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1 **Direct evidence of a high-concentration basal layer in a submarine turbidity current**

2 **Zhiwen Wang¹, Jingping Xu^{2,3}, Peter J. Talling⁴, Matthieu J.B. Cartigny⁴, Stephen M.**
3 **Simmons⁵, Roberto Gwiazda⁶, Charles K. Paull⁶, Katherine L. Maier⁷, Daniel R. Parsons⁵,**

4 ¹College of Marine and Geosciences, Ocean University of China, 238 Songling Rd., Qingdao,
5 Shandong, China, 266100

6 ²Department of Ocean Science and Engineering, Southern University of Science and
7 Technology, 1088 Xueyuan Rd., Shenzhen, Guangdong, China, 518055

8 ³Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and
9 Technology, Qingdao, Shandong, China, 266061

10 ⁴Department of Earth Sciences and Geography, University of Durham, South Road, Durham
11 DH1 3LE, United Kingdom

12 ⁵Department of Geography, Environment and Earth Sciences, University of Hull, Cottingham
13 Road, Hull HU6 7RX, United Kingdom

14 ⁶Monterey Bay Aquarium Research Institute, 7700 Sandholdt Rd., Moss Landing, CA 95039,
15 USA

16 ⁷Pacific Coastal and Marine Science Center, U.S. Geological Survey, 2885 Mission St., Santa
17 Cruz, CA 95060, USA

18 Corresponding author: Jingping Xu (xujp@sustech.edu.cn)

19 **Abstract**

20 Submarine turbidity currents are one of the most important sediment transfer processes
21 on earth. Yet the fundamental nature of turbidity currents is still debated; especially whether they
22 are entirely dilute and turbulent, or a thin and dense basal layer drives the flow. This major
23 knowledge gap is mainly due to a near-complete lack of direct measurements of sediment
24 concentration within active submarine flows. Here we present the most detailed near-bed
25 sediment concentrations measurements from a powerful turbidity current in Monterey Canyon,
26 offshore California. We employ a novel approach using correlations between conductivity and
27 sediment concentration, which unlike previous methods can measure very high concentrations
28 and not sensitive to grain size. We find that sediment concentrations close to the canyon floor
29 gradually increased after the arrival of the turbidity current, until reaching a maximum value of
30 12%, the highest concentration ever inferred from direct measurements in turbidity currents. We
31 also show a two-layer flow head, with a fast (up to 4 m/s), thin and dense basal layer overlain by
32 a thicker (~50 m) dilute flow. At the interface of these two layers, there seems to be a sharp steep
33 concentration gradient. Such quantitative measurements of sediment concentration can produce a
34 key step forward in understanding the basic character and dynamics of these powerful submarine
35 flows.

36 **Keywords:** Turbidity currents; Sediment concentration; Seawater conductivity; Monterey
37 canyon

