides  
49 may not be consistently recorded in seafloor deposits. First-order estimates from  
50 comparing organic carbon content of core and trap samples results in low organic carbon  
51 specific burial efficiency (ranging from ~26% to ~0.1% ) and suggests that the modern  
52 upper Monterey Canyon may not be an effective sink for carbon. Organic carbon isotopic  
53 signatures from sediment traps in the water column show more marine influence than  
54 seafloor sediment cores; this is likely due to the deposition and reworking of seafloor  
55 deposits by sediment density flows and preferential consumption of fresh marine organic  
56 carbon on the seafloor, which is better preserved in the traps. Sediment and remaining  
57 organic carbon in canyon floor and lower flank deposits preferentially reflect episodic  
58 sediment density flow events that are unrelated to internal tides. This study provides a  
59 quantified example and conceptual model for internal-tide-related sediment and organic  
60 carbon transport, mixing, and burial trends along a submarine canyon that are likely to be  
61 similar in many canyons worldwide.

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64 **Keywords** (4–6): submarine canyon; sediment trap; internal tide; organic carbon;  $x_s^{210}\text{Pb}$

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## 68 1. Introduction

69 Submarine canyons are globally important as conduits for offshore transport of  
70 sediment and organic carbon, as dynamic areas of ocean mixing, and as biodiversity  
71 hotspots (e.g., Shepard, 1979; Hotchkiss and Wunsch, 1982; Harris and Whiteway, 2011;  
72 Talling et al., 2015; Amaro et al., 2016; Liao et al., 2017; Mountjoy et al., 2018). These  
73 canyon systems funnel terrestrial- and marine-sourced organic carbon into the deep-sea,  
74 feeding deep-sea ecosystems within and beyond canyon environments (e.g., Amaro et al.,  
75 2015; Baudin et al., 2017; Liao et al., 2017; Campaña-Llovet et al., 2018). A fraction of  
76 organic carbon in these deep-sea conduits is buried and contributes to global carbon  
77 biogeochemical cycling and atmospheric carbon dioxide levels over time (e.g., Galy et  
78 al., 2007; Masson et al., 2010; Zheng et al., 2017; Mountjoy et al., 2018). Comprehensive  
79 direct sampling of submarine canyon deep-sea environments is needed to more fully  
80 elucidate the geological, ecological, and oceanographic role of submarine canyons over  
81 time.

82 The transport of sediment and organic matter along submarine canyons can occur  
83 in sediment density flows and internal tidal flows. Episodic turbidity currents and other  
84 sediment density flow events can move vast amounts of sediment into deeper water and  
85 rapidly alter the seafloor on the scale of meters to tens of meters in a single event (e.g.,  
86 Talling et al., 2015; Mountjoy et al., 2018; Paull et al., 2018; Vendettouli et al., 2019).  
87 Between sediment density flow events, submarine canyons can focus internal wave  
88 energy, creating internal tidal flows that transport, erode, and inhibit deposition of fine-  
89 grained sediment (e.g., Shepard and Marshall, 1969; Shepard, 1976, 1979; Gardner,  
90 1989; Petruncio et al., 1998; Cacchione et al., 2002; Carter and Gregg, 2002; Xu et al.,  
91 2002b; Lee et al., 2009; Xu and Noble, 2009; Wain et al., 2013; Waterhouse et al., 2017;  
92 Li et al., 2019). Herein, we refer to internal tides generally as internal waves with tidal  
93 frequencies, after Pomar et al. (2012).

94 Monterey Canyon, offshore central California (Fig. 1), is one of the most studied  
95 submarine canyons on Earth (e.g., Matos et al., 2018) and has been a focus of studies on  
96 canyon sediment transport processes, as well as depositional facies, for many years (e.g.,  
97 Paull et al., 2003, 2010a, 2011, 2018; Smith et al., 2005, 2007; Xu et al., 2002b, 2014;  
98 Stevens et al., 2014; Symons et al., 2017; Maier et al., 2019). Episodic sediment density  
99 flow events occur in Monterey Canyon with sub-annual frequency, and semi-diurnal  
100 internal tides have been measured to 3300 meters water depth along the canyon-channel  
101 axis (e.g., Xu and Noble, 2009; Paull et al., 2010a, 2018). Xu and Noble (2009)  
102 documented internal tidal variation in Monterey Canyon being offset from the sea surface  
103 semi-diurnal tide and noted that internal tidal flows may prevent Monterey Canyon axis  
104 from infilling with fine-grained sediment. Internal tidal flows in Monterey Canyon have  
105 been measured with speeds of 20–80 cm/s and are an order of magnitude larger than open  
106 ocean tidal currents (e.g., Petruncio et al., 1998; Kunze et al., 2002). Internal tides appear  
107 to be generated from seafloor topography offshore central California, in and around

108 Monterey Canyon (e.g., Petruncio et al., 1998, 2002; Kunze et al., 2002; Hall and Carter,  
109 2011). Internal tidal velocities increase up-canyon, enhanced by the slope of the canyon  
110 floor ( $1.7^\circ$ , Paull et al., 2005) and headward narrowing of the canyon (Fig. 1) (e.g.,  
111 Hotchkiss and Wunsch, 1982; Petruncio et al., 1998, 2002; Carter and Gregg, 2002).

112 An international collaborative effort was developed to comprehensively  
113 instrument Monterey Canyon and address the need for detailed direct measurements of  
114 submarine canyon sediment transport (Paull et al., 2018). This novel experiment, referred  
115 to as the Coordinated Canyon Experiment (CCE), was designed primarily to measure  
116 sediment density flow events (Paull et al., 2018). The resulting dataset provides the most  
117 detailed monitoring yet of a submarine canyon, including 15 sediment density flow  
118 events (criteria detailed in Paull et al., 2018) during 18 months of high-frequency water  
119 column measurements and sediment samples, collected during and between sediment  
120 density flow events (Paull et al., 2018; Maier et al., 2019). Specifically, the CCE array  
121 included an unprecedented number of sediment traps deployed in close proximity to the  
122 seafloor, allowing analysis of submarine canyon sediment transport and organic carbon  
123 down 50 km of the canyon axis on moorings anchored at 278 to 1849 meters water depth  
124 (Figs. 1, 2).

125 In this study, our primary aim is to investigate how sediment and organic carbon  
126 are transported, mixed, and preserved within a submarine canyon, specifically focusing  
127 on samples from intervals between sediment density flow events that represent most of  
128 the CCE study time period. For these intervals not associated with sediment density flow  
129 events, we compare organic carbon content and composition sampled directly from the  
130 water column in sediment traps with results from previously analyzed (Paull et al., 2006)  
131 samples of seafloor sediments. We address three interrelated questions: (1) How are fine-  
132 grained sediment and organic carbon transported in a submarine canyon between  
133 sediment density flow events? (2) How is organic carbon fractionated and (or) mixed  
134 along the canyon? (3) How are transported (water column) organic carbon and fine-  
135 grained sediment preserved in canyon deposits? Results from Monterey Canyon are then  
136 considered more broadly to develop a generalized conceptual scheme for organic carbon  
137 transport and burial in submarine canyons.

138

## 139 **2. Monterey Canyon**

140 Monterey Canyon incises 30 km across the relatively flat ( $<1.0^\circ$ ) continental shelf  
141 to near the shoreline at Moss Landing (Fig. 1). The canyon widens seaward from 800 m  
142 in the canyon head to 15 km at the shelf edge. The canyon has an average slope of  $1.7^\circ$   
143 (e.g., Paull et al., 2005) along an axial channel with adjacent benches (morphologically  
144 defined as relatively flat areas above and adjacent to the axial channel; after Maier et al.,  
145 2012) along the canyon lower flanks.

146 The axial channel contains narrow and sharp turns in the upper canyon (here  
147 defined as 0–1000 m water depth), where it is incised through older canyon sediments



148 that record migration of the canyon position during the Pleistocene (after Maier et al.,  
149 2018). The lower canyon (here defined as 1000–2000 m water depths) contains broad  
150 axial channel bends incised into sedimentary and crystalline bedrock (e.g., Maier et al.,  
151 2018). The Monterey depositional system continues seaward from the lower canyon for  
152 >100 km, contributing to the Monterey Fan (e.g., Normark, 1970; Fildani and Normark,  
153 2004).

154 Monterey Canyon is currently offset from rivers around Monterey Bay but  
155 intercepts sediment transported in littoral cells (e.g., Griggs and Hein, 1980; Inman and  
156 Jenkins, 1999; Farnsworth and Warrick, 2007). The canyon floor is dominated by coarse  
157 grained sand, gravel and larger clasts in the axial channel and finer-grained sediment with  
158 layers of silt and sand on the canyon benches and flanks (e.g., Paull et al., 2005, 2010a;  
159 Symons et al., 2017; Maier et al., 2019). Episodic sediment density flow events  
160 (commonly referred to as turbidity currents) move sand and gravel down the canyon axial  
161 channel up to multiple times a year, at velocities exceeding 4 m/s, and result in  
162 geomorphic change in the axial channel (e.g., Xu et al., 2008, 2014; Smith et al., 2005,  
163 2007; Paull et al., 2010a, 2011, 2018; Symons et al., 2017; Maier et al., 2019). Between  
164 the episodic events, fine-grained sediment (median grain size silt) is transported through  
165 Monterey Canyon via internal tides and can be collected in sediment traps (Xu et al.,  
166 2014).

167

### 168 **3. Methods**

#### 169 *3.1. Approach*

170 The focus of this study is the sediment and organic material collected in sediment  
171 traps during periods between episodic, powerful sediment density flow events along  
172 Monterey Canyon. Timing of sediment trap sub-samples along the CCE array is best  
173 constrained at the base of the sediment trap tubes, where sediment accumulated shortly  
174 after deployment, and thus, these samples are analyzed and compared in this study. We  
175 first discuss the sampling methodology, which allows interpretation of sediment trap  
176 samples in the context of internal tide sediment transport through Monterey Canyon, and  
177 as a basis to interpret down-canyon trends or the lack of trends. We then present  
178 analytical procedures, followed by a summary of portions of the CCE instrument dataset  
179 that most closely relate to, and thus, are the most relevant for interpretation of, sediment  
180 trap samples. We later compare these results to other submarine canyons, to create a  
181 general conceptual scheme for processes of organic carbon transport and deposition in  
182 submarine canyons.

183

#### 184 *3.2. Coordinated Canyon Experiment (CCE)*

185 Three moorings in the upper canyon (MS1, MS2, MS3), and three in the lower  
186 canyon (MS4, MS5, MS7) (Fig. 1) were deployed during three consecutive six-month  
187 periods (I: October 2015 – April 2016; II: April – October 2016; III: October 2016 –

188 April 2017) (Paull et al., 2018). These moorings included oceanographic instruments and  
189 Anderson-type sediment traps at 10 to 300 meters above the seafloor (masf) (Paull et al.,  
190 2018; Lundsten, 2019; Maier et al., 2019). The CCE recorded 15 sediment density flow  
191 events moving down the canyon with maximum durations of 4–6 hours (Paull et al.,  
192 2018). The first sediment density flow event during deployments I, II, and III occurred on  
193 December 1, 2015, September 1, 2016, and November 24, 2016, respectively (Paull et al.,  
194 2018). We focus this study on sediment accumulated in traps before the first sediment  
195 density flow event in each deployment.

196

### 197 3.3. Anderson-type sediment traps

#### 198 3.3.1. Procedure for sample acquisition and processing

199 Anderson-type sediment traps (Anderson, 1977; Rendigs et al., 2009) consist of  
200 an open top, baffled, fiberglass funnel (95–110 cm long, and ~25 cm diameter (0.05 m<sup>2</sup>)  
201 top opening) above a clear plastic liner tube (5–6 cm inner diameter) inside a PVC pipe  
202 (up to ~110 cm long) (after Maier et al., 2019) (Fig. 2). A dilute hypersaline solution of  
203 sodium azide (<5%) was added to most traps to deter bioturbation and preserve organic  
204 carbon content in the sample (e.g., Hedges et al., 1993). Intervalometers (after Rendigs et  
205 al., 2009) were used to insert up to 20 discs at pre-set intervals (typically every 8 days)  
206 into the liner tube to define sampling intervals. Liner tubes were stored upright in cold  
207 storage for ~1 month or more following recovery.

208 Sediment trap liner tubes were scanned with x-ray computed tomography (CT). In  
209 Deployment I, this was conducted using a GE LightSpeed Ultra instrument at the  
210 Stanford University Petroleum Research Institute (SUPRI-A) Enhanced Oil Recovery  
211 and Unconventional Resources laboratory facility, at 120 kV and 140 mA with 1.25 mm  
212 axial slices. In deployments II and III, this was conducted using a General Electric  
213 LightSpeed 16 CT scanner at the Lawrence Berkeley National Laboratory Rock Dynamic  
214 and Imaging Lab at 120 kV and 160 mA reconstructed to 0.625 mm axial slices.

215 Sediment from liner tubes were extruded in 1-cm intervals, split for grain size and  
216 other geochemical analyses, and stored in Whirlpak plastic bags (Maier et al., 2019).  
217 Deformation from sand loading into underlying fine-grained sediment occurred primarily  
218 in Deployment I samples (e.g., Fig. 3A). Sediment accumulation rates were estimated  
219 using averaged dry sediment density of fine-grained intervals of 0.95 g/cm<sup>3</sup> and an  
220 average dry:wet ratio of 0.84. For traps with functioning intervalometers, apparent  
221 sediment accumulation rates were averaged from the 1-cm slices between discs. An  
222 average apparent sediment accumulation rate was calculated from the 1-cm slices  
223 accumulated over the entire deployment or before the first sediment density flow event  
224 (Table 1).

225

#### 226 3.3.2. Conceptual basis for sediment trap sample interpretation

227           Geochemical analyses of samples from the bottom of the trap tubes represent  
228 approximately concurrent time periods across the CCE array from early in each  
229 deployment (i.e., April, October). Because the liner tubes on most traps filled before the  
230 end of each deployment and intervalometers were not available throughout the array,  
231 samples from the base of liner tubes have the greatest certainty for coincidence along the  
232 entire array. These samples represent ‘background’ sediment transport and intentionally  
233 exclude sediment density flow events (as defined in Paull et al., 2018 and interpreted  
234 from sediment traps in Maier et al., 2019) (Table 1).

235           Previous studies suggest that traps can provide a representative record of the  
236 composition of sediment and organic matter transported immediately over the trap, and  
237 results can be compared between traps of similar geometry (e.g., Gardner, 1980, 1989;  
238 Gardner et al., 1983b; Bruland et al., 1981; Buesseler et al., 2007; Liu et al., 2016).  
239 Anderson-type sediment traps were designed to measure flux of sediment settling  
240 vertically through the water column in quiescent, low-flow conditions (e.g., Anderson,  
241 1977; Gardner, 1980, 1985). However, settling velocity of fine-grained sediment particles  
242 is orders of magnitude lower than even low horizontal current speeds (e.g., Gardner et al.,  
243 1997), and Anderson-type sediment traps function by fluid exchange of the water inside  
244 the trap with water from the passing current (e.g., Gardner, 1980, 1985). Baffles (Fig. 2B)  
245 reduce turbulence and grain size segregation (e.g., Anderson, 1977; Butman, 1986).  
246 Anderson (1977) noted that collection of fine-grained particles may be enhanced by high  
247 sediment concentration, allowing collection of measurable amounts of sediment over  
248 short time periods that can be sub-sampled and analyzed.

249           Although previous studies were mostly in lower flow velocity settings than  
250 Monterey Canyon, the underlying principles and methodology of the sediment traps from  
251 these earlier studies suggest that CCE traps likely provide reliable records of the sediment  
252 composition moving through Monterey Canyon. Gardner (1985) noted that trap tilt could  
253 result in fine-grained sediments  $<63 \mu\text{m}$  being over-collected relative to sediment  $>63$   
254  $\mu\text{m}$ , compared to rate of fall past a horizontal plane, but he found no statistically  
255 significant variations in organic matter content related to trap tilt. Gardner et al. (1983b)  
256 concluded that resuspension dominates sediment trap flux over trap tilt and current  
257 velocities.

258           Anderson-type sediment traps can be important tools for capturing representative  
259 samples of suspended sediment in high sediment flux areas. Similar trap designs have  
260 been used to interpret sediment transport in Gaoping Canyon (e.g., Huh et al., 2009b; Liu  
261 et al., 2012, 2016; Zheng et al., 2017), Hueneme and Mugu canyons (Xu et al., 2010). In  
262 this study, intervalometer discs and deployment dates constrain sediment that  
263 accumulated in the trap tubes prior to the first sediment density flow event during each  
264 CCE deployment. We acknowledge that the calculated in-trap sediment accumulation  
265 rates are ‘capture’ rates and may vary substantially from both the horizontal fluxes  
266 through the canyon and vertical accumulation rates on the seafloor (e.g., Xu et al., 2010;

267 Martín et al., 2011). Quantitative down-canyon comparisons herein assume that the  
268 Anderson-type sediment traps capture sediment in the same way throughout the CCE  
269 array, and thus, the apparent in-trap sediment accumulation rates and compositions  
270 provide useful down-canyon comparisons (e.g., Xu et al., 2010).

271

#### 272 *3.4. Laser particle grain size analyses*

273 Grain size was measured on each 1-cm sub-sample from Deployment I, which  
274 showed similar grain size distributions within fine-grained intervals. Subsequently, grain  
275 size was measured more efficiently by analyzing only every fifth 1-cm sub-sample from  
276 deployments II and III. Laser particle grain size analyses used a Malvern II Mastersizer  
277 instrument measuring in quarter phi bins at the National Oceanography Centre  
278 Southampton (Maier et al., 2019). Grain-size samples were processed by (1)  $\sim 1 \text{ cm}^3$  of  
279 each sample was added into measurement vials; (2) samples with grain sizes  $>2 \text{ mm}$  were  
280 sieved to remove the fraction  $>2 \text{ mm}$ ; (3) 10% sodiumhexametaphosphate solution was  
281 added to make up to 20 ml solution in each sample pot; (4) samples were agitated on a  
282 mechanical shaker overnight ( $>12 \text{ hours}$ ); (5) the Malvern II autosampler was used to  
283 conduct the sampling; (6) random samples were selected and measured manually using  
284 the Mastersizer for comparison. Each sample was run three times and grain sizes  
285 averaged.

286

#### 287 *3.5. Radiocarbon analyses*

288 Radiocarbon analysis focused on individual 1-cm sub-samples from near the base  
289 of liner tubes. Analyses were conducted at Beta Analytic Inc. (Florida, USA) using  
290 standard accelerator mass spectrometry (AMS) procedure. Samples were pretreated with  
291 repeated liquid acid (HCl) washes until carbonate material was removed, according to  
292 Beta Analytic Inc. acid washes pre-treatment procedure. The remaining organic carbon  
293 sample was converted to graphite for AMS analysis. Results are reported as  $\delta^{13}\text{C}$ -  
294 corrected percent modern carbon (pMC) after Stuiver and Polach (1977).

295

#### 296 *3.6. Organic carbon analyses*

297 Organic carbon stable isotopes  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  have been used to distinguish  
298 terrestrial and marine sources (e.g., Peters et al., 1978; Paull et al., 2006; Prouty et al.,  
299 2017). As a simplified general distinction herein, marine organic carbon is considered as  
300 having  $\delta^{13}\text{C}$  values between  $-22$  and  $-20$  per mil (PDB) and  $\delta^{15}\text{N}$  values  $>+7$  per mil (air)  
301 (e.g., Peters et al., 1978; Cifuentes et al., 1988; Paull et al., 2006). Likewise, terrestrial  
302 organic carbon is considered as having  $\delta^{13}\text{C}$  values between  $-25$  and  $-23$  per mil (PDB)  
303 and  $\delta^{15}\text{N}$  values  $<+3$  per mil (air) (e.g., Peters et al., 1978; Cifuentes et al., 1988; Paull et  
304 al., 2006). Organic carbon stable isotope and total organic carbon values, analyzed as in  
305 this study, are available from two samples of the nearby Salinas River ( $\delta^{13}\text{C}$ :  $-26.5$  per  
306 mil; TOC: 0.18) and Pajaro River ( $\delta^{13}\text{C}$ :  $-23.7$  per mill; TOC: 0.37) (Paull et al., 2006).

307 Stable isotopes from organic material ( $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ) and total organic carbon  
 308 content were measured from two fine-grained 1-cm sub-samples per trap from the base of  
 309 the tube and from 5–10 cm above. Analyses were conducted at the Stanford Stable  
 310 Isotope Laboratory at Stanford University, California, using a Carlo Erba NA1500 Series  
 311 II elemental analyzer and a Finnigan MAT 252 isotope ratio mass spectrometer. An  
 312 initial set of 23.9–24.1 microgram samples were acidified with liquid sulfuric acid (for  
 313 at least 24 hours at room temperature until no reactions were apparent) to remove  
 314 carbonate and analyzed for total organic carbon content,  $\delta^{13}\text{C}$ , and C/N atomic ratio using  
 315 L-glutamic acid USGS-40 standard reference material 8573 and acetamide conditioner. A  
 316 secondary set were analyzed without acidification for  $\delta^{15}\text{N}$ .

317

### 318 3.7. $^{210}\text{Pb}$ analyses

319 Excess  $^{210}\text{Pb}$  activity ( $x\text{s}^{210}\text{Pb}$ ;  $t_{1/2} = 22.23$  years) is widely used as a chronometer  
 320 in recent (<200 years) sediments (e.g., Swarzenski, 2014 and references therein).  
 321 Supported, time-independent  $^{210}\text{Pb}$  is present in recent sediments from decay of  $^{226}\text{Ra}$  as  
 322 part of the  $^{238}\text{U}$  decay chain (e.g., Kirchner, 2011). Excess, time-variable  $^{210}\text{Pb}$  is  
 323 produced in the atmosphere through decay of  $^{222}\text{Rn}$ , transported via wet and dry  
 324 deposition to the Earth surface, and adsorbed (i.e., scavenged) by fine-grained particulate  
 325 matter in the water column (e.g., Xu et al., 2010; Kirchner, 2011; Swarzenski, 2014).

326 Excess  $^{210}\text{Pb}$  activity ( $x\text{s}^{210}\text{Pb}$ ) was analyzed from traps at the shallowest (MS1),  
 327 middle (MS3), and deepest (MS7) part of the CCE mooring array. Three consecutive 1-  
 328 cm sub-samples of fine-grained sediments from near the base of trap tubes were  
 329 combined, oven-dried, finely-ground, and homogenized. Approximately 6–10 g of  
 330 sample was analyzed with gamma-spectroscopy in small-volume HPGe well detectors at  
 331 the U.S. Geological Survey in Santa Cruz, California, following methods described in  
 332 Swarzenski et al. (2006) and Xu et al. (2010). Excess  $^{210}\text{Pb}$  activity was calculated as the  
 333 difference between total  $^{210}\text{Pb}$  and supported  $^{210}\text{Pb}$  from decay of  $^{226}\text{Ra}$  ( $x\text{s}^{210}\text{Pb} =$   
 334  $\text{total}^{210}\text{Pb} - ^{226}\text{Ra}$ ) (e.g., Xu et al., 2010; Swarzenski, 2014).

335

### 336 3.8. Oceanographic instrumentation

337 Portions of the CCE instrument dataset (Paull et al., 2018) that are immediately  
 338 relevant to the sediment trap samples are summarized in this study (see also Ferreira et  
 339 al., 2019). Downward-looking 300 kHz acoustic Doppler current profilers (ADCPs) at 65  
 340 masf (e.g., Fig. 2A) measured velocity in 7-ping ensembles every 30 seconds, and plots  
 341 presented here from individual bins of ADCP data show 2-minute averages of the 30-  
 342 second ensembles. Statistics for current speeds along the canyon are derived from ADCP  
 343 data using the closest reliable 1-meter bin to the seafloor at each mooring for  
 344 deployments II and III because MS1 was ripped off its anchor during Deployment I,  
 345 resulting in a complete dataset throughout the entire array only in deployments II and III  
 346 (see Paull et al., 2018). Turbidity sensors measured every minute. Transmissometer beam

347 attenuation was used to estimate concentration of fine-grained sediment captured in traps,  
348 following Xu et al. (2002a), and converted to along-canyon flux using ADCP velocity at  
349 10 masf. To relate transmissometer-derived suspended sediment concentrations with  
350 sediment trap samples, sediment and organic carbon flux are estimated in the upper  
351 canyon for the first 32 internal tidal cycles (e.g., Wang et al., 2009; Xu and Noble, 2009)  
352 from Deployment III, when the same type of transmissometers were deployed on MS1,  
353 MS2, and MS3 at approximately 10 masf. A directional wave gauge, deployed on the  
354 continental shelf outside of Monterey Canyon (WHS in Fig. 1), acquired 1 Hz  
355 measurements for 17 minutes every 2 hours.

356

### 357 *3.9. Sediment cores used for comparison of organic carbon transport and deposition*

358 We compare new sediment trap analyses in this study to previous organic carbon  
359 analyses by Paull et al. (2006) of fine-grained sediment in and around Monterey Canyon.  
360 These include sediment core samples collected between 1999 and 2002 along Monterey  
361 Canyon axial channel, adjacent benches, and flanks in 107–1169 m water depths, as well  
362 as grab samples and suspended sediment samples from surrounding nearshore areas and  
363 rivers. Paull et al. (2006) selected clay-rich sediment core sub-samples (from the seafloor  
364 to >5 m depth in the cores) for organic carbon analyses (including  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ,  $\delta^{14}\text{C}$ , total  
365 organic carbon) from clay clasts within the canyon axial channel and accumulated fine-  
366 grained sediments draping the axial channel, benches and flanks up to 129 m above.  
367 Notably, the Paull et al. (2006) organic carbon stable isotope analyses were conducted in  
368 the same manner and in the same laboratory as trap samples in this study.

369

## 370 **4. Results**

### 371 *4.1. Sediment traps and grain size*

372 A total of 25 Anderson-type sediment traps were successfully recovered during  
373 the CCE (Table 1). Nine of the traps contained intervalometers that released discs  
374 throughout the liner tubes (Table 1; Fig. 3), showing that liners filled and began to  
375 overflow before the deployment ended. The in-trap sediment accumulation rate measured  
376 with intervalometers in the upper canyon traps (MS1, MS2, MS3) was over twice as rapid  
377 compared to the lower canyon traps (MS5). In-trap sediment accumulation rates along the  
378 entire array are comparably high (up to hundreds of  $\text{g}/\text{m}^2/\text{day}$ ) between deployments and  
379 estimation methods, and generally decrease down-canyon (Table 1).

380 CT scans and grain size analyses show that traps filled primarily with fine-grained  
381 sediment which contain subtle <1-cm-thick layers (Fig. 3). Grain size distributions  
382 averaged from measurements throughout the fine-grained units are unimodal with median  
383 grain sizes between 13–18  $\mu$ , and slightly coarser (median grain size 22–27  $\mu$ ) at MS1  
384 (Fig. 4; Supplementary Table 1). Fine- to coarse-grained sand intervals correspond to the  
385 timing of sediment density flow events recorded by ADCPs (Paull et al., 2018) and are  
386 concentrated in mid- to upper portions of the tubes (e.g., Fig. 3A, C). Additional sandy

387 (d0.9 up to 200  $\mu$ ) units are present at MS1 (asterisks in Fig. 3A, C).  
 388

#### 389 4.2. Radiocarbon analyses

390 Percent modern carbon from radiocarbon analyses of 23 individual 1-cm samples  
 391 ranges from  $87.2 \pm 0.3$  to  $67.5 \pm 0.3$ , which equates to conventional radiocarbon ‘ages’  
 392 of  $1100 - 3160 \pm 30$  years before present (without reservoir corrections; Stuiver and  
 393 Polach, 1977) (Fig. 5; Supplementary Table 2). Analyses are from traps at  $\sim 10$ –300 masf,  
 394 but most of the analyzed samples were from traps at  $\sim 10$  masf. No systematic changes are  
 395 apparent between the three deployments or down-canyon. Lowest pMC values occur with  
 396 depleted  $\delta^{13}\text{C}$  values in deployments II and III, suggesting that, in some time periods,  
 397 younger carbon may be preferentially provided by marine sources.  
 398

#### 399 4.3. Organic carbon content and stable isotope analyses

400 Total organic carbon content (TOC) and stable isotopes were analyzed from 50  
 401 individual 1-cm-extruded trap samples (Figs. 6, 7; Supplementary Table 3). TOC  
 402 increases down-canyon, from 1.2 to 2.9 weight percent (Fig. 6A). Nitrogen isotopes  
 403 ( $\delta^{15}\text{N}$ ) range from 5.8 to 7.4 per mil (Fig. 7B), and nitrogen content ranges from 0.2 to  
 404 0.4 weight percent.  $\delta^{13}\text{C}$  ranges from -22.2 to -24.4 per mil (PDB), but only four samples  
 405 resulted in  $\delta^{13}\text{C} < -23.0$  per mil (Fig. 7; Supplementary Table 3). Carbon-nitrogen (C:N)  
 406 atomic ratios range from 7.9 to 9.4 (Supplementary Table 3). Increasing carbon and  
 407 nitrogen stable isotopes show significant correlations ( $p < 0.05$ ) only for the Deployment  
 408 II (Fig. 7B), and carbon isotopes are enriched down-canyon only in one set of samples  
 409 from the Deployment II (Fig. 7A).  
 410

#### 411 4.4. $^{210}\text{Pb}$ analyses

412 Excess  $^{210}\text{Pb}$  ( $x_s^{210}\text{Pb}$ ; dpm/g) activities consistently increase down-canyon (Fig.  
 413 8A; Supplementary Table 4).  $x_s^{210}\text{Pb}$  activities are over three times greater at MS7 ( $56.2$ –  
 414  $73.9 \pm 1.1$ – $1.4$  dpm/g) than at MS1 ( $13.6$ – $18.3 \pm 0.6$ – $0.7$  dpm/g). The MS7  $x_s^{210}\text{Pb}$   
 415 activity in the trap at 300 masf is greater than in the trap at 10 masf on the same mooring.  
 416 Measured  $x_s^{210}\text{Pb}$  activities increase with increasing weight percent TOC measured from  
 417 the same trap (Fig. 8C). Small amounts of  $^{137}\text{Cs}$  are measured in all samples (mean 0.13  
 418 dpm/g, standard deviation 0.05 dpm/g), but no trends are apparent between traps or  
 419 deployments (Supplementary Table 4).  
 420

#### 421 4.5. Instrument measurements

422 Oscillations in along-canyon velocity and turbidity occur throughout the mooring  
 423 array, related to semi-diurnal and diurnal internal tidal flows within Monterey Canyon  
 424 (e.g., Wang et al., 2009; Xu and Noble, 2009). Along-canyon velocities, measured by the  
 425 ADCPs, alternate orientation up- and down-canyon sub-daily, and occur with fluctuations  
 426 in turbidity (e.g., Fig. 9; Ferreira et al., 2019). Notably, up-canyon velocities at 10 masf

427 reach 1 m/s at the shallowest mooring (MS1; 287 meters water depth) (Fig. 9A). Mean  
 428 current speeds range from 12.4 to 19.8 cm/s at a single mooring and deployment (Table  
 429 2). Many up-canyon and down-canyon peaks in ADCP-measured velocity at 10 or 65  
 430 masf on MS1 coincide with peaks in turbidity measured by a sensor at 35 masf, while  
 431 other turbidity peaks coincide with the switching orientation of the internal tide at MS1  
 432 (Fig. 9A, B).

433         Suspended sediment fluxes are estimated herein for a rough comparison to the  
 434 Anderson-type sediment traps. Suspended sediment concentrations, estimated from  
 435 transmissometers at 10 masf, were  $\leq 0.03$  g/L for MS1 and  $< 0.02$  g/L for MS2 and MS3  
 436 during the first 16 days of Deployment III (Fig. 10), when the same type of  
 437 transmissometers were deployed on MS1, MS2, and MS3 at approximately 10 masf.  
 438 Suspended sediment flux varied between  $0.02$  kg/m<sup>2</sup>/s down-canyon and  $0.01$  kg/m<sup>2</sup>/s up-  
 439 canyon. Most sediment fluxes were  $< 0.005$  kg/m<sup>2</sup>/s. Cumulative suspended sediment flux  
 440 through a square meter vertical cross-section of the canyon at the mooring sites during  
 441 the first 16 days (32 tidal cycles) of Deployment III were  $1.25 \cdot 10^6$  kg down-canyon at  
 442 MS1,  $1.60 \cdot 10^5$  kg up-canyon at MS2, and  $2.36 \cdot 10^5$  kg down-canyon at MS3.

443         The wave height record from the continental shelf south of Monterey Canyon  
 444 (WHS in Fig. 1) contains variation on the order of meters within days (Paull et al., 2018).  
 445 The top tenth percentile of wave heights (H10) can exceed 3.0 meters (Fig. 11). Mean  
 446 direction and peak period direction during these spikes in wave height are oriented  
 447 towards the northeast and southeast.

448

## 449 **5. Discussion**

### 450 *5.1. How are fine-grained sediment and organic carbon transported in a submarine* 451 *canyon between sediment density flow events?*

452         Monterey Canyon experiences persistent, dynamic sediment and organic carbon  
 453 transport that is concentrated near the seafloor along the canyon's axial channel. This  
 454 includes sub-daily variations in velocity and turbidity (e.g., Fig. 9) that are interpreted to  
 455 be primarily the result of semi-diurnal and diurnal internal tides within Monterey Canyon  
 456 (e.g., Petruncio et al., 1998; Xu et al., 2002b; Xu and Noble, 2009). Internal tidal flow  
 457 velocities documented in the CCE ADCP measurements exceed previous velocity  
 458 measurements and estimations in Monterey Canyon (Petruncio et al., 1998; Xu et al.,  
 459 2002b; Xu and Noble, 2009; Jingling et al., 2015). Unlike the adjacent continental shelf  
 460 (Rosenberger et al., 2016), internal tides appear to be an important mechanism in  
 461 sediment transporting sediment and organic carbon within Monterey Canyon, dominating  
 462 between sediment density flow events. Internal tide sediment and organic matter transport  
 463 also may be important for canyon ecosystems, providing food to filter-feeding organisms  
 464 and possibly influencing distributions of canyon biomass (e.g., Shea and Broenkow,  
 465 1982; Amaro et al., 2015, 2016; Prouty et al., 2017).

466         Sediment flux estimates (e.g., Fig. 10) provide a broad, first-order comparison for



467 flux near the canyon floor during background, internal-tide-dominated conditions. We  
468 note that these estimates only included 16 days of data (corresponding to the sediment  
469 trap samples analyzed herein) and suggest a convergence of flux in the upper canyon (net  
470 down-canyon at MS1 and MS3 with net up-canyon at MS2), which is clearly not  
471 representative of persistent, long-term conditions throughout the water column in these  
472 locations. This apparent discrepancy may result from some cross-canyon (orthogonal to  
473 along-canyon flows) shear in the flow (leading to the net up-canyon flux observed at  
474 MS2), or there may be a return flow farther up in the water column that is not captured in  
475 the CCE near-seafloor dataset.