38 **1 Introduction**

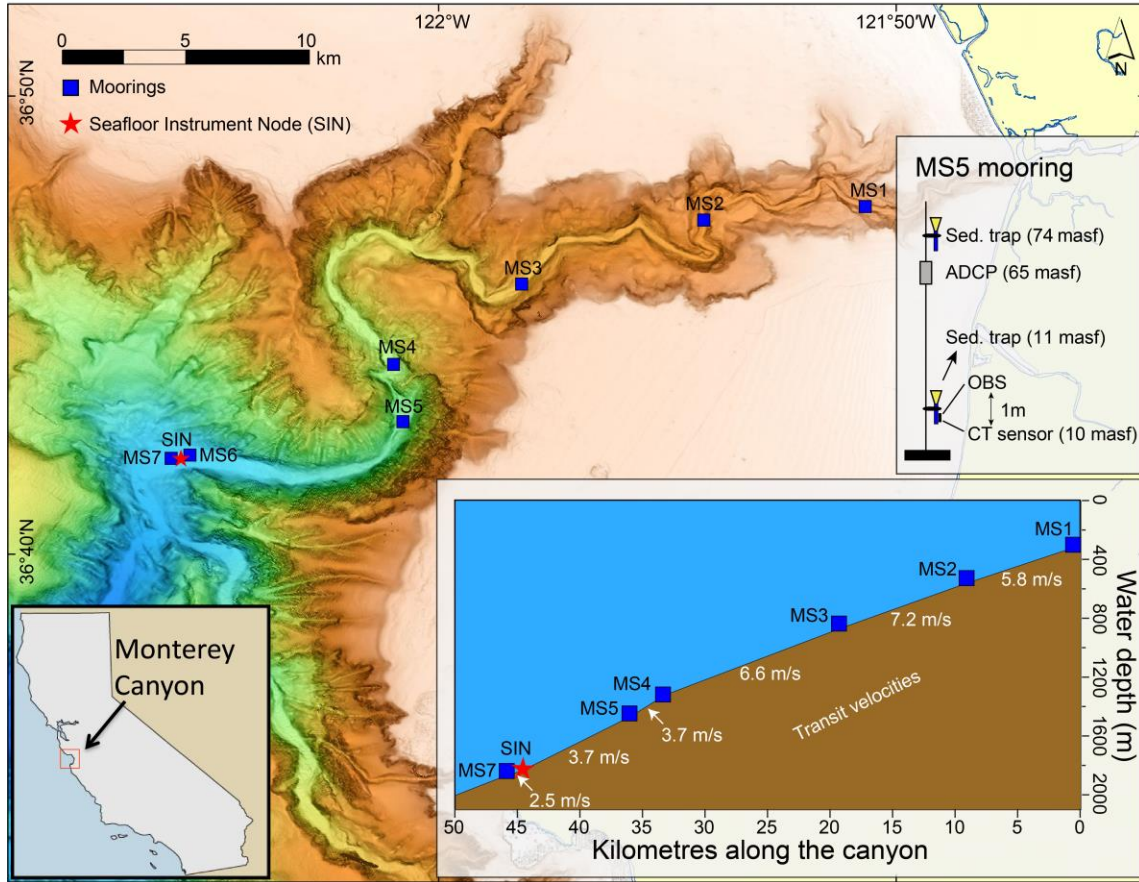
39 Whether high sediment concentration layers occur at the base of turbidity currents has
40 long been debated (Kuenen and Migliorini, 1950; Middleton, 1967; Lowe, 1982; Postma et al.,

41 1988; LeClair and Arnott, 2003; Talling et al., 2012). The controversy mainly focuses on
42 whether these submarine flows are entirely dilute (\ll 1-2% by volume) and fully turbulent,
43 perhaps with a bedload layer just a few grains thick (as is the case for almost all rivers), or
44 whether a dilute layer overlies a much denser (~10-40%), up to several meters thick basal layer
45 that drives the flow (Kuenen and Migliorini, 1950; Sanders, 1965; Lowe, 1982; Middleton, 1993;
46 Kneller and Branney, 1995; Talling et al., 2012). The fundamental differences between entirely
47 dilute flows and flows with dense basal layers are very important because they control flow
48 speed, runout, impact forces on seabed structures or cables, and how flows deposit sediment.
49 This question is hard to answer using flow deposits or physical and mathematical modelling, as
50 dense or dilute flows can potentially produce similar deposits (Talling et al., 2012), whilst initial
51 flow density is a predefined input condition for modelling. Lack of direct measurements in full-
52 scale submarine flows is one of the root causes of the debate.

53 More recently, rare field observations have provided limited evidence for the multiple
54 layer structure that has been theoretically or experimentally predicted (Middleton, 1969; Garcia
55 and Parker, 1993; Mulder and Alexander, 2001). Hughes Clarke (2016) used multibeam sonars
56 to show a thin (< 2 m) layer of higher sediment concentration within flows at Squamish Delta in
57 British Columbia, and this dense basal layer caused up-slope migration of bedforms. Based on a
58 multibeam sonar image of a turbidity current from the Scheldt River, Netherlands, Clare et al.
59 (2015) observed a highly reflective basal layer underlying a more dilute layer. However, these
60 field studies were unable to quantify the density of the basal layers due to lack of direct
61 measurements. Quantifying sediment concentration in the field thus remains a key challenge for
62 understanding what turbidity currents are, and how they work (Bornhold et al., 1994; Clare et al.,
63 2015; Talling et al., 2015, Stevenson et al., 2018).