476 The lateral organic carbon flux can be estimated by combining the TOC (weight  
477 %) analyses with suspended sediment flux (Fig. 10). Organic carbon flux for the first 16  
478 days of Deployment III at 10 m above the seafloor was net down-canyon  $1.8 \cdot 10^4 \text{ kg/m}^2$  at  
479 MS1 and  $4.7 \cdot 10^3 \text{ kg/m}^2$  at MS3. Because MS2 sediment traps were ripped from the  
480 mooring during Deployment III, we use an average of TOC analyses from deployments I  
481 and II to estimate organic carbon flux for the first 16 days in Deployment III at 10 m  
482 above the seafloor of  $2.56 \cdot 10^3 \text{ kg/m}^2$  up-canyon at MS2. As with sediment flux, these  
483 estimates may not be representative of longer timescales or across the entire canyon  
484 cross-section.

485 We interpret that internal tide sediment transport and resuspension result in the  
486 fine-scale layering and high accumulation rates of fine-grained sediments in the near-  
487 seafloor (primarily 10 masf) sediment traps (Table 1; Fig. 3). The coarser (fine sand to  
488 silt), thin (<1 cm) layers (Fig. 3) appear to record variations in sediment transported by  
489 internal tides that intensify up-canyon. This interpretation is similar to where Xu et al.  
490 (2010) noted strong internal tidal currents suspending sandy sediment (46% sand) that  
491 was collected in sediment traps 60 masf in Hueneme and Mugu submarine canyons,  
492 offshore southern California. Similarly, the internal tide in Gaoping Canyon increased the  
493 coarse fraction present in Anderson-type sediment traps (Liu et al., 2016). A bottom  
494 nepheloid layer composed of resuspended sediment (e.g., Drake and Gorsline, 1973; Xu  
495 et al., 2002b) may be repeatedly moved past the Monterey Canyon moorings by internal  
496 tides, resulting in high apparent sediment accumulation rates in sediment traps (Table 1).  
497 Increases in internal tide velocities may amplify coarse sediment transport and total  
498 sediment accumulation in traps, but the complex association of velocity, turbidity, and  
499 timing of trap accumulation cannot be further distinguished from intervalometer discs  
500 alone in this study (e.g., Fig. 9A, B).

501 The fine-scale layering in the sediment trap on MS1 is augmented by thicker ( $\leq 5$   
502 cm), sandier layers that did not coincide with the timing of sediment density flow events  
503 (after Paull et al., 2018) or with strong internal tide events (Fig. 11). We suggest that  
504 these thicker, sandier layers may accumulate in association with increased wave height  
505 on the adjacent shelf oriented towards the southeast or northeast during deployments I  
506 and III (Fig. 11). Sediment resuspension and transport on the shelf adjacent to the canyon

507 could have moved sediment over the rim of the canyon to the north and (or) south of  
508 MS1 (Fig. 1). Similar shelf re-working and resuspension by storms was interpreted from  
509 traps in Hueneme and Mugu canyons, offshore southern California, where these two  
510 canyons incise close to the shoreline and remain in close proximity to the shelf (Inman et  
511 al., 1976; Xu et al., 2010).

512

### 513 *5.2. How is organic carbon fractionated and (or) mixed along the canyon?*

514 We consider mixing and along-canyon trends during periods between episodic  
515 sediment density flow events (i.e., only during background conditions). The observed  
516 down-canyon increase in the concentration of organic carbon (measured weight percent  
517 TOC; Fig. 6A) appears to reflect higher input of clastic sediment nearer the canyon head.  
518 Overall sediment accumulation rates in traps decrease down-canyon (Table 1; Fig. 3),  
519 such that a 1-cm sub-sample from a lower canyon trap at 10 masf represents a longer  
520 timeframe than a 1-cm sub-sample from an upper canyon trap at 10 masf. Normalizing  
521 TOC measurements for in-trap accumulation rates results in a down-canyon decrease in  
522 the rate of organic carbon delivery (g/day TOC; Fig. 6B). Clastic sediment may have  
523 settled more rapidly than organic matter with down-canyon decreases in internal tide  
524 velocities. This could have resulted in an increase in the fraction of organic matter  
525 relative to clastic sediment (weight percent TOC), despite a decrease in organic carbon  
526 flux down-canyon (g/day TOC).

527 Lack of consistent down-canyon trends in pMC (Fig. 5A) and organic carbon  
528 stable isotopes (Fig. 7) suggests effective mixing of organic carbon composition in the  
529 water column, likely by internal tides. Sediment and organic carbon moving through the  
530 canyon represent a mixture of sources, including marine, terrestrial, and resuspended  
531 canyon deposits. Organic carbon isotopic signatures measured from traps likely represent  
532 a mixture of terrestrial and marine sources (Fig. 7), but may also reflect variability in  
533 marine sources noted in surface waters above the Monterey Bay continental shelf  
534 adjacent to the canyon (Rau et al., 2001). Terrestrial to mixed terrestrial-marine  
535 endmember  $\delta^{13}\text{C}$  signatures (-24.4 to -22.2 per mil) occur throughout the Monterey  
536 Canyon sediment trap array (Fig. 7), and C:N ratios (7.9–9.4) are consistently higher than  
537 marine organic material (6.7; Redfield, 1934), suggesting a likely input of terrestrial  
538 organic material along the canyon near-seafloor from adjacent rivers and (or)  
539 resuspension. Secondary mobilization of older canyon deposits along the upper canyon  
540 (e.g., Paull et al., 2006, 2010a, b; Maier et al., 2018) through internal tide resuspension  
541 and (or) sediment density flow events may contribute to isotopic signatures and TOC  
542 measured from sediment trap samples. However, the average pMC of trap samples (Fig.  
543 5; Supplementary Table 2) is similar to that of water column samples from Moss Landing  
544 Harbor and immediately offshore (Paull et al., 2006). In addition, water column  
545 productivity and resuspension of nepheloid layer material from the adjacent continental  
546 shelf or canyon likely contribute to TOC, pMC, and organic carbon isotopic signatures in

547 Monterey Canyon during non-event periods.

548

549 *5.3. How are transported organic carbon and fine-grained sediment preserved in canyon*  
550 *deposits?*

551 *5.3.1. Organic carbon burial*

552 Available organic carbon analyses of fine-grained sediments collected in cores  
553 from deposits in Monterey Canyon prior to the CCE (Paull et al., 2006) warrant  
554 comparison to organic carbon transported through the canyon that is captured in CCE  
555 sediment traps. Trap samples, reflecting sediment that moves through the canyon via  
556 internal tides, have organic carbon with enriched  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  (likely more marine  
557 signature) compared to organic carbon preserved in sediment cores (Fig. 12A, B). Core  
558 samples from Paull et al. (2006) lack the down-canyon trends in TOC found in traps (Fig.  
559 12C). The two sample sets are lithologically similar fine-grained sediment, although the  
560 same type of grain size analyses are not available for canyon floor deposits that were  
561 analyzed for organic carbon, and thus, grain size effects are possible. Notably, the two  
562 sample sets are from different time periods and locations in the canyon, yet the Paull et  
563 al. (2006) core analyses are the best sample set available for comparison with trap  
564 analyses from this study.

565 Comparison of these two available sample sets suggests that seafloor deposits  
566 may substantially underestimate the composition and supply of organic carbon in the  
567 suspended sediment moving within the canyon. For example, first-order estimates of  
568 burial efficiency can be made by dividing TOC results from core samples in Paull et al.  
569 (2006) ( $0.5 \pm 0.4\%$ ; average and single standard deviation) by TOC results in the nearby  
570 sediment trap samples ( $1.9 \pm 0.3\%$ ) (e.g., Fig. 12C). Both sample sets are analyzed from  
571 fine-grained material, but Paull et al. (2006) cores are dominantly from higher above the  
572 axial channel than traps at 10 masf. The ratio of TOC in background sediment in traps  
573 located 10 m above the axial channel floor and fine-grained deposits in cores results in  
574 organic carbon specific burial efficiency estimate of  $\sim 26\%$ .

575 Sediment transport processes will influence organic carbon burial efficiency. Our  
576 analyses in Monterey Canyon exclude (sand-dominated) turbidity current units in  
577 sediment trap samples (Maier et al., 2019). Sandy-deposits that dominate the canyon  
578 floor may have lower organic carbon contents, as organic carbon is preferentially  
579 associated with fine-grained deposits (e.g., Masson et al., 2010). Paull et al. (2006) do not  
580 distinguish between organic carbon contents of fine-grained background settling and fine-  
581 grained turbidity current deposits, which likely are both contained in fine-grained  
582 sediment accumulating along the canyon floor and lower flanks (e.g., Paull et al., 2010a;  
583 Symons et al., 2017). It remains unclear whether mud-rich seafloor deposits from  
584 turbidity currents have higher or lower organic carbon contents than deposits from  
585 background sediment transport analyzed from sediment traps; and thus, it is not possible  
586 to determine exactly how inclusion of flow deposits in seafloor cores affects organic

587 carbon burial efficiency estimates. In this study, we can provide only specific burial  
588 efficiency estimates, meaning that they incorporate only background sediment transport.  
589 If turbidity current deposits have relatively low organic carbon contents compared with  
590 background sediment transport, then incorporating turbidity currents would increase our  
591 burial efficiency estimates. Conversely, burial efficiency estimates might decrease if  
592 sediment and organic matter in traps are derived largely from internal tide resuspension  
593 and contain a mixture of new and resuspended seafloor organic carbon (e.g., Masson et  
594 al., 2010).

595 As noted by Masson et al. (2010), differences in sedimentation accumulation rates  
596 should be considered in estimates of organic carbon burial efficiency because burial  
597 efficiency calculations should compare total amounts of sediments deposited over a unit  
598 of time, rather than organic carbon abundance per unit volume of sediment. For example,  
599 corrections based on differences in trap and core sediment accumulation rates decreased  
600 Nazaré Canyon organic carbon burial efficiency calculations from ~80% to ~30%  
601 (Masson et al., 2010). Our trap samples and Paull et al. (2006) core samples are not from  
602 the same time period, but both can be approximately converted into accumulation over  
603 unit time, as a first-order comparison. Accumulation rates of organic carbon in traps are  
604  $0.2 \pm 0.1$  g/day, estimated using TOC (weight percent) and averaged density and water  
605 content (Fig. 6B; Supplementary Table 3). Sedimentation rates of Paull et al. (2006) core  
606 samples are estimated over a longer time-scale where pollen data suggests >5 m sediment  
607 accumulation in historic times (i.e., 5 m in 200 years; ~0.007 cm/day), which suggests  
608 sediment accumulation on the seafloor that is >140 times slower than trap accumulation.  
609 If we estimate sediment density in the core samples as similar to the trap samples and use  
610 Paull et al. (2006) reported TOC values (weight percent) with a core diameter of 7.8 cm  
611 (e.g., Paull et al., 2010a), then the core sediments accumulated organic carbon at ~0.002  
612 g/day. Thus, if sediment accumulation rates are incorporated, then estimates of organic  
613 carbon specific burial efficiency in upper Monterey Canyon decrease by orders of  
614 magnitude from ~26% to ~0.1%. Despite the large CCE dataset that facilitates these first-  
615 order estimates, additional investigation is needed to better constrain organic carbon  
616 burial efficiency calculations in this and other submarine canyons.

617 A likely contributor to organic carbon specific burial efficiency and isotopic  
618 signatures preserved through time is post-depositional alteration. Oxidation, bioturbation  
619 and metabolism of organic matter on the seafloor by grazing and infaunal organisms  
620 (e.g., Lehmann et al., 2002; Baudin et al., 2017; Symons et al., 2017), and local  
621 ecosystem variability (e.g., Martiny et al., 2013) will influence the organic carbon  
622 preserved in sediment deposits. For example, preferential consumption of organic carbon  
623 with greater pMC and enriched  $\delta^{13}\text{C}$ , would deplete the measured organic carbon  $\delta^{13}\text{C}$   
624 and enhance the more terrestrial signature observed in seafloor deposits compared with  
625 sediment trap samples (e.g., Fig. 12). Likewise, degradation of organic material on the  
626 canyon floor may deplete  $\delta^{15}\text{N}$  in seafloor deposits relative to trap samples (e.g.,

627 Lehmann et al., 2002). Lesser organic matter degradation and consumption in sodium  
628 azide-treated trap samples (e.g., Gardner et al., 1983a) preserves a snapshot of organic  
629 carbon available to organisms in the canyon. Additionally, use of hypersaline brine in  
630 sediment traps might have resulted in under-collection of low-density organic matter  
631 (e.g., Fawcett et al., 2018), which would imply under-measurement of TOC in this study  
632 and result in even lower specific burial efficiency estimates.

633 Previous studies have also estimated organic carbon burial efficiency by  
634 comparing river sediment to submarine canyon deposits. For example, a study of the  
635 Bengal Fan system (Galy et al., 2007) compared similar organic carbon abundance in  
636 river sediment and deep-sea cores, suggesting much more efficient organic carbon burial  
637 than estimated in this study for Monterey Canyon. It is also instructive to compare  
638 organic carbon content supplied by rivers around Monterey Bay to those in Monterey  
639 Canyon traps and deposits. We note that, at present, sediment is dominantly supplied to  
640 Monterey Bay by longshore drift, and ultimately the rivers supply sediment into the  
641 coastal systems. TOC (weight percent) in the Salinas and Pajaro river beds (<0.5%; Paull  
642 et al., 2006) is much lower than in sediment traps (1.2–2.9%), but comparable to seafloor  
643 core samples (0.5 %; Paull et al., 2006) (Fig. 12C). This suggests a possible higher  
644 specific burial efficiency when comparing only river and canyon floor samples.

645

#### 646 5.3.2. *Patterns in fine-grained sediment from excess $^{210}\text{Pb}$ activities*

647 Analyses of  $x_s^{210}\text{Pb}$  activities from Monterey Canyon sediment traps provide a  
648 geochemical tool to evaluate fine-grained sediment transport and deposition in  
649 conjunction with organic carbon analyses. Increasing water depths along the CCE  
650 sediment trap array increase the amount of time that particles falling vertically through  
651 the water column had to adsorb  $x_s^{210}\text{Pb}$  (e.g., Lewis et al., 2002; Martín et al., 2006;  
652 Alexander and Venherm, 2003); however, adsorption from vertically settling particles  
653 does not account for the high measured  $x_s^{210}\text{Pb}$  activities in Monterey Canyon near-  
654 seafloor sediment traps. For example, the atmospheric  $^{210}\text{Pb}$  deposition rate of 4.1  
655  $\text{dpm}/\text{m}^2/\text{day}$  for central California (Fuller and Hammond, 1983) and maximum  $x_s^{210}\text{Pb}$   
656 scavenging of 9.4  $\text{dpm}/\text{m}^2/\text{day}$  from sediment settling vertically through 800 m water  
657 depth would result in measured  $x_s^{210}\text{Pb}$  activities of  $\sim 14$   $\text{dpm}/\text{m}^2/\text{day}$  (after Alexander  
658 and Venherm, 2003). This maximum amount of  $x_s^{210}\text{Pb}$  produced from vertical settling is  
659 orders of magnitude less than the measured  $x_s^{210}\text{Pb}$  activities from MS3. If adsorption via  
660 vertical settling controlled  $x_s^{210}\text{Pb}$  activities in Monterey Canyon sediment traps, then  
661  $x_s^{210}\text{Pb}$  activity ( $\text{dpm}/\text{g}$ ) in a trap at 300 masf would not have been greater than a  
662 contemporaneous measurement from 290 meters closer to the seafloor on the same  
663 mooring (Fig. 8A). Sediment transported laterally near the seafloor via internal tides can  
664 adsorb significantly more  $x_s^{210}\text{Pb}$  than would have been possible from vertical settling  
665 alone (e.g., Krishnaswami et al., 1975; Smoak et al., 2000; Alexander and Venherm,  
666 2003).

667 The observed down-canyon increase in  $x_s^{210}\text{Pb}$  activities (dpm/g) (Fig. 8A) is  
668 primarily a result of down-canyon decrease in sediment accumulation rate. This inverse  
669 relationship has been widely noted in other submarine canyons (e.g., Hung and Chung,  
670 1998; Palanques et al., 2005; Martín et al., 2006, 2011; de Stigter et al., 2007; Huh et al.,  
671 2009b; Xu et al., 2010; Prouty et al., 2017). As in-trap accumulation rates decrease, a  
672 gram of analyzed sub-sample represents a longer time interval, resulting in higher  $x_s^{210}\text{Pb}$   
673 activities (dpm/g).

674 Weight percent TOC also increases down-canyon and may add to trends in  
675  $x_s^{210}\text{Pb}$  activities (dpm/g) (Fig. 8C). Yang et al. (2015) suggested that higher organic  
676 carbon content could increase  $^{210}\text{Pb}$  adsorption onto inorganic nanoparticles. However,  
677 the  $x_s^{210}\text{Pb}$  (dpm/g) trend is not apparent when  $x_s^{210}\text{Pb}$  activities are normalized for  
678 sediment accumulation rate (dpm/day) (Fig. 8B), suggesting no systematic variation of  
679 scavenging or  $x_s^{210}\text{Pb}$  availability related to organic carbon delivery.

680 The possible influence of grain size on the down-canyon trend in  $x_s^{210}\text{Pb}$   
681 activities (dpm/g) (e.g., Kirchner, 2011) was also considered. Although MS1 is slightly  
682 coarser, background grain size is similar throughout the remainder of the array (Fig. 4).  
683 This suggests that grain size has little contribution to the down-canyon increase in  
684  $x_s^{210}\text{Pb}$  activities (dpm/g).

685 Xu et al. (2010) noted that  $x_s^{210}\text{Pb}$  activities in sediment transported through  
686 Hueneme and Mugu canyons, offshore southern California, was diluted by low  $x_s^{210}\text{Pb}$   
687 activities in laterally transported sediments resuspended from the shelf or canyon walls  
688 during storms. Down-canyon trends in  $x_s^{210}\text{Pb}$  activities (dpm/g) in this study are likely  
689 related to sediment transported and resuspended by internal tides, wherein the upper  
690 canyon sediment both spend less time in the water column adsorbing  $^{210}\text{Pb}$  than lower  
691 canyon samples and may be resuspended from relatively  $^{210}\text{Pb}$ -poor upper canyon  
692 deposits.

693 Measured  $x_s^{210}\text{Pb}$  activities of sediment moving through the canyon are  
694 fundamentally different than, but have implications for,  $^{210}\text{Pb}$  analyses on sediment  
695 sampled from seafloor deposits. In sediment cores, the  $^{210}\text{Pb}$  profile is used as a  
696 chronometer and measure of deposition rates (e.g., Lewis et al., 2002; Zúñiga et al.,  
697 2009). Notably, the down-canyon increase in  $x_s^{210}\text{Pb}$  activities (dpm/g) from traps is  
698 apparent in the  $x_s^{210}\text{Pb}$  activities (dpm/g) measured from the top centimeter of seafloor  
699 sediments adjacent to the CCE sediment traps (Fig. 12D). Previous studies of organic  
700 carbon signatures (Fig. 12A–C; Paull et al., 2006), and canyon facies (e.g., Paull et al.,  
701 2010a; Symons et al., 2017) suggest that fine-grained bench deposits may be  
702 predominantly sediment density flow deposits, but  $x_s^{210}\text{Pb}$  activities of fine-grained  
703 sediment in canyon bench deposits appear to be recording an aspect of along-canyon  
704 trends in the water column, possibly related to internal tide transport and resuspension of  
705 fine-grained sediment.

706

#### 707 5.4. Implications for submarine canyon studies

##### 708 5.4.1. Submarine canyon deposits

709 Sediment traps provide direct samples of sediment moving through the water  
710 column but do not necessarily reflect the lithology or geochemistry of sediment deposited  
711 and preserved on the seafloor in submarine canyons. Despite the importance of internal  
712 tides in Monterey Canyon, seafloor samples may not reflect sediment or organic carbon  
713 transported via internal tides; instead deposits along and near the canyon axial channel  
714 appear to be dominated by episodic and powerful sediment density flow events (e.g.,  
715 Paull et al., 2005, 2010a; Maier et al., 2019). In particular, organic carbon analyses of  
716 fine-grained seafloor deposits are distinctly different than nearby traps (Fig. 12).  
717 Sediment sampled from seafloor deposits show little clear record of internal tide  
718 signatures, background sediment transport, and organic carbon available to deep-sea  
719 communities in the canyon, except in  $xs^{210}\text{Pb}$  activity (dpm/g) down-canyon trends. This  
720 is critical to address in more detail in the future because much of our knowledge of  
721 submarine canyons through geologic time is derived from their remaining deposits (e.g.,  
722 Talling et al., 2015; Covault et al., 2016). Studies in other submarine canyons and deep-  
723 water settings have interpreted internal tide processes from deposits without the benefit of  
724 direct measurements and sampling achieved in this study with sediment traps (e.g.,  
725 Zhenzhong and Eriksson, 1991; Kudrass et al., 1998; Shanmugam, 2003; He et al., 2011;  
726 Pomar et al., 2012), and others have noted that accumulation of sediment in upper canyon  
727 traps exceeds contemporaneous seafloor deposition (e.g., de Stigter et al., 2007). It  
728 appears that internal tides are a significant, consistent process moving sediment through  
729 Monterey and other submarine canyons that may not be adequately reflected in seafloor  
730 deposits.

##### 731 5.4.2. Generalized scheme and comparisons

732 Below, we briefly compare Monterey Canyon results with other submarine  
733 canyons where focused study has provided estimates of accumulation in sediment traps,  
734 internal tide velocities, and (or) organic carbon delivery and burial efficiency. We use  
735 Nazaré Canyon, Gaoping (Kaoping) Canyon, and Whittard Canyon to discuss similarities  
736 and variability in internal tides and organic carbon in submarine canyon environments.

737 5.4.2.1. Nazaré Canyon: Like Monterey Canyon, Nazaré Canyon, offshore the  
738 Western Iberian Margin, is incised to near the shoreline and contains sandy crescentic-  
739 shaped bedforms along the canyon axis (e.g., Arzola et al., 2008). Internal tidal flows  
740 decrease down Nazaré Canyon and have been measured up to 80 cm/s along with  
741 sediment trap apparent accumulation rates (mean 65 g/m<sup>2</sup>/day; maximum 265 g/m<sup>2</sup>/day)  
742 on the order of those in this study (de Stigter et al., 2007; Martín et al., 2011). Despite  
743 these similarities between Nazaré and Monterey canyons, organic carbon contents in  
744 sediment traps from upper Monterey Canyon generally are lower than in Nazaré Canyon,  
745 although some Nazaré Canyon sites are in deeper water depths and at greater distances  
746 offshore than upper Monterey Canyon (Epping et al., 2002; Masson et al., 2010).

747 Likewise, Masson et al. (2010) organic carbon burial efficiency estimates from Nazaré  
748 Canyon are much higher than the specific burial efficiency estimates from Monterey  
749 Canyon in this study, including ~80% compared with ~26% by direct core and trap  
750 comparison, and ~30% compared with ~0.1% when accounting for sediment  
751 accumulation rates. Higher organic carbon content in cores from Nazaré Canyon  
752 compared with Monterey Canyon may be related to the overall muddier sediments in  
753 Nazaré Canyon (e.g., Arzola et al., 2008; Pusceddu et al., 2010), even compared with  
754 fine-grained sediment accumulation along Monterey Canyon benches (e.g., Paull et al.,  
755 2006, 2010a; Symons et al., 2017). Organic carbon delivery to Nazaré Canyon decreases  
756 down-canyon, as in Monterey Canyon, and has been demonstrated to impact fauna and  
757 food webs within the submarine canyon environment (van Oevelen et al., 2011).

758 *5.4.2.2. Gaoping (Kaoping) Canyon:* Gaoping (Kaoping) Canyon, offshore  
759 Taiwan, can be compared with Monterey Canyon particularly because similar Anderson-  
760 type sediment traps have been deployed in studies of both canyons (e.g., Huh et al.,  
761 2009b; Liu et al., 2012, 2016; Zheng et al., 2017). Like Monterey and Nazaré canyons,  
762 Gaoping (Kaoping) Canyon heads near the shoreline, and sedimentation rates are high  
763 (e.g., Huh et al., 2009a). As in Monterey Canyon, internal tidal flows in Gaoping  
764 (Kaoping) Canyon reach >1 m/s near the seafloor, facilitate a bottom nepheloid layer,  
765 impact benthic communities, and transport fine-grained sediment into traps deployed in  
766 the canyon (e.g., Lee et al., 2009; Liu et al., 2010, 2013, 2016; Liao et al., 2017).  
767 Apparent sediment accumulation rate estimates for traps are within similar ranges in  
768 Gaoping (Kaoping) and Monterey canyons (Liu et al., 2016). However, the two canyons  
769 differ in organic carbon content (overall lower in Gaoping (Kaoping) than in Monterey,  
770 particularly during internal-tide-dominated intervals) and  $\delta^{13}\text{C}$  (more depleted in Gaoping  
771 (Kaoping) compared with Monterey), likely owing to the higher terrestrial input to  
772 Gaoping (Kaoping) Canyon from hyperpycnal and hypopycnal flows, frequent typhoons,  
773 and abundant sediment run-off (e.g., Kao et al., 2014; Liu et al., 2016; Zheng et al.,  
774 2017). Accordingly, organic carbon burial efficiency may be higher in Gaoping  
775 (Kaoping) Canyon than specific estimates from Monterey Canyon, owing to the muddier  
776 sediment and rapid transport and deposition of river sediment into Gaoping (Kaoping)  
777 Canyon head (e.g., Huh et al., 2009a; Liu et al., 2009, 2013; Liao et al., 2017).

778 *5.4.2.3. Whittard Canyon:* Powerful sediment density flows occur much less  
779 frequently in Whittard Canyon because the Whittard Canyon head is >300 km from the  
780 shoreline and thus, terrestrial sediment sources (Amaro et al., 2016). Whittard Canyon  
781 nevertheless remains a dynamic environment for benthic ecosystems, sediment transport,  
782 and organic matter transport and mixing, owing to internal tide velocities >40 cm/s that  
783 intensify towards the seafloor (e.g., Amaro et al., 2016; Hall et al., 2017). As in Monterey  
784 Canyon, net flux from internal tides is up-canyon in some portions of Whittard Canyon  
785 (e.g., Amaro et al., 2015, 2016; Aslam et al., 2018). Internal tidal flows focus organic  
786 carbon in Whittard Canyon, providing food for benthic communities and submarine



787 canyon ecosystems (e.g., Huvenne et al., 2011; Amaro et al., 2015). Based on direct  
788 comparison of trap and core organic matter measurements at one location in Whittard  
789 Canyon by Amaro et al. (2015), organic carbon burial efficiency may exceed specific  
790 estimates for Monterey Canyon. Higher organic carbon content in sediment traps (up to  
791 4.5 weight percent) and an overall quieter environment (Amaro et al., 2015) may enhance  
792 organic carbon burial efficiency in Whittard Canyon compared with Monterey Canyon.

793 *5.4.2.4. Generalized conceptual model:* Based on the results and insights from the  
794 novel array of sediment traps along Monterey Canyon, we propose a generalized scheme  
795 for organic carbon transport and burial (Fig. 13), which may be representative of  
796 transport and mixing processes in submarine canyon environments. Key components of  
797 this conceptual model contribute to the sediment accumulation and organic carbon  
798 signatures observed in near-seafloor sediment traps. These include primarily marine and  
799 terrestrial sources of organic carbon (A) that are effectively mixed along Monterey  
800 Canyon (B) by internal tides, which are enhanced near the seafloor (C). Flux of sediment  
801 (D) and organic carbon (E) into traps appear to decrease down Monterey Canyon. Water  
802 column factors (A–E) occur in conjunction with seafloor exchanges, including internal  
803 tide resuspension of fine-grained seafloor sediments (F) and burial of organic carbon (G).

804 Because our generalized scheme (Fig. 13) is based on intervals dominated by  
805 internal tide transport that occur throughout many global submarine canyons (e.g.,  
806 Shanmugam, 2003; Li et al., 2019), it is possible to extend the process concepts beyond  
807 Monterey, Nazaré, and Gaoping (Kaoping) canyons, which are incised through the  
808 continental shelf, to submarine canyons that do not experience frequent sediment density  
809 flow events. Quantities of, and along-canyon changes in, organic carbon transport,  
810 mixing, and burial efficiency will vary based on numerous factors specific to each canyon  
811 environment (e.g., Pusceddu et al., 2010).

812

## 813 **6. Conclusions**

814 Sediment transport in the axis of Monterey Canyon during intervals between  
815 sediment density flow events is dominated by internal tides, which move suspended  
816 sediment and organic carbon along the canyon at velocities that increase up-canyon, are  
817 enhanced with proximity to the seafloor, and create fine-scale layering in sediment trap  
818 samples. Sediment trap samples record composition of organic carbon and fine-grained  
819 sediment moving through water column within the submarine canyon, which are not  
820 clearly reflected or preserved in canyon deposits. The lack of down-canyon trends in  
821 percent modern carbon and organic carbon isotopes ( $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ) is likely the result of  
822 mixing of organic carbon along the canyon, driven by internal tides. Sediment flux into  
823 the traps decreases down-canyon, leading to an increase in organic carbon content and  
824  $x\text{s}^{210}\text{Pb}$  activities (dpm/g). Conversely, the rate of organic carbon delivery to the sediment  
825 trap (g/day) decreases down-canyon. Measured  $x\text{s}^{210}\text{Pb}$  activities (dpm/g) in traps and  
826 seafloor samples increase down-canyon, reflecting lateral transport via internal tides that

827 may contribute to deposition along the canyon.

828       Organic carbon content and isotopic signatures in trap samples differ from  
829 previous analyses of seafloor samples. The differences between water column and  
830 seafloor organic carbon content suggest that organic carbon specific burial efficiency  
831 may be low in modern upper Monterey Canyon. Preferential consumption of fresher  
832 marine organic carbon, combined with seafloor deposits dominated by sediment density  
833 flow event deposits, result in more terrestrial organic carbon isotopic signatures in cores  
834 than in sediment trap samples, and may contribute to low first-order organic carbon  
835 specific burial efficiency estimates. Our results from an array of sediment traps sampling  
836 from the water column between sediment density flow events represent background  
837 conditions that are dominated by internal tides. Because internal tidal flow occurs in  
838 many submarine canyons globally, we suggest that our detailed results and generalized  
839 scheme of organic carbon transport, mixing, and burial developed from Monterey  
840 Canyon may be broadly relevant to other submarine canyon settings.

841

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1356

1357 **Tables**1358 **Table 1.** Anderson-type sediment trap deployments.1359 **Table 2.** Summary of ADCP current velocities.

1360

1361 **Figures**1362 **Fig. 1.** Map of study area in Monterey Canyon, offshore central California. Blue squares  
1363 indicate locations of CCE moorings (MS#). Dashed arrows depict littoral transport paths  
1364 into Monterey Canyon. WHS: wave height sensor. Modified from Paull et al. (2018).

1365

1366 **Fig. 2.** Schematic illustrations of moorings and sediment traps deployed in the  
1367 Coordinated Canyon Experiment in Monterey Canyon. (A) Schematic representation of  
1368 an Anderson-type sediment trap deployed on mooring (not to scale) (modified from Paull  
1369 et al., 2018). ADCP: acoustic Doppler current profiler. masf: meters above the seafloor.  
1370 (B) Schematic Anderson-type sediment trap (not to scale) filling with sediment between  
1371 times  $t_1$  and  $t_2$ .

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1373 **Fig. 3.** Correlation of sediment trap samples with computed tomography (CT) scan and  
1374 grain size plots. Trap names contain mooring (MS#), type of sediment trap (AST), meters  
1375 above the seafloor (##m), and numeric deployment date (year month day). Trap tubes  
1376 shown as abbreviated datasets of CT scan coronal images (shaded individually to  
1377 highlight features) and grain size analyses (d<sub>0.1</sub>:red; D<sub>[4,3]</sub>:black; d<sub>0.9</sub>:gray; see  
1378 Supplementary Table 1 and Lundsten, 2019). Disc dates are shown as numeric month and  
1379 day. (A) Deployment I. (B) Deployment II. (C) Deployment III. (D) Enlarged portions of  
1380 CT images highlighting fine-scale layering in the upper canyon traps.

1381

1382 **Fig. 4.** Grain size distribution plots of background sediment (averaged fine-grained, non-  
1383 sediment density flow event intervals) in Anderson-type sediment traps. Trap names as in  
1384 Figure 3. masf: meters above the seafloor. (A) Deployment I. (B) Deployment II. (C)  
1385 Deployment III.

1386

1387 **Fig. 5.** Plots of radiocarbon analyses (see Supplementary Table 2). masf: meters above  
1388 the seafloor. (A) Percent modern carbon (pMC) plotted with mooring water depth. (B)  
1389 pMC results normalized for apparent sediment flux into the traps.

1390

1391 **Fig. 6.** Organic carbon content (see Supplementary Table 3). (A) Weight percent (wt. %)   
1392 total organic carbon (TOC) plotted with mooring water depth. (B) TOC flux.

1393

1394 **Fig. 7.** Organic carbon stable isotopes (see Supplementary Table 3). masf: meters above  
1395 the seafloor. (A)  $\delta^{13}\text{C}$  plotted with mooring water depth. (B) Plot of  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$ .

1396

1397 **Fig. 8.** Excess (xs)  $^{210}\text{Pb}$  activities (see Supplementary Table 4). (A) xs  $^{210}\text{Pb}$  activities



1398 plotted with sediment trap water depth. masf: meters above the seafloor. (B)  $x_s^{210}\text{Pb}$   
 1399 activities normalized for apparent sediment flux into traps. (C) Plot of  $x_s^{210}\text{Pb}$  activities  
 1400 and total organic carbon (TOC) from the same sediment traps.

1401

1402 **Fig. 9.** Internal tide at MS1. (A) Profiles from a downward-looking 300 kHz acoustic  
 1403 Doppler current profiler (ADCP) showing semi-diurnal velocity variations oriented up-  
 1404 canyon (positive) and down-canyon (negative) at 10 meters above the seafloor (masf;  
 1405 red) and 65 masf (blue) from November 26 – December 6, 2015. Internal tide velocities  
 1406 increase near the seafloor and reach up to 1 m/s oriented up-canyon at 10 masf. (B) Semi-  
 1407 diurnal turbidity oscillations from a sensor at 35 masf during the same period as Part A.  
 1408 Solid gray lines between plots in Part A and Part B highlight spikes in turbidity at 35  
 1409 masf coinciding with spikes in velocity at 10 or 65 masf, and dashed gray lines highlight  
 1410 spikes in turbidity at 35 masf coinciding with periods of low velocities at 10 and (or) 65  
 1411 masf where internal tide orientation switches. (C) November 30, 2015, ADCP  
 1412 measurements of an up-canyon internal tide.