64 This paper presents evidence of a high-concentration basal layer within a submarine
65 turbidity current in Monterey Canyon. Concentrations as high as 12% by volume were
66 determined innovatively by using a conductivity sensor.

67 We first describe a turbidity current that was recorded on 15 January 2016 by an array of
68 seven moorings and one Seafloor Instrument Node (Paull et al., 2018). This array, extending for
69 50 km along the canyon between 300 and 2000 m water depth (Figure 1), recorded the most
70 detailed measurements yet of submarine turbidity currents. We then show experimental
71 calibrations between sediment concentration and conductivity, which allowed us to calculate
72 sediment concentrations in the basal layer recorded by the MS5 mooring at 1450 m water depth.
73 Finally, we interpret the field results, and discuss the wider implications for better understanding
74 turbidity currents.



75

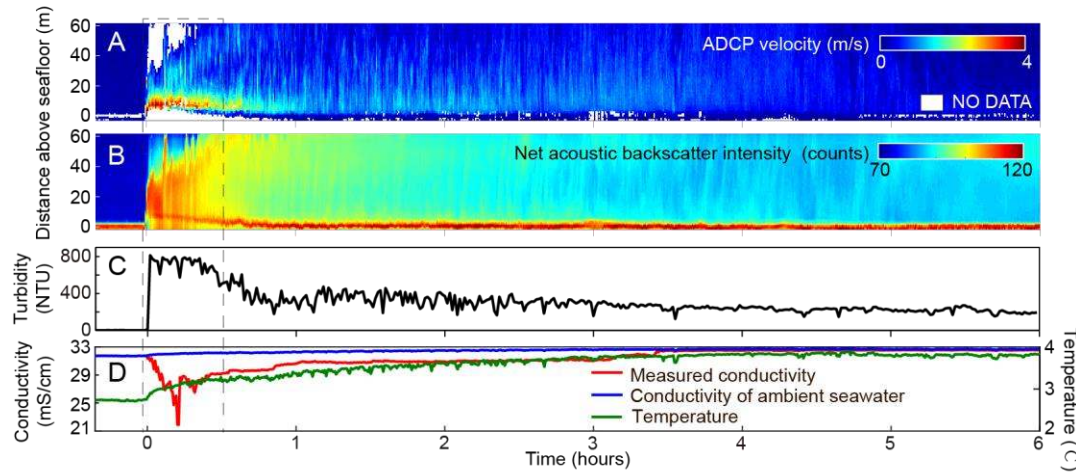
76 **Figure 1.** Location map of Monterey Canyon showing the seven moorings, and one seabed
 77 frame (SIN), along the submarine canyon. Axial bathymetric profile, with mooring sites, along
 78 the canyon are shown in the inset at the lower right. Transit velocities (white numbers) of the 15
 79 January 2016 flow are calculated from distance along the canyon-floor thalweg, and difference in
 80 arrival time between moorings. The mooring configuration for MS5 is shown by the mooring
 81 conceptual diagram.

82 **2 Turbidity Current Event on 15 January 2016**

83 The turbidity current was recorded by 7 moorings (Figure 1) that were equipped with
 84 Acoustic Doppler Current Profiler (ADCP), Conductivity/Temperature (CT) sensors, optical
 85 backscatter sensors (OBS), and sediment traps. The general character of the flow was previously

86 reported by Paull et al. (2018). And in this study, we only focus the data of the mooring at 1450
87 m (MS5), the RBR[®] CT sensor on which recorded a conductivity anomaly during the event that
88 allowed us to apply a novel approach of quantifying the super-high sediment concentration. The
89 initial thickness of the flow estimated by the ADCP was about 20 m (Figure 2A). Thus, CT
90 sensor mounted 10 meters above sea floor (masf) and OBS mounted 11 masf were well inside
91 the body of the flow (Figure 1). At the arrival of the flow, the measured turbidity increased very
92 quickly to reach a peak value of over 800 NTU (nephelometric turbidity units) before gradually
93 returning to pre-event level (Figure 2C). At the same time, the measured conductivity of turbidity
94 current rapidly decreased, by as much as 30%, before it gradually returned to pre-event values
95 over the next three and a half hours (Figure 2D). Temperature increased by as much as 1°C
96 during the same period. The transit velocities of the flow ranged between 2.5 and 7.2 m/s, and
97 averaged 5.4 m/s for the stretch of the canyon occupied by the mooring array (Paull et al., 2018;
98 Figure 1). The maximum instantaneous velocity measured by the MS5 ADCP was 4.1 m/s (Paull
99 et al., 2018), and the transit speed here is 3.7 m/s (Figure 1). They are by far the fastest velocities
100 directly measured by moored sensors in submarine flows (Xu et al., 2004, 2014). The entire
101 turbidity current lasted about 6 hours (Figures 2A and 2B).

102 Two sediment traps on MS5, at 11 and 74 masf, collected sediment in the flow (Figure
103 1). The lower trap contains coarser sand than the upper sediment trap (Maier et al., 2019).
104 Because the thickness of the flow is much less than 70 m, judging from the ADCP measured
105 flow structure, sand in the upper trap either came from the billows in the flow or clouds that
106 arrived after the main body of the flow, or the trap was pulled closer to the sea bed (Paull et al.,
107 2018).



108

109 **Figure 2.** Velocity and echo intensity during 15 January 2016 flow event. A: Time series of flow
 110 speed measured by a downward-looking ADCP initially mounted 65 meters above sea floor
 111 (masf). B: Time series of net acoustic backscatter intensity (averaged over four beams) measured
 112 by the ADCP; the influence of water attenuation and spherical spreading have been corrected. C:
 113 Time-series of water turbidity measured by OBS initially mounted at 11 masf. D: Time series of
 114 temperature (green) and conductivity (red) measured by CT sensor initially mounted at 10 masf.
 115 Conductivity of ambient seawater (blue) was calculated using a standard formula (Poisson, 1980)
 116 by assuming a constant salinity.

117 3 Conductivity Anomaly and Sediment Concentration Calculations

118 3.1 Cause of the conductivity anomaly

119 The most common and direct cause of conductivity decrease is addition of freshwater.
 120 Assuming this is the case for the conductivity anomaly shown in Figure 2D, the volume of the
 121 added freshwater ($V_{freshwater}$) can be estimated by the salinity difference between the ambient
 122 seawater ($S_{seawater}$) and the water mass inside the turbidity current ($S_{turbidity}$):

$$123 \quad V_{freshwater} = V(S_{seawater} - S_{turbidity})/S_{seawater}, \quad (1)$$

124 where V is the volume of the turbid water mass that can be grossly estimated by simplifying the
125 flow to a cuboid of 50 m (flow depth) \times 50 m (canyon width at the MS5 mooring site) \times flow
126 length. The flow length can be obtained by multiplying the average flow speed and the duration
127 of the peak flow. Such calculations show that it would require $4.6 \times 10^6 \text{ m}^3$ of freshwater in
128 order to produce the observed conductivity anomaly at MS5. It is almost certain that influx of
129 this much freshwater into the canyon was impossible because: 1) there was hardly any rainfall in
130 the Monterey area during the week before the event; and 2) a sudden release of several millions
131 of cubic meters of fresh groundwater is very unlikely. Thus, the freshwater cause of the
132 conductivity anomaly can be ruled out, and the increase of the temperature (Figure 2D) during
133 the flow was induced by the warmer seawater input from the upstream canyon.

134 Very high sediment content can also cause conductivity decrease because the
135 conductivity of sediment grains is several orders of magnitude smaller than the conductivity of
136 seawater (Traykovski et al., 2000). Applying Archie's law (Archie, 1942) that relates
137 conductivity and volume sediment concentration, we obtain:

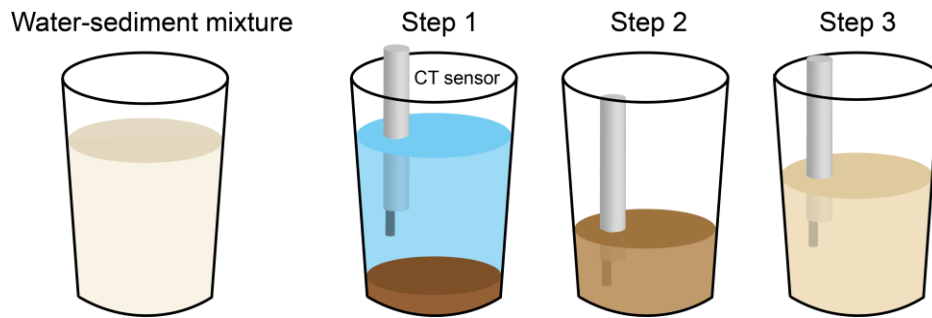
$$138 \quad \frac{\gamma_{mixture}}{\gamma_{seawater}} = (1 - C_{sediment})^m, \quad (2)$$