1413

1414 **Fig. 10.** Suspended sediment estimation for the first 16 days (32 tidal cycles) of  
 1415 Deployment III at MS1, MS2, and MS3. Dates are shown as numeric year month day.  
 1416 (A) Along-canyon velocity at 10 meters above the seafloor (masf) measured from a  
 1417 downward-looking ADCP at 65 masf. Positive velocities are oriented up-canyon, and  
 1418 negative velocities are oriented down-canyon. (B) Suspended sediment concentration  
 1419 converted from transmissometer beam attenuation using fine-grained background  
 1420 sediment in this study and the calibration of Xu et al. (2002a). (C) Suspended sediment  
 1421 flux calculated from Parts (A) and (B).

1422

1423 **Fig. 11.** Additional sandy layers at MS1. (A, E) Sediment trap CT images (see Fig. 3),  
 1424 (B, F) wave height (H10 – top 10th percentile of wave height measurements), (C, G)  
 1425 mean wave direction (blue; average of wave spectrum weighted by energy) and peak  
 1426 period direction (red), and (D, H) turbidity at MS1 measured 35 meters above the  
 1427 seafloor from (A–D) Deployment I November 22–30, 2015 and (E–H) Deployment III  
 1428 November 7–15, 2016. Stars (A, E) indicate sandy units that do not correspond to  
 1429 sediment density flow events or strong up-canyon internal tide events; they appear to  
 1430 coincide with intervals of increased wave height oriented towards the southeast to  
 1431 northeast.

1432

1433 **Fig. 12.** Comparison of seafloor sediment core samples and sediment trap analyses. (A)  
 1434  $\delta^{13}\text{C}$ . Trap samples generally show equal or depleted  $\delta^{13}\text{C}$  signatures compared with  
 1435 canyon seafloor deposits. (B)  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ . Core samples have depleted  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$   
 1436 values compared with sediment trap samples (simplified marine and terrestrial signatures  
 1437 after Peters et al., 1978; Paull et al., 2006). (C) Total organic carbon (TOC). Sediment

1438 traps consistently contain more organic carbon than deposits from similar canyon water  
1439 depths. (D) Plot of  $x_s^{210}\text{Pb}$  activities in sediment traps (this study; plotted as sediment  
1440 trap water depth) and the top centimeter (0–1 cm below the seafloor) from Monterey  
1441 Canyon push core samples adjacent to the axial channel (Symons et al., 2017;  
1442 unpublished data, courtesy of T. Lorenson).  $x_s^{210}\text{Pb}$  activities increase down canyon in  
1443 both sample sets, with push core seafloor values consistently equal to or lower than traps  
1444 at 10+ m above the seafloor.

1445

1446 **Fig. 13.** Schematic summary of submarine canyon sediment and organic carbon transport  
1447 and deposition along a down-canyon-axis profile. Key components noted (letters), with  
1448 Monterey Canyon examples italicized. Sizes of labels and lines are broadly representative  
1449 of the relative quantity and importance of processes down the canyon. Not to scale. mwd:  
1450 meters water depth. ADCP: acoustic Doppler current profiler. OMZ: oxygen minimum  
1451 zone.

1452

### 1453 **Supplementary Tables**

1454 **Supplementary Table 1.** Laser particle grain size summary.

1455 **Supplementary Table 2.** Radiocarbon analyses.

1456 **Supplementary Table 3.** Organic carbon content and stable isotope analyses.

1457 **Supplementary Table 4.**  $^{210}\text{Pb}$  analyses.

Table 1. Anderson-type sediment trap deployments.

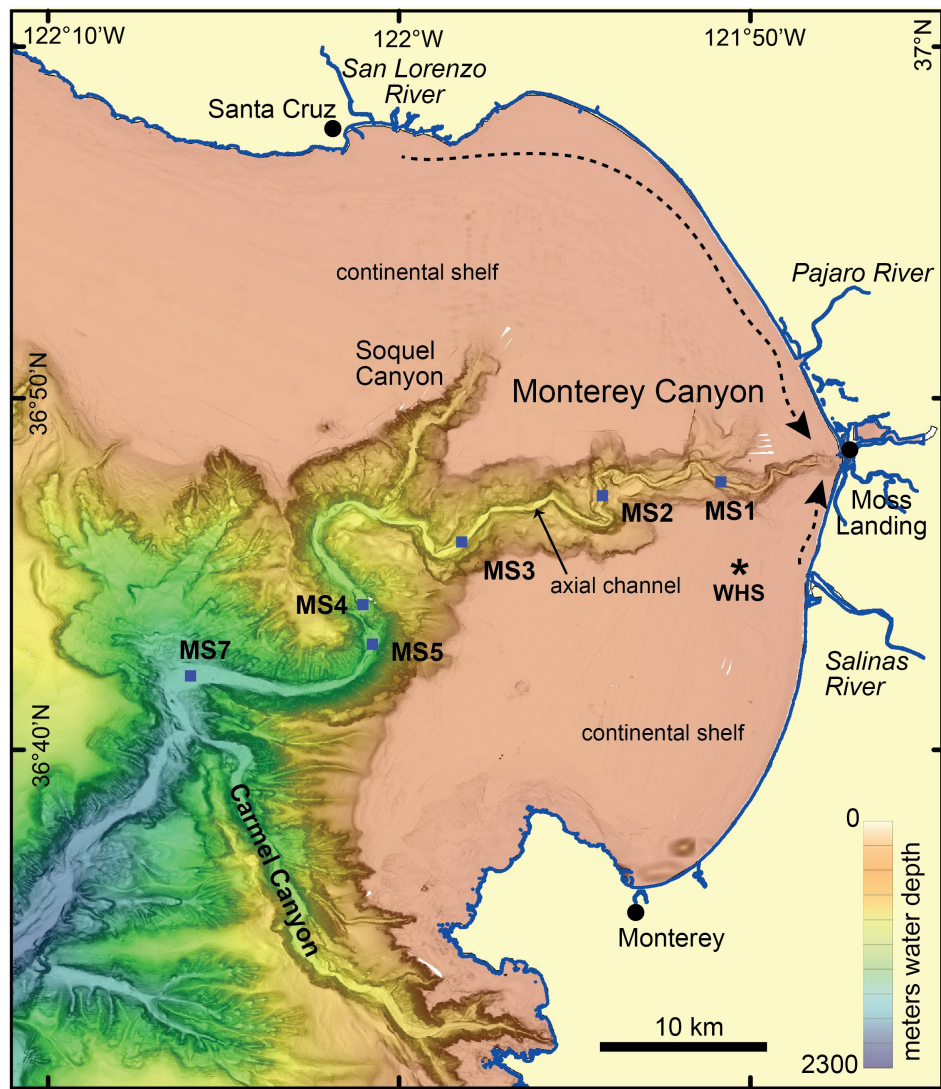
Deployment	Mooring	Mooring Water Depth (m)	Sediment Trap Position		Deployed <sup>2</sup>	Recovered <sup>2</sup>	Sediment Trap Status at Recovery	Total 1-cm Slices	Date <sup>2</sup> of First Sediment Density Flow Event in Trap <sup>4</sup>	Background Sediment Accumulated (cm) <sup>5</sup>	Average Apparent Sediment Accumulation Rate (g/m <sup>2</sup> /day)	Intervalometer Sediment Accumulation Rate (g/m <sup>2</sup> /day) <sup>6</sup>	
			(masf) <sup>1</sup>	Latitude									Longitude
I	MS1	287	10	36.793280	-121.844600	20151006	N/A	ripped off	N/A	N/A	N/A	N/A	
I	MS1	287	35	36.793280	-121.844600	20151006	20160117	overflow	79	20151201	79	460	450 ±187
I	MS2	527	10	36.788270	-121.903400	20151005	20160405	overflow	80	20160115	80	380	398 ±158
I	MS3	831	10	36.764970	-121.969700	20151005	20160405	overflow	89	20160115	77	440	400 ±169
I	MS4	1286	10	36.735795	-122.016478	20151007	20160405	overflow	95	20160115	60	220	N/A
I	MS5	1449	11	36.714960	-122.013000	20151020	20160405	overflow	95	20160115	32	180	164 ±57
I	MS5	1449	74	36.714960	-122.013000	20151020	20160405	overflow	91	20160115	26	120	N/A
I	MS7	1849	10	36.701620	-122.097500	20151027	20160412	full	87	20160115	10	40	N/A
I	MS7	1849	300	36.701620	-122.097500	20151027	20160412	underfilled	9	N/A	9	20	N/A
II	MS1	278	10	36.793240	-121.844716	20160404	20161003	overflow	93	20160901	86	220	N/A
II	MS2	527	10	36.787832	-121.903508	20160407	20161003	overflow	95	20160901	95	400	383 ±206
II	MS3	822	10	36.764763	-121.969575	20160407	20161004	overflow	89	20160901	89	460	503 ±195
II	MS4	1285	10	36.736000	-122.016667	20160408	20161004	overflow	97	20160901	96	240	N/A
II	MS5	1445	11	36.715517	-122.012875	20160408	20161004	overflow	91	20160901	64	160	N/A
II	MS5	1445	74	36.715517	-122.012875	20160408	20161004	full	74	20160901	52	140	N/A
II	MS7	1849	10	36.701784	-122.098400	20160420	20161010	full <sup>3</sup>	N/A	N/A	N/A	N/A	N/A
II	MS7	1849	300	36.701784	-122.098400	20160420	20161010	underfilled	19	N/A	19	40	N/A
III	MS1	290	10	36.793557	-121.845658	20161006	20170321	full	77	20161124	66	620	618 ±289
III	MS1	290	35	36.793557	-121.845658	20161006	20170321	underfilled	13	20161124	N/A	N/A	N/A
III	MS2	523	10	36.787250	-121.903383	20161006	N/A	ripped off	N/A	N/A	N/A	N/A	N/A
III	MS3	817	10	36.765045	-121.969880	20161006	20170321	overflow	96	20161124	38	300	307 ±74
III	MS3	817	35	36.765045	-121.969880	20161006	20170321	overflow	89	20161124	38	300	N/A
III	MS4	1263	10	36.735898	-122.016470	20161007	20170322	overflow	80	20170122	80	280	N/A
III	MS5	1439	11	36.716333	-122.012833	20161007	20170206	overflow	87	20170122	65	220	238 ±92
III	MS5	1439	74	36.716333	-122.012833	20161007	20170206	overflow	84	20170122	48	180	N/A
III	MS7	1849	10	36.701549	-122.098372	20161019	20170404	full	67	20170203	32	120	N/A
III	MS7	1849	300	36.701549	-122.098372	20161019	20170404	underfilled	24	N/A	24	60	N/A

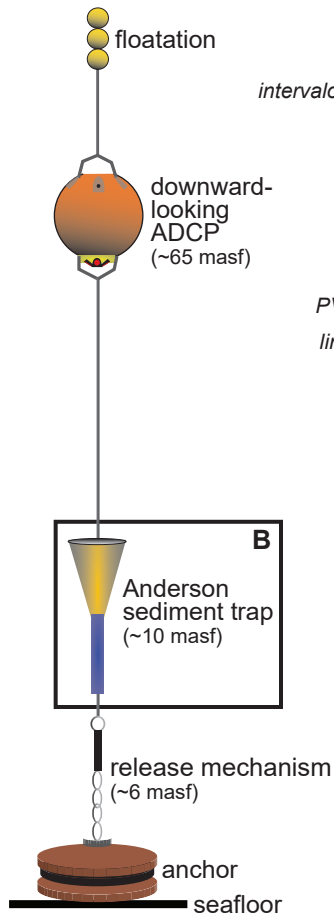
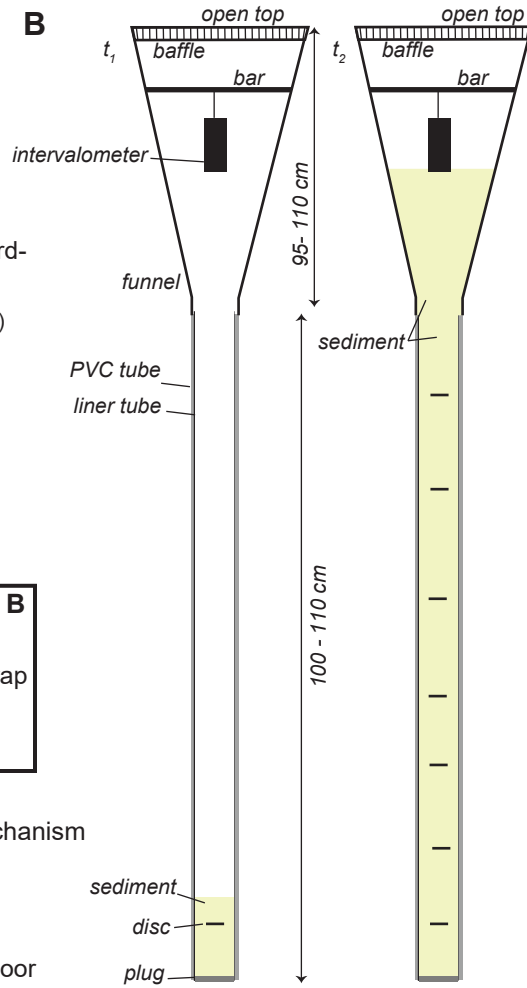
<sup>1</sup>masf: meters above the seafloor<sup>2</sup>dates shown as year, month, day<sup>3</sup>material recovered but not stratigraphy<sup>4</sup>see Paull et al. (2018)<sup>5</sup>calculated from intervalometer discs, CT scans and grain size data<sup>6</sup>shown as averages and single standard deviation

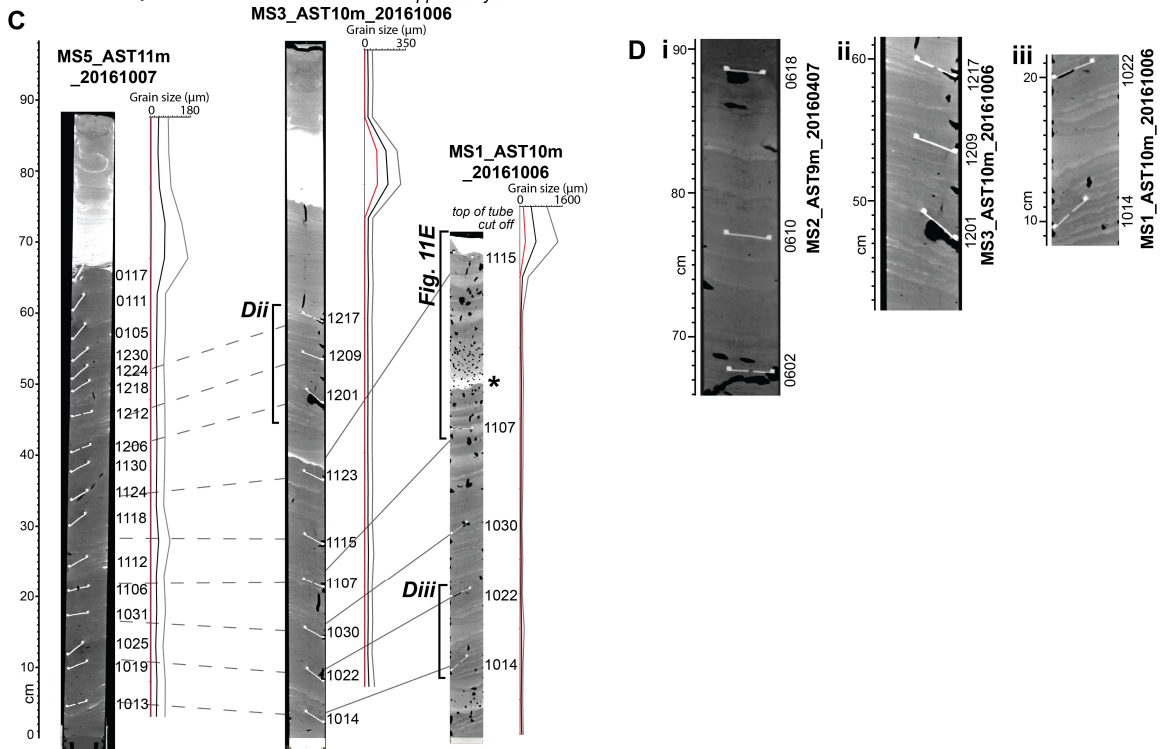
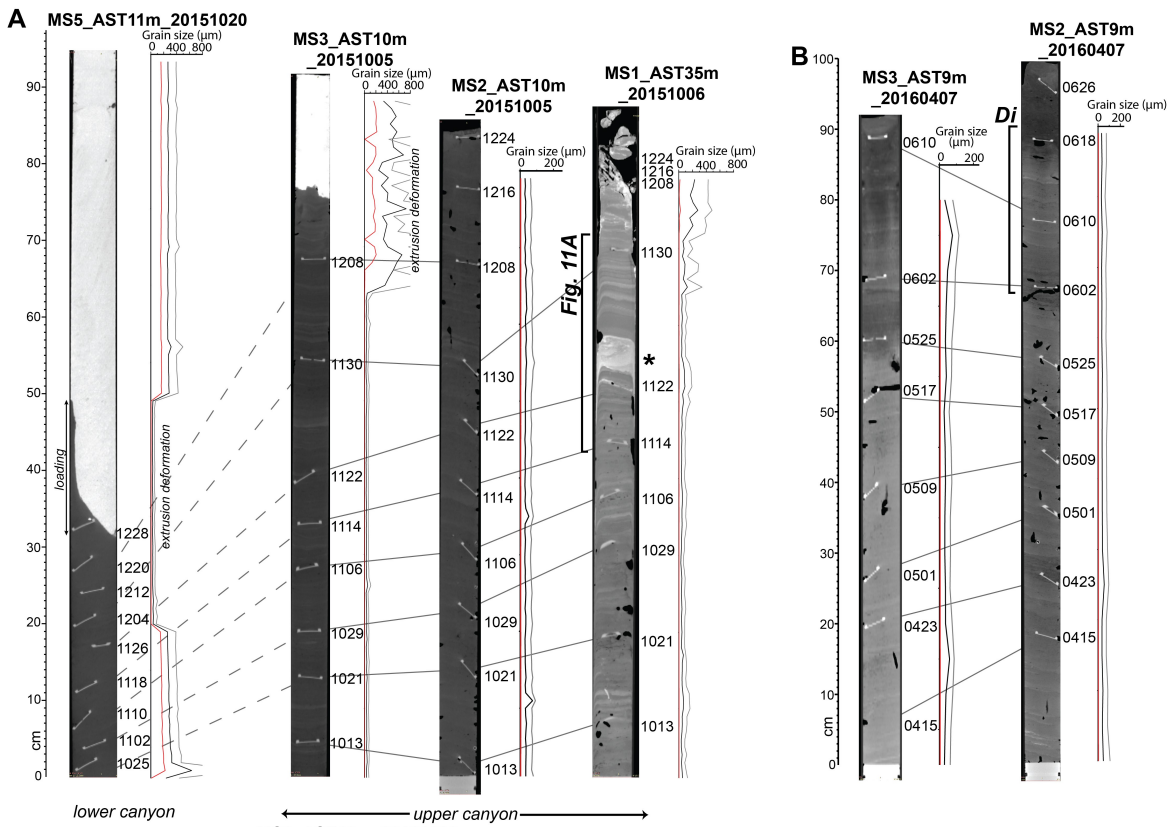
Table 2. Summary of ADCP current velocities.