139 where γ is the conductivity that can be measured by CT sensor, C is the volume concentration,
140 and m is an empirical parameter that ranges from 1.2 to 3.0 (Jackson et al., 1978). Equation (2)
141 would allow us to estimate the sediment concentration C if the constant m becomes known.

142 3.2 Laboratory experiments of estimating m

143 To quantify the relationship between conductivity and sediment concentration (Equation
144 2), a series of laboratory experiments were conducted to measure the variations of conductivity
145 of sea-water and sediment mixtures under different combinations of sediment concentration and

146 temperature conditions. The experiment started with making a saline solution of 34-35‰ by
147 dissolving table salt in a container (bucket#1) with 25 liters of tap water. Roughly 2 kg (dry
148 weight) of sediment was poured into the saline solution while stirring vigorously to make a well-
149 mixed slurry (Figure 3). An incremental scheme of measuring the conductivity of the sediment-
150 water mixture was carried out as follows:



152 **Figure 3.** Interpretive diagram showing the experiment process.

153 1) After all sediment particles had completely settled on the bottom of bucket #1, the
154 salinity, conductivity and temperature of the clear solution in the upper part of the bucket was
155 measured with a RBR[®] CT sensor (the same type of instrument as used on the mooring during
156 the January 15th flow).

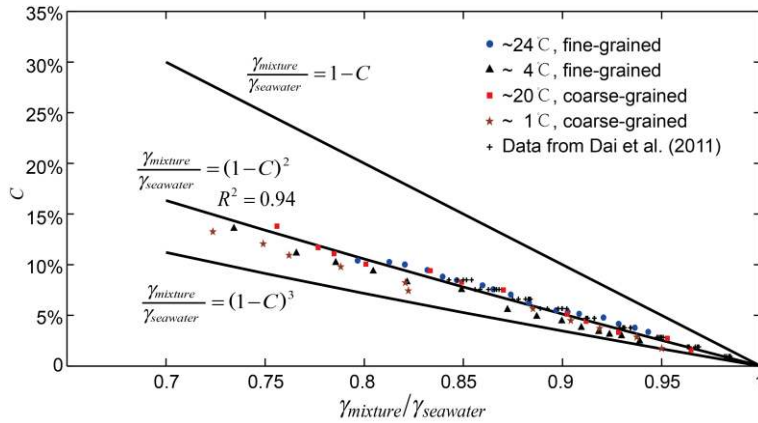
157 2) About 80% of the clear water was removed from bucket#1 to another empty bucket
158 (bucket#2). The remaining mixture of water and sediment in bucket#1 was vigorously stirred to a
159 well-mixed state while continuously measuring the conductivity and temperature of the mixture
160 with the same RBR[®] CT sensor. A sample of the sediment-water mixture was collected into a
161 small jar for sediment concentration calculation using a drying and weighing method. This first
162 sample had the highest concentration and the lowest conductivity value.

163 3) A small amount of the clear saline water from bucket#2 was added back to bucket#1,
164 vigorously stirred to a well-mixed suspension while continuously measuring the conductivity and
165 temperature. A sample was taken for sediment concentration determination.

166 4) Step 3 was repeated until all the clear saline water in bucket#2 was added back to the
167 mixture in bucket#1. This incremental dilution made the last sample the lowest sediment
168 concentration but the highest conductivity value.

169 Two types of sediment were used in the experiments: finer material (clay) with median
170 diameter of 0.03 mm collected from a mud flat, and coarser sediment (quartz sand) with median
171 diameter of 0.29 mm. Considering that the influence of the sediment content in the seawater to
172 the mixture's conductivity, depend on the ratio of sediment particles' conductivity to the
173 seawater conductivity. And the conductivity of sediment grains is always several orders of
174 magnitude smaller than the conductivity of seawater. Hence, the impacts of the mineralogy of the
175 sediment, which can only influence the absolute conductivity of the sediment grains, are rather
176 limited to the mixture's conductivity changes.

177 The experiments were conducted at room temperature (20-24°C) and in a refrigerated
178 environment (1-4°C). The same procedure (steps 1-4) was repeated for a total of 4 times: 2 grain
179 sizes (fine and coarse) and 2 temperatures (room temperature and refrigerated). The results of
180 these four experiments are listed in Table S1. As shown in Figure 4, the correlation coefficient is
181 0.94 when the empirical exponent m is 2. This suggests that Equation (2) can be used to calculate
182 the sediment concentration from measured conductivity, at least for the range of grain-sizes and
183 temperatures used in these calibration experiments.



184

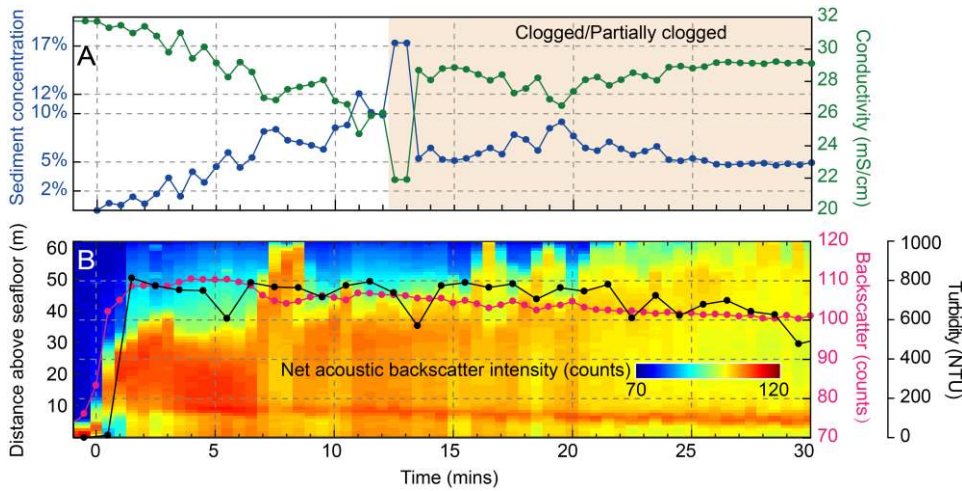
185 **Figure 4.** Plot of sediment volume concentration (C) against the conductivity ratio between the
 186 sediment-water mixture ($\gamma_{mixture}$) and seawater ($\gamma_{seawater}$). Symbols denote measurements
 187 from the four laboratory experiments and a previous calibration dataset from Dai et al. (2011).
 188 $\gamma_{mixture}$ was measured with 30 different combinations of environmental factors in Dai's
 189 experiment: 2 grain sizes (27 and 52 microns, median diameter), 3 salinities (22‰, 27‰, 32‰),
 190 and 5 temperatures (9.2°C, 10.2°C, 15.2°C, 19.2°C, 34.2°C). Solid lines are volume sediment
 191 concentrations derived using Equation (2), with $m = 1, 2,$ and 3 respectively. $m = 2$ gives the best
 192 fit to experimental data.

193 3.3 Sediment concentration calculations

194 Assuming seawater salinity throughout the event was constant at the pre-event value
 195 (35.4‰), the conductivity of the ambient seawater in the turbidity current (Figure 2D) can be
 196 calculated using a standard formula (Poisson, 1980). The ratio between measured and ambient
 197 conductivities (Figure 2D) is then used to estimate sediment concentration of the first 30 minutes
 198 of the 15 January 2016 flow event (Figure 5A) by Equation (2), with $m = 2$. The rapid decrease
 199 of conductivity (i.e. increase of concentration) around minute 12 is believed to result from sensor

200 failure (clogged or partially clogged, see the discussion below for details), therefore the
 201 maximum valid concentration is 12% that was recorded at minute 11 (Figure 5A).