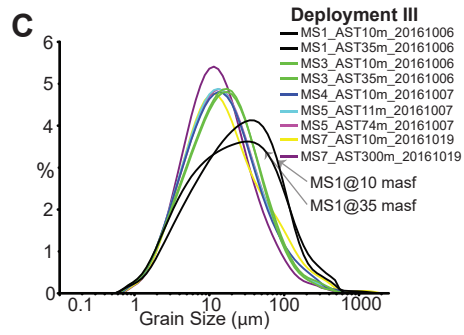
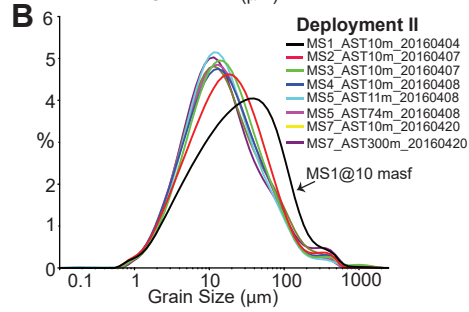
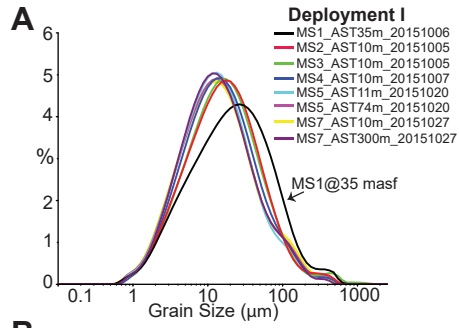
Deployment <sup>1</sup>	Mooring	Statistics		Distribution (% deployment time)						
		Mean (cm/s)	Standard Deviation (cm/s)	0–10 cm/s	10–20 cm/s	20–30 cm/s	30–40 cm/s	40–50 cm/s	50–60 cm/s	60–70 cm/s
II	MS1	19.4	11.8	24.2	34.1	23.1	12.3	4.7	1.3	0.2
III	MS1	17.5	11.6	29.1	36.5	20.9	9.1	3.1	0.8	0.2
II	MS2	17.1	10.5	28.5	38.1	21.0	8.5	2.7	0.6	0.1
III	MS2	15.1	9.4	31.5	41.3	17.8	4.3	0.9	0.3	0.1
II	MS3	13.6	8.0	36.8	43.7	15.3	3.0	0.4	0.1	0
III	MS3	16.6	10.7	30.3	37.8	20.9	8.3	2.1	0.3	0.1
II	MS4	13	7.4	39.8	43.0	14.0	2.3	0.2	<0.1	<0.1
III	MS4	16.7	9.4	26.1	39.7	23.4	7.2	1.2	0.2	0.1
II	MS5	12.4	7.3	42.0	44.1	11.4	1.9	0.3	<0.1	<0.1
III	MS5	15.9	9.8	31.0	41.3	18.0	7.2	2.0	0.3	0.1
II	MS7	17.7	10.1	23.9	40.7	22.8	9.0	2.9	0.5	<0.1
III	MS7	19.8	11.1	20.2	36.1	25.7	12.6	4.3	1.0	0.1

<sup>1</sup>Deployment II (April–October 2016); Deployment III (October 2016 – April 2017)

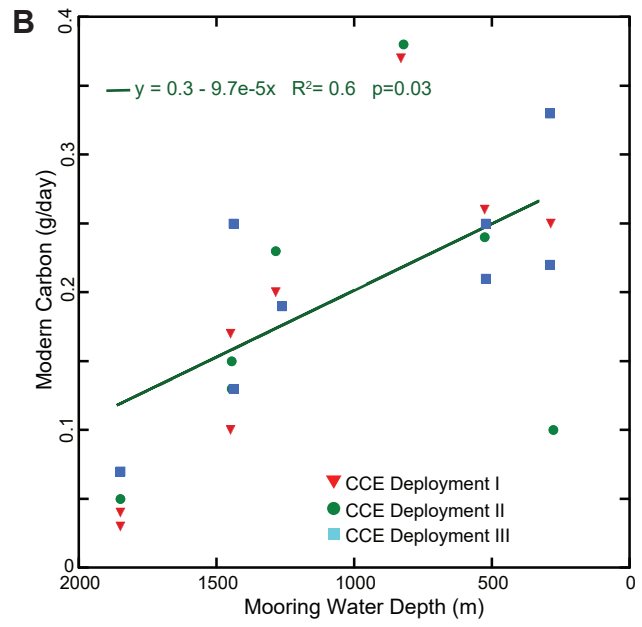
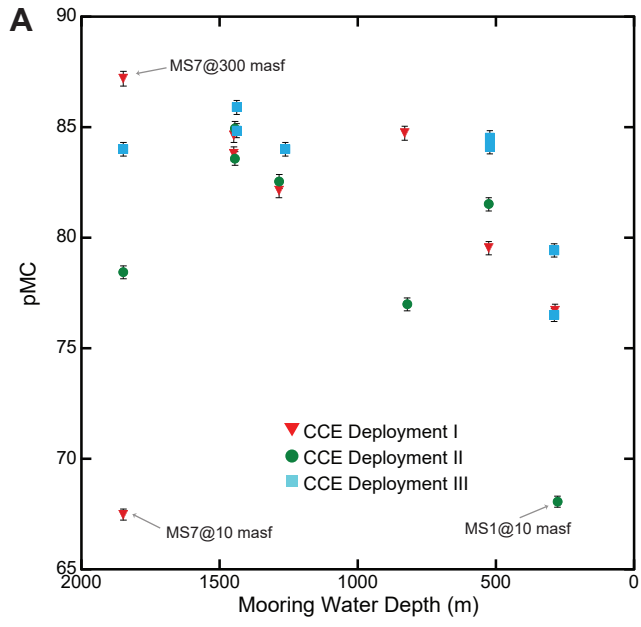


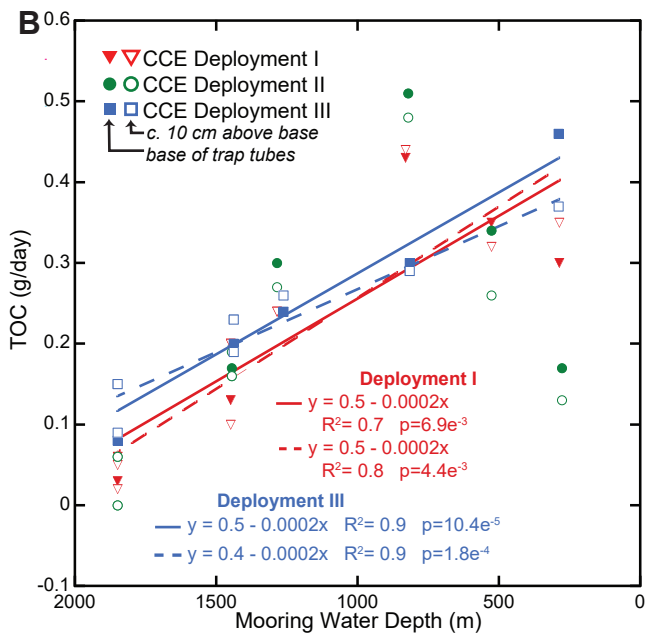
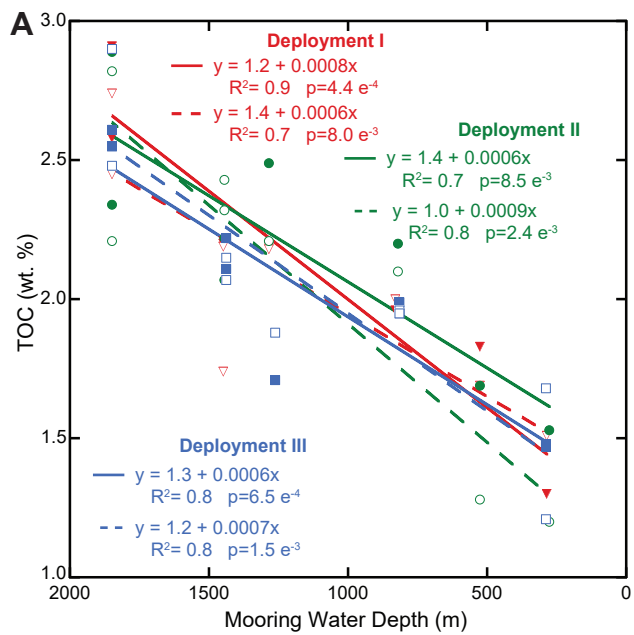
**A****B**

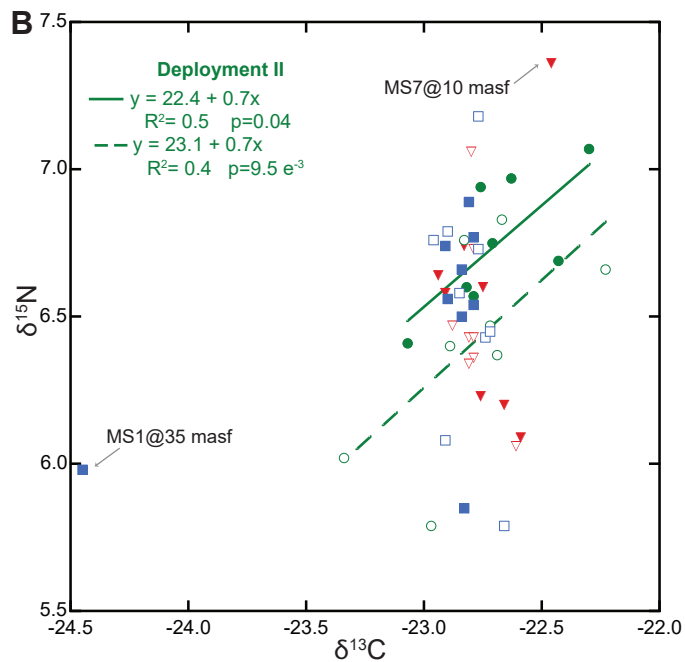
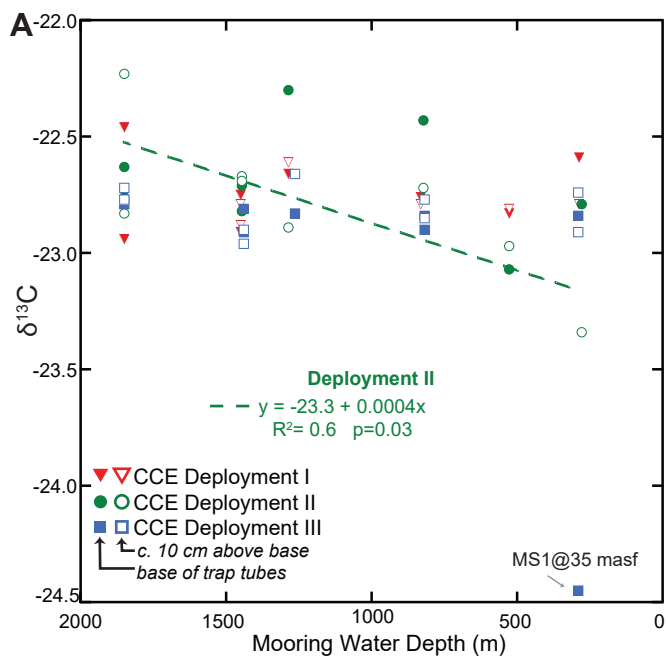


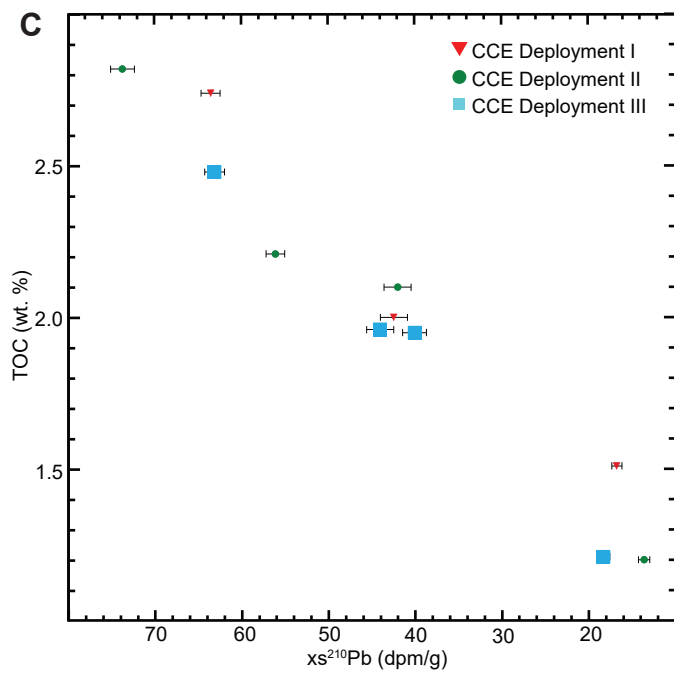
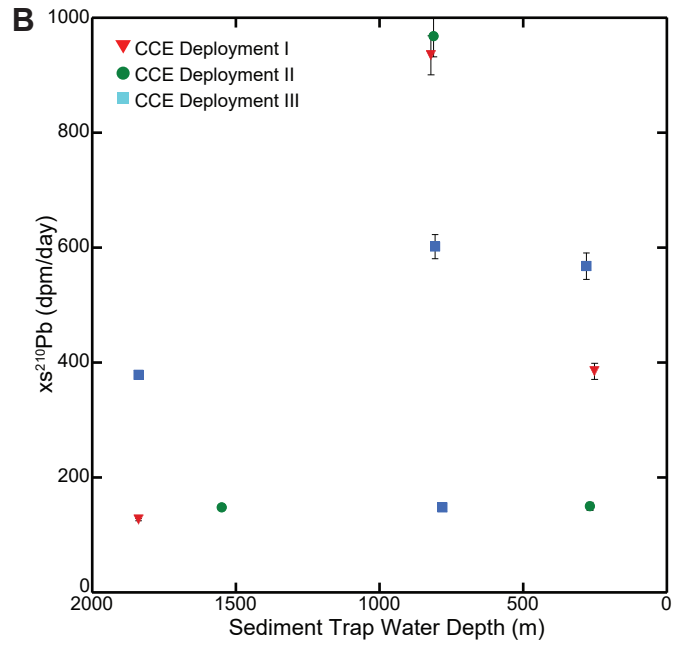
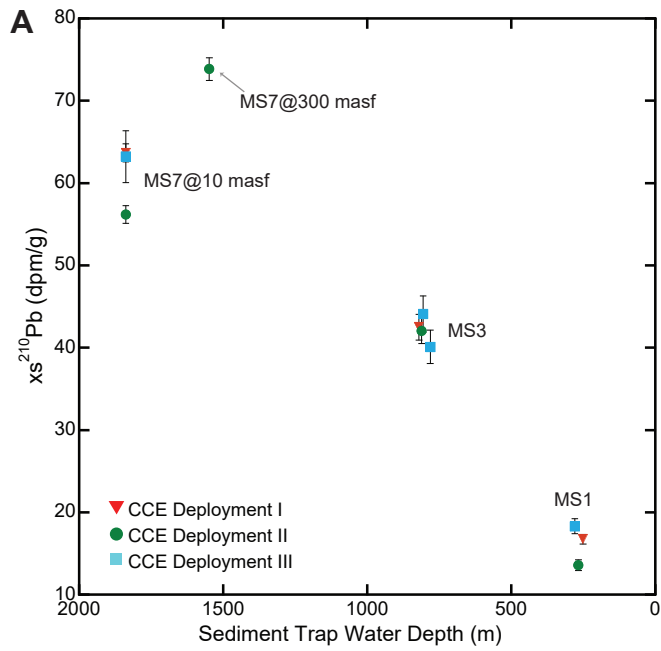


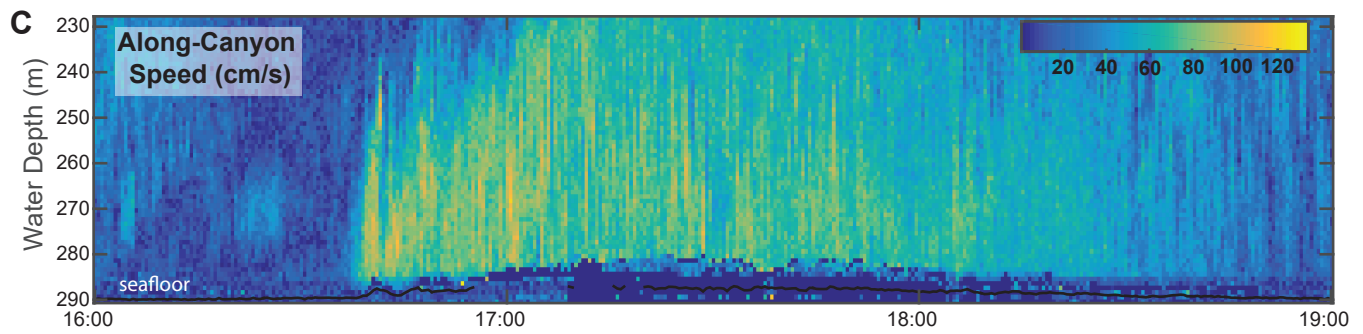
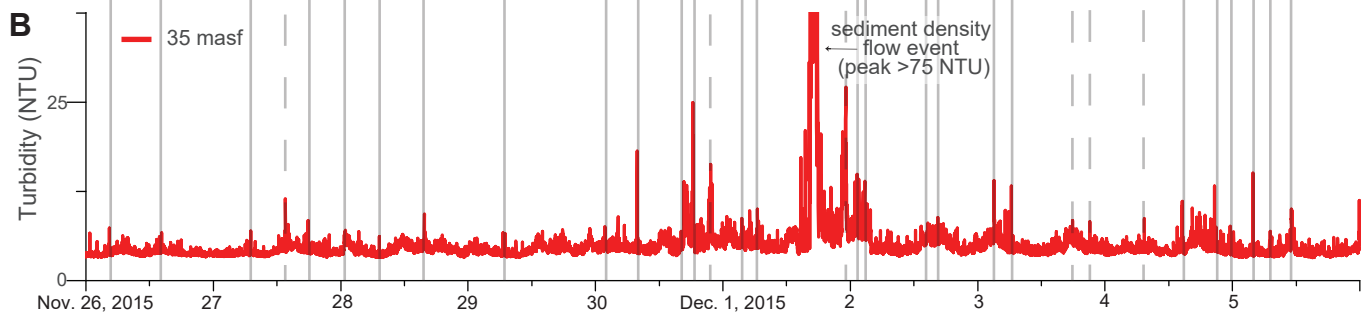
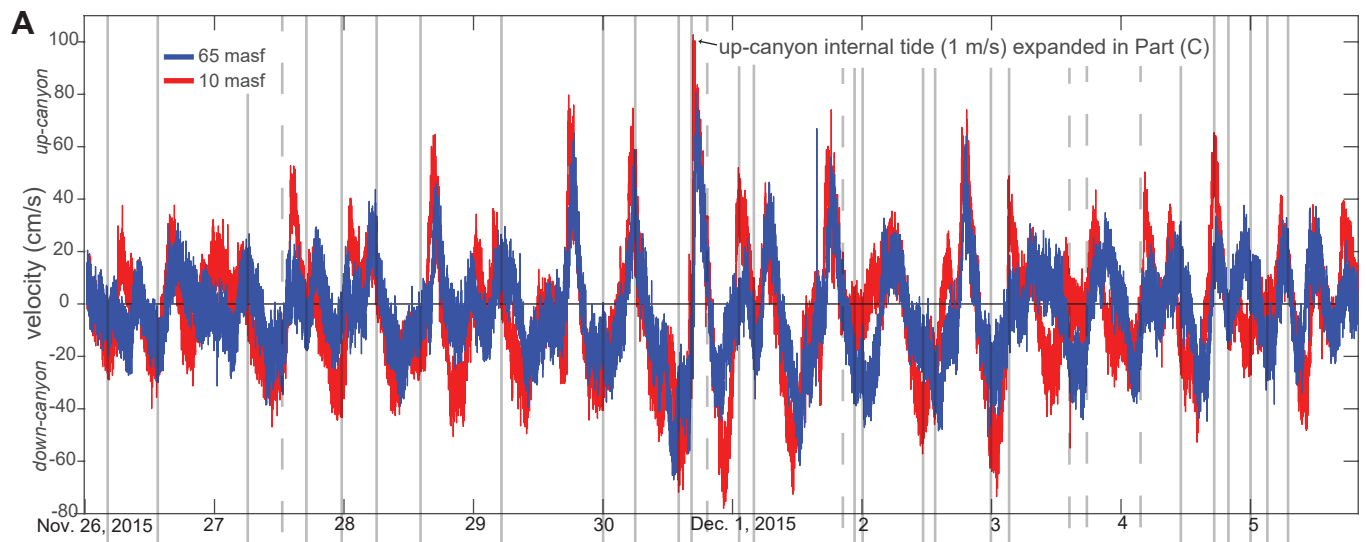


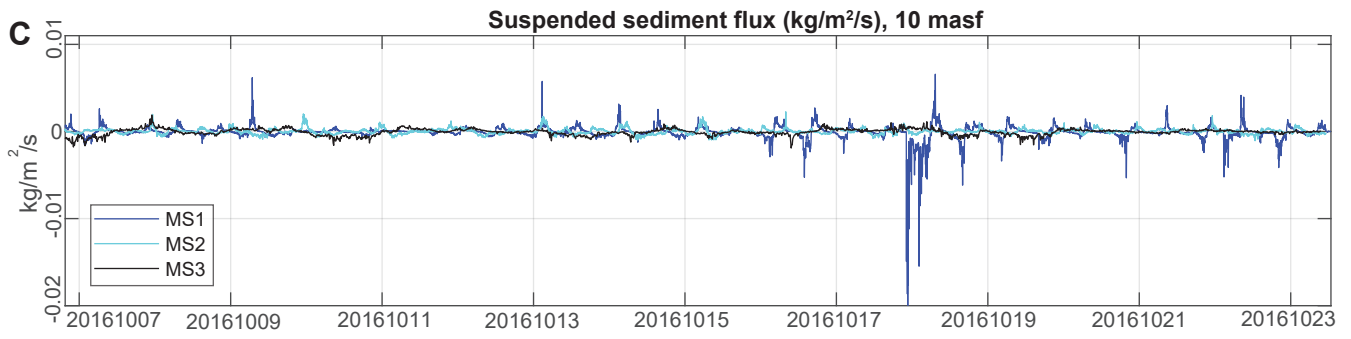
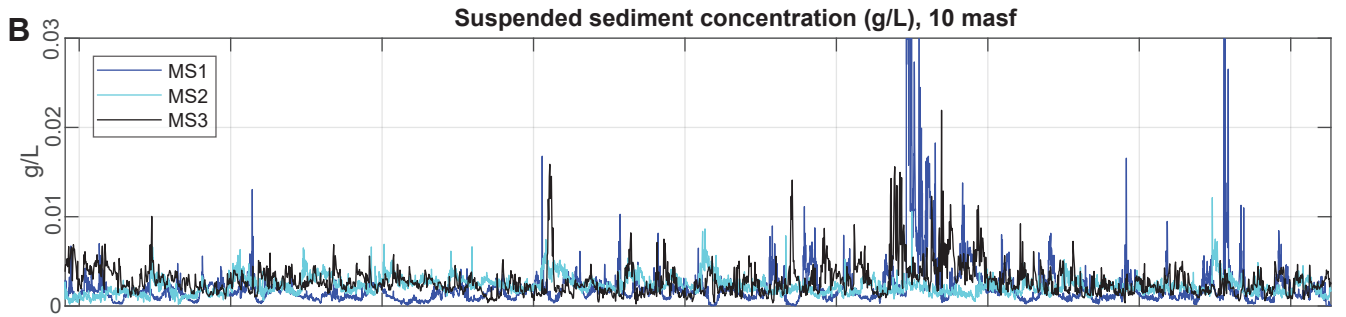
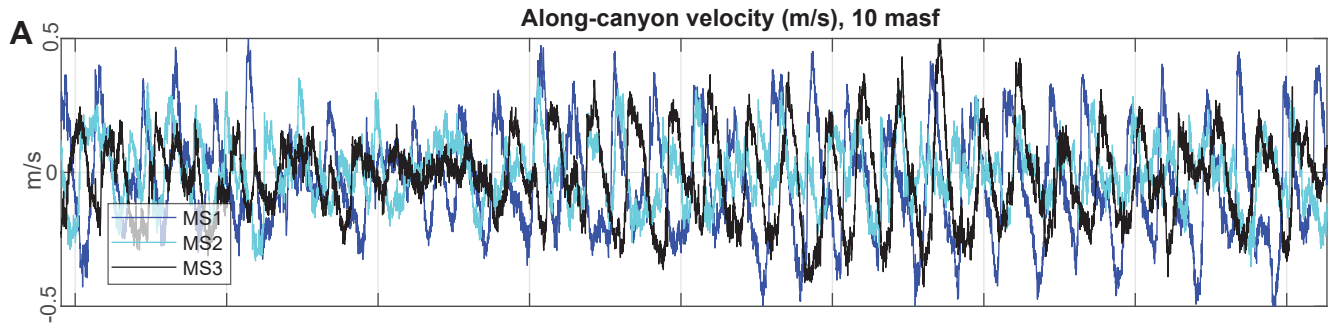


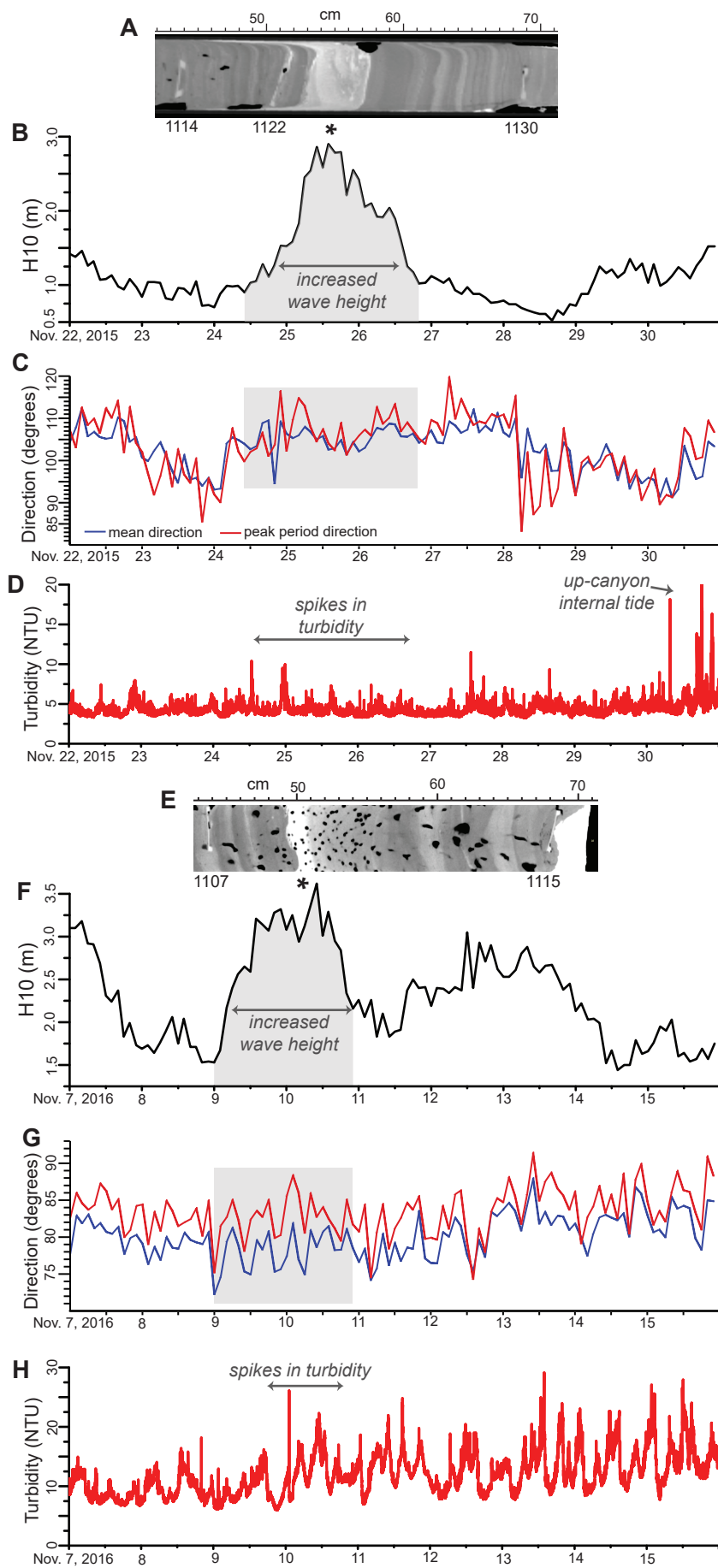


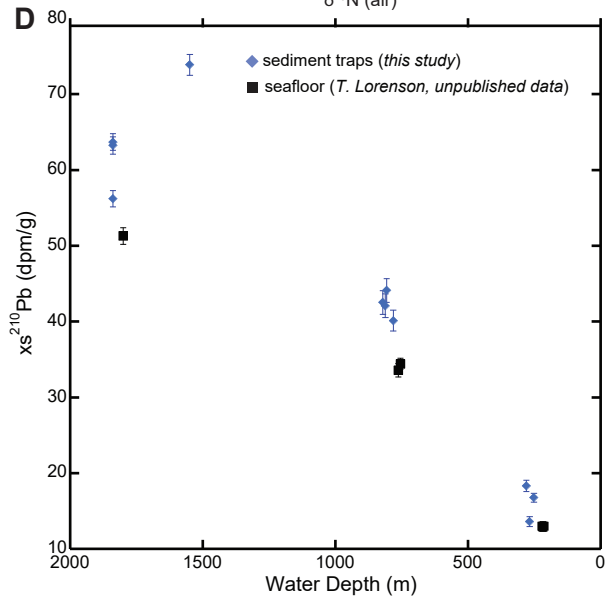
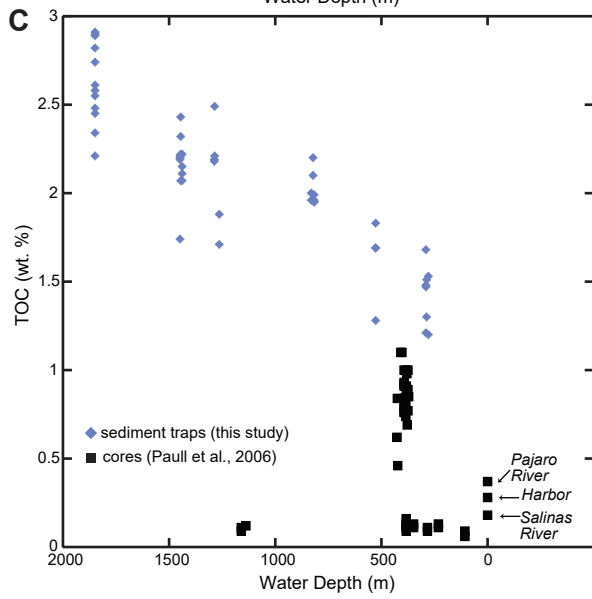
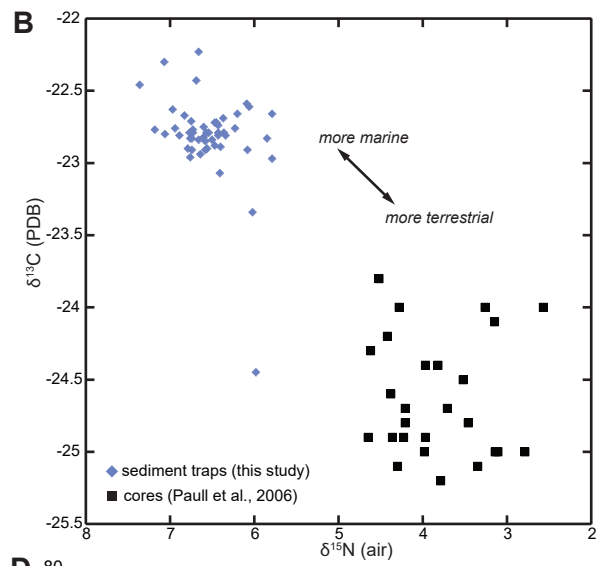
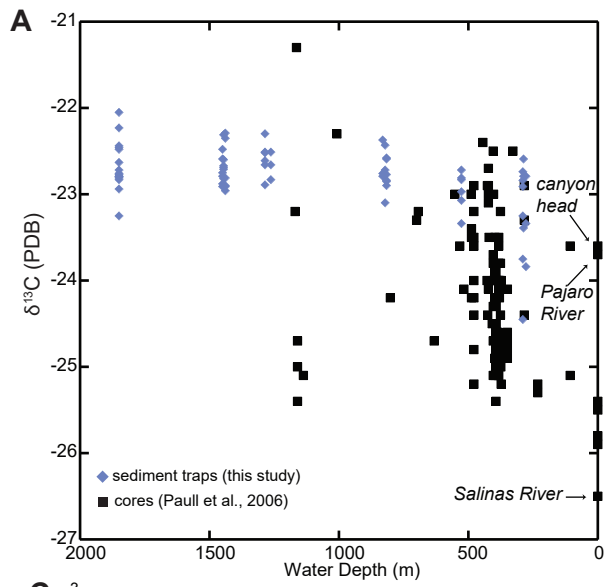




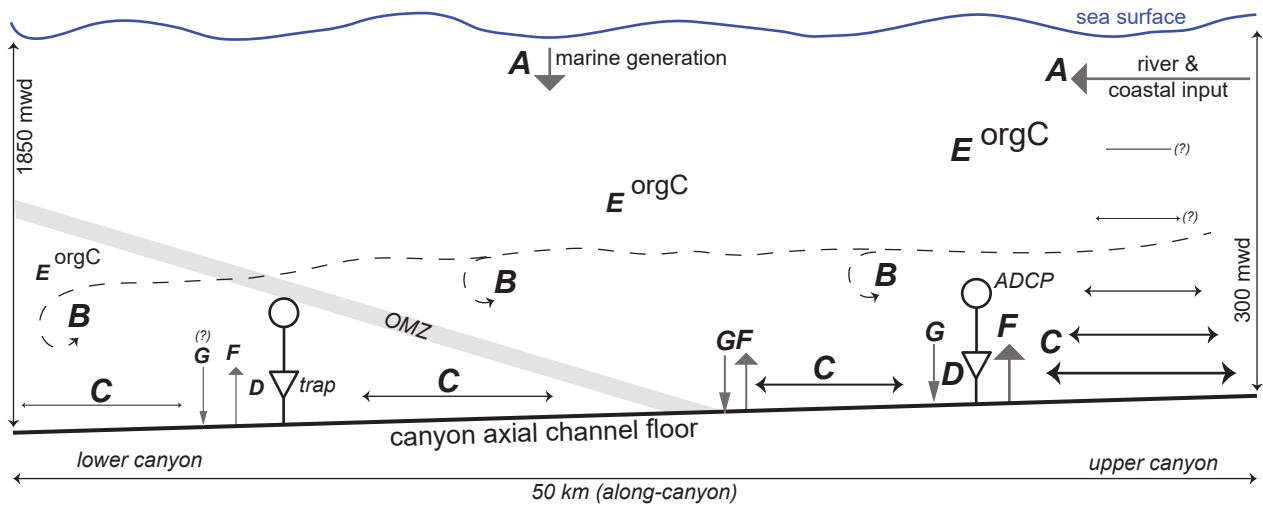












- A** sources of organic carbon - including marine & terrestrial  
**B** along-canyon mixing (dashed) - isotopes & pMC  
**C** internal tide transport of sediment  
 - increases towards seafloor & up-canyon  
**D** trap accumulation - rate decreases down-canyon

- E** rate of organic matter delivery to near-seafloor traps  
 - decreases down-canyon with sediment flux  
**F** internal tide resuspension of sediment and organic carbon  
 from canyon floor and walls - decreases down-canyon  
**G** organic carbon specific burial efficiency  
 - low compared to trap capture

Supplementary Table 1. Laser particle grain size summary.