202 For comparison, ADCP acoustic backscatter and OBS outputs, both proxies for sediment
 203 concentration (Gartner, 2004; Ha et al., 2011), are plotted for the same 30 minutes time window
 204 after the arrival of the turbidity current (Figure 5B). It clearly shows that the 26 mS/cm
 205 conductivity (maximum sediment concentration) took place about 11 minutes after the arrival of
 206 the turbidity current that was marked by the rapid increase of both the ADCP backscatter and the
 207 OBS measurements (Figure 5). The measurements of OBS (located 1 m above the CT sensor),
 208 which are normally used in dilute flows for estimating sediment concentrations, shows the same
 209 pattern as vertically averaged ADCP backscatter (Figure 5B).



210
 211 **Figure 5.** A: Sediment concentration (blue line) converted from the measured conductivity
 212 (green line) reduction for the first 30 minutes of 15 January 2016 flow event, using Equation (2),
 213 with $m = 2$. The shaded section after minute 12 indicates a clogged or partially clogged sensor.
 214 B: Close-up view of the net acoustic backscatter intensity (Figure 2B) for the first 30 minutes of
 215 the flow. Overlaid are the vertically averaged acoustic backscatter shown in the red line and the

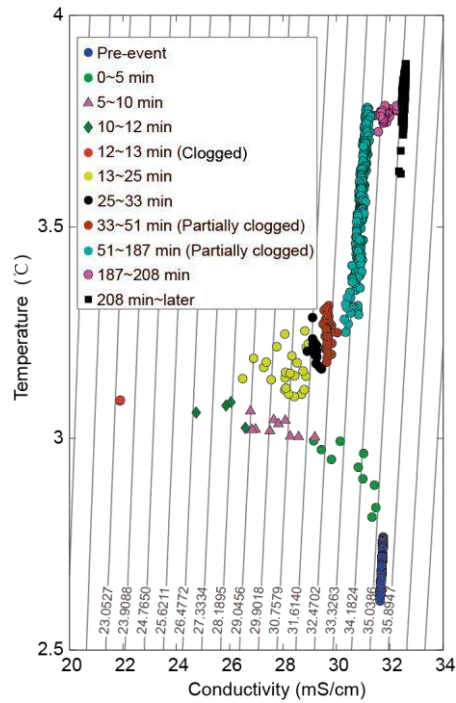
216 OBS measurements in black. The flow thickness, necessary for the vertical averaging, is defined
217 as: $h = (\int_0^z u dz)^2 / \int_0^z u^2 dz$, where z is the height above the bed, u is the flow speed.

218 **4 Discussion**

219 This paper describes a new and robust way of measuring high sediment concentrations,
220 however, when used in turbidity currents, its limitation needs to be aware of. This method will
221 not work in environments where the salinity changes appreciably, because we cannot distinguish
222 whether the conductivity decrease in a flow is caused by sediment content or salinity variations.
223 Hence, our approach assumes a constant seawater salinity of 35.4‰ throughout the 15 January
224 2016 flow event. If the salinity measured at the shallower mooring MS1 at 300 m water depth
225 (34.1‰) was used instead for the ambient value, sediment concentration would have been
226 overestimated by a maximum of 1.6 % volume. The actual error would be smaller because of
227 entrainment of saltier water and turbulent diffusion of salt (Zhao et al., 2018) in the head of the
228 flow as it travels down canyon.

229 4.1 Was the CT sensor clogged?

230 The inductive conductivity cell of the RBR[®] CT sensor is normally used to measure
231 salinity by allowing seawater to flow freely through the 13 mm diameter hole (with a cross-
232 section area of 1.33 cm²) in the center of the cell. In some extremely high concentration with
233 coarse grains or clasts, such as near the bottom of turbidity currents, the hole could be clogged or
234 partially clogged by gravel(s) or mud clast(s). Any clogging will reduce the effective cross-
235 section area that will lead to a decrease of measured conductivity (Light et al., 1989).

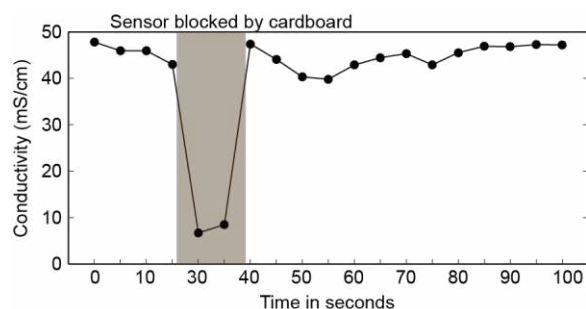


236

237 **Figure 6.** Temperature-conductivity plot of the 15 January 2016 turbidity current (green and red
 238 lines in Figure 2D). The measurements were separated into several segments. The thin, parallel
 239 lines are isohaline (units: ‰) computed using the formula in Poisson (1980).