Sediment Trap Sample	Background Sediment Intervals (cm) <sup>1</sup>	D[4,3] (μm) <sup>2</sup>	d0.1 (μm) <sup>3</sup>	d0.5 (μm) <sup>4</sup>	d0.9 (μm) <sup>5</sup>
MS1_AST35m_20161006	15, 16, 20-21, 35-66, 70-76	44.0	4.1	22.6	99.1
MS2_AST10m_20151005	0-76	32.6	3.8	17.1	69.5
MS3_AST10m_20151005	30-86	36.8	3.9	16.9	72.2
MS4_AST10m_20151007	40-56, 75-91	30.2	3.8	15.2	67.2
MS5_AST11m_20151020	45-66	27.7	3.5	13.7	60.1
MS5_AST74m_20151020	0-16, 65-86	29.8	3.4	14.0	66.9
MS7_AST10m_20151027	0-1, 9-22, 79-85	29.5	3.4	14.0	69.0
MS7_AST300m_20151027	0-9	27.2	3.5	13.7	62.8
MS1_AST10m_20160404	10-91	53.3	4.4	27.1	120.8
MS2_AST10m_20150407	0-91	37.9	3.8	18.1	79.9
MS3_AST10m_20150407	0-86	37.8	4.1	16.4	75.1
MS4_AST10m_20150408	5-96	37.7	3.7	15.4	77.4
MS5_AST11m_20150408	30-91	32.0	3.9	14.5	68.9
MS5_AST74m_20150408	0-16, 25-71	31.3	3.7	15.0	70.9
MS7_AST10m_20150420	all (see Table 1)	39.7	3.8	15.0	91.7
MS7_AST300m_20150420	0-16	37.7	3.9	14.4	83.9
MS1_AST10m_20161006	15-76	51.0	4.3	26.7	112.1
MS1_AST35m_20161006	0-11	50.1	3.9	23.8	122.8
MS3_AST10m_20161006	25-96	31.6	3.7	16.6	70.6
MS3_AST35m_20161006	10-86	29.6	3.7	16.1	65.6
MS4_AST10m_20161007	0-26, 40-76	33.0	3.7	15.1	72.8
MS5_AST11m_20161007	25 - 85	29.4	3.7	14.7	66.5
MS5_AST74m_20161007	10-11, 40-81	29.8	3.7	15.0	67.3
MS7_AST10m_20161019	0-56, 65-66	43.5	3.9	15.8	95.0
MS7_AST300m_20161019	0-11, 15-21	25.3	3.7	13.2	54.8

<sup>1</sup>measured from top of Anderson sediment trap liner tube sediment

<sup>2</sup>volume mean diameter of grain

<sup>3</sup>10<sup>th</sup> percentile diameter of grain

<sup>4</sup>median diameter of grain

<sup>5</sup>90<sup>th</sup> percentile diameter of grain

Supplementary Table 2. Radiocarbon analyses.

Sediment Trap Sample	Interval (cm) <sup>1</sup>	$\delta^{13}\text{C}$ (PDB)	pMC <sup>2</sup>	$\pm$ pMC <sup>2</sup>	Apparent modern carbon flux (g/day) <sup>3</sup>	Apparent modern carbon flux (g/m <sup>2</sup> /day) <sup>3</sup>
MS1_AST35m_20151006	78-79	-23.4	76.7	0.3	0.2	4.9
MS2_AST10m_20151005	79-80	-23.3	79.5	0.3	0.3	5.2
MS3_AST10m_20151005	88-89	-22.4	84.7	0.3	0.4	7.5
MS4_AST10m_20151007	94-95	-22.5	82.1	0.3	0.2	3.9
MS5_AST11m_20151020	70-71	-22.6	84.6	0.3	0.2	3.4
MS5_AST74m_20151020	89-90	-22.5	83.8	0.3	0.1	2.0
MS7_AST10m_20151027	86-87	-23.3	67.5	0.3	0.0	0.8
MS7_AST300m_2015102	8-9	-22.1	87.2	0.3	0.0	0.5
MS1_AST10m_20160404	92-93	-23.8	68.1	0.3	0.1	2.0
MS2_AST9m_20160407	93-94	-22.7	81.5	0.3	0.2	4.9
MS3_AST9m_20160407	88-89	-23.1	77.0	0.3	0.4	7.5
MS4_AST10m_20160408	95-96	-22.5	82.6	0.3	0.2	4.6
MS5_AST11m_20160408	89-90	-22.3	85.0	0.3	0.2	3.1
MS5_AST74m_20160408	73-74	-22.6	83.6	0.3	0.1	2.7
MS7_AST300m_2016042	17-18	-22.4	78.5	0.3	0.0	0.9
MS1_AST10m_20161006	76-77	-23.3	79.4	0.3	0.3	6.7
MS1_AST35m_20161006	12-13	-23.8	76.5	0.3	0.2	4.4
MS3_AST10m_20161006	94-95	-22.6	84.5	0.3	0.3	5.1
MS3_AST35m_20161006	88-89	-22.6	84.1	0.3	0.2	4.2
MS4_AST10m_20161007	79-80	-22.5	84.0	0.3	0.2	3.9
MS5_AST11m_20161007	77-78	-22.4	84.9	0.3	0.3	5.1
MS5_AST74m_20161007	75-76	-22.3	85.9	0.3	0.1	2.6
MS7_AST10m_20161019	64-65	-22.5	84.0	0.3	0.1	1.3

<sup>1</sup>measured from top of Anderson sediment trap liner tube sediment<sup>2</sup>pMC: percent modern carbon<sup>3</sup>calculated using averaged apparent sediment flux (g/day) in Table 1 and TOC (wt.%) in Table 4

Supplementary Table 3. Organic carbon content and stable isotope analyses.

Sediment Trap Sample	Interval (cm) <sup>1</sup>	Lab #	$\delta^{13}\text{C}$ (PDB)	$\delta^{15}\text{N}$ (air)	C/N atomic	TOC <sup>2</sup> (wt. %)	TOC (g/day) <sup>3</sup>	TOC (g/m <sup>2</sup> /day)	Total N (wt. %)
MS1_AST35m_20151006	64-65	3502	-22.6	6.1	8.6	1.3	0.3	6.0	0.2
MS1_AST35m_20151006	74-75	3503	-22.8	6.7	8.7	1.5	0.3	7.0	0.2
MS2_AST10m_20151005	60-61	3510	-22.8	6.7	8.5	1.8	0.3	7.0	0.3
MS2_AST10m_20151005	70-71	3511	-22.8	6.4	8.5	1.7	0.3	6.4	0.2
MS3_AST10m_20151005	73-74	3517	-22.8	6.2	8.6	2.0	0.4	8.6	0.3
MS3_AST10m_20151005	83-84	3518	-22.8	6.4	8.6	2.0	0.4	8.8	0.3
MS4_AST10m_20151007	87-88	3523	-22.7	6.2	8.5	2.2	0.2	4.8	0.3
MS4_AST10m_20151007	92-93	3524	-22.6	6.1	8.5	2.2	0.2	4.8	0.3
MS5_AST11m_20151020	65-66	3527	-22.8	6.6	9.0	2.2	0.2	4.0	0.3
MS5_AST11m_20151020	94-95	3528	-22.8	6.4	8.9	2.2	0.2	3.9	0.3
MS5_AST74m_20151020	80-81	3536	-22.9	6.6	9.0	2.2	0.1	2.6	0.3
MS5_AST74m_20151020	90-91	3537	-22.9	6.5	9.0	1.7	0.1	2.1	0.2
MS7_AST10m_20151027	78-79	3542	-22.5	7.4	7.9	2.9	0.1	1.2	0.4
MS7_AST10m_20151027	84-85	3543	-22.8	7.1	8.9	2.7	0.1	1.1	0.4
MS7_AST300m_20151027	1-2	3544	-22.9	6.6	8.9	2.6	0.0	0.5	0.3
MS7_AST300m_20151027	6-7	3545	-22.8	6.3	8.7	2.4	0.0	0.5	0.3
MS1_AST10m_20160404	80-81	3553	-22.8	6.6	8.8	1.5	0.2	3.4	0.2
MS1_AST10m_20160404	90-91	3554	-23.3	6.0	9.3	1.2	0.1	2.6	0.2
MS2_AST9m_20160407	80-81	3563	-23.1	6.4	9.0	1.7	0.3	6.8	0.2
MS2_AST9m_20160407	90-91	3564	-23.0	5.8	8.9	1.3	0.3	5.1	0.2
MS3_AST9m_20160407	71-72	3572	-22.4	6.7	8.7	2.2	0.5	10.1	0.3
MS3_AST9m_20160407	80-81	3573	-22.7	6.5	8.8	2.1	0.5	9.7	0.3
MS4_AST10m_20160408	82-83	3582	-22.3	7.1	8.6	2.5	0.3	6.0	0.3
MS4_AST10m_20160408	92-93	3583	-22.9	6.4	8.8	2.2	0.3	5.3	0.3
MS5_AST11m_20160408	77-78	3589	-22.7	6.7	8.9	2.1	0.2	3.3	0.3
MS5_AST11m_20160408	87-88	3590	-22.7	6.8	8.9	2.4	0.2	3.9	0.3
MS5_AST74m_20160408	60-61	3597	-22.8	6.6	8.8	2.2	0.2	3.1	0.3
MS5_AST74m_20160408	70-71	3598	-22.7	6.4	9.0	2.3	0.2	3.3	0.3
MS7_AST10m_20161420	B1*	3599	-22.8	6.9	9.0	2.3	N/A	N/A	0.3
MS7_AST10m_20161420	B6*	3600	-22.8	6.8	8.9	2.2	N/A	N/A	0.3
MS7_AST300m_20160420	10-11	3603	-22.6	7.0	8.8	2.9	0.1	1.2	0.4
MS7_AST300m_20160420	15-16	3604	-22.2	6.7	8.8	2.8	0.1	1.1	0.4
MS1_AST10m_20161006	60-61	3610	-22.8	6.5	9.0	1.5	0.5	9.2	0.2
MS1_AST10m_20161006	70-71	3611	-22.9	6.1	8.8	1.2	0.4	7.5	0.2
MS1_AST35m_20161006	1-2	3612	-24.4	6.0	9.4	1.5	N/A	N/A	0.2
MS1_AST35m_20161006	9-10	3613	-22.7	6.4	8.9	1.7	N/A	N/A	0.2
MS3_AST10m_20161006	80-81	3622	-22.9	6.6	8.9	2.0	0.3	5.9	0.3
MS3_AST10m_20161006	90-91	3623	-22.8	6.7	8.8	2.0	0.3	5.9	0.3
MS3_AST35m_20161006	70-71	3631	-22.8	6.7	8.8	2.0	0.3	6.0	0.3
MS3_AST35m_20161006	80-81	3632	-22.8	6.6	8.8	1.9	0.3	5.8	0.3
MS4_AST10m_20161007	61-62	3639	-22.8	5.8	8.3	1.7	0.2	4.8	0.2
MS4_AST10m_20161007	71-72	3640	-22.7	5.8	8.4	1.9	0.3	5.3	0.3
MS5_AST11m_20161007	70-71	3648	-22.8	6.9	8.9	2.1	0.2	4.6	0.3
MS5_AST11m_20161007	78-79	3649	-22.9	6.8	8.9	2.1	0.2	4.6	0.3
MS5_AST74m_20161007	69-70	3656	-22.9	6.7	9.0	2.2	0.2	4.0	0.3
MS5_AST74m_20161007	76-77	3657	-23.0	6.8	9.0	2.2	0.2	3.9	0.3
MS7_AST10m_20161019	57-58	3663	-22.8	6.5	8.9	2.6	0.2	3.1	0.3
MS7_AST10m_20161019	62-63	3664	-22.7	6.4	9.0	2.5	0.1	3.0	0.3
MS7_AST300m_20161019	15-16	3668	-22.8	6.8	8.8	2.6	0.1	1.6	0.3
MS7_AST300m_20161019	20-21	3669	-22.8	7.2	8.8	2.9	0.1	1.7	0.4

<sup>1</sup>measured from top of Anderson sediment trap liner tube sediment<sup>2</sup>TOC: total organic carbon<sup>3</sup>calculated using averaged apparent sediment accumulation rate from Table 1

Supplementary Table 4. <sup>210</sup>Pb analyses.

Sediment Trap Sample	Interval (cm) <sup>1</sup>	Dry bulk density (g/cm <sup>3</sup> )	Total <sup>210</sup> Pb (dpm/g)	<sup>226</sup> Ra (dpm/g)	± <sup>226</sup> Ra (dpm/g)	x <sub>s</sub> <sup>210</sup> Pb (dpm/g)	± x <sub>s</sub> <sup>210</sup> Pb (dpm/g)	x <sub>s</sub> <sup>210</sup> Pb (dpm/day) <sup>3</sup>	± x <sub>s</sub> <sup>210</sup> Pb (dpm/day) <sup>3</sup>	x <sub>s</sub> <sup>210</sup> Pb (dpm/m <sup>2</sup> /day) <sup>3</sup>	± x <sub>s</sub> <sup>210</sup> Pb (dpm/m <sup>2</sup> /day) <sup>3</sup>	<sup>137</sup> Cs (dpm/g)	± <sup>137</sup> Cs (dpm/g)
MS1_AST35m_20151006	74-77	0.91	18.38	1.62	0.09	16.76	0.59	385	14	7700	280	0.12	0.04
MS1_AST10m_20160404	87-90	1.02	15.23	1.64	0.08	13.59	0.65	150	7	3000	140	0.16	0.07
MS1_AST10m_20161006	72-75	0.88	20.21	1.87	0.11	18.34	0.74	568	23	11360	460	0.15	0.05
MS3_AST10m_20151005	86-89	0.75	45.02	2.51	0.19	42.51	1.57	935	34	18700	680	0.06	0.01
MS3_AST10m_20160407	86-89	0.77	44.59	2.50	0.22	42.09	1.56	968	36	19360	720	0.11	0.03
MS3_AST10m_20161006	93-96	0.70	46.78	2.67	0.22	44.10	1.55	662	23	13240	460	0.21	0.02
MS3_AST35m_20161006	86-89	0.71	42.59	2.46	0.20	40.13	1.37	602	21	12040	420	0.06	0.01
MS7_AST10m_20151027	81-84	0.65	67.21	3.52	0.12	63.69	1.10	127	2	2540	40	0.10	0.03
MS7_AST10m_20160420	B9-B11 <sup>2</sup>	0.62	59.20	2.98	0.13	56.21	1.09	N/A	N/A	N/A	N/A	0.17	0.07
MS7_AST300m_20160420	12-15	0.63	77.92	4.05	0.16	73.87	1.40	148	3	2960	60	0.13	0.05
MS7_AST10m_20161019	59-62	0.64	66.48	3.25	0.14	63.24	1.14	379	7	7580	140	0.16	0.05

<sup>1</sup>measured from top of Anderson sediment trap liner tube sediment<sup>2</sup>bulk samples from intervals 9 to 11<sup>3</sup>calculated using averaged apparent sediment accumulation rates from Table 1