240 The seawater temperature and conductivity at MS5 prior to the arrival of the turbidity
 241 current co-vary on a T-C plot along an isohaline corresponding to the ambient salinity of 35.4‰
 242 (Figure 6). After the flow arrived (minute 0-12), the measured conductivity, now affected by the
 243 high sediment concentration in the flow, varies independently of measured temperature. Rapid
 244 decrease of conductivity between minutes 12 and 13 (Figure 5A) is almost identical to the
 245 response of the sensor in laboratory experiment when its cell was blocked by a piece of
 246 cardboard (Figure 7), suggesting that the sensor was clogged by coarser sediment or mud clasts.
 247 The recovery of the conductivity value from minutes 13 to 24 seems to indicate that the clogging
 248 was eased or even completely unclogged. If the latter is the case, it shows that the concentration
 249 hovered around 5‰ for another 11 minutes (Figure 5A). We are not confident about this because

250 there is no good explanation why the sensor became unclogged between minutes 13 and 24
251 before it was surely clogged again (see below).



252
253 **Figure 7.** Conductivity readings of the CT sensor in a laboratory experiment with saline water of
254 salinity of 33‰. When the hole of the CT sensor was blocked with a piece of cardboard, the
255 conductivity reading rapidly decreased.

256 From minutes 25 to 33 (Figure 6), however, the measured conductivity and temperature
257 co-varied parallel to an isohaline of much lower salinity (31.8‰). From minutes 33 to 51, the co-
258 variation followed the isohaline of 32.2‰, and from minutes 51 to 187 followed the isohaline of
259 33.3‰. Noticeably both salinities are much lower than the salinity of 34.1‰ measured by a
260 mooring near the head of the canyon. This unusual structure, where the conductivity is off by a
261 fixed amount in each segment, is unlikely due to the high sediment concentration because (1)
262 sediment concentration alone cannot induce the co-variation of conductivity and temperature,
263 and (2) the near bed salinity at the mooring site should be no less than the salinity of the canyon
264 head (34.1‰). Therefore, it is much more likely that the sensor was partially clogged, producing
265 a ‘false’ signal of low conductivity.

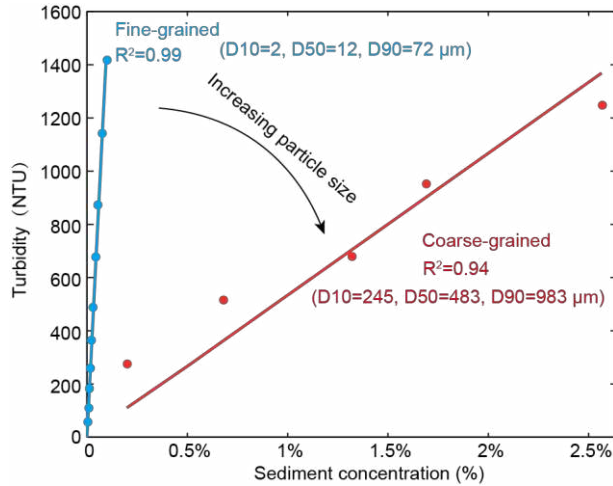
266 All things considered, only the conductivity measurements in the first 12 minutes can be
267 reliably used to estimate sediment concentrations of the turbidity current, which include the
268 maximum concentration that we are confident is valid.

269 4.2 A two-layer system

270 If we apply a Chezy-type model (Bowen et al., 1984), the vertically-averaged
271 concentration inside the flow had to be at least 9% (240 g/l) to maintain the depth-averaged
272 velocity of the turbidity current body measured by the ADCP, assuming no momentum inherited
273 from upslope. Such concentrations would be too high for acoustic penetration by ADCP
274 according to previous studies (Thorne et al., 1993; Shen and Lemmin, 1996), yet the MS5 ADCP
275 recorded valid data throughout the water during the event (Figure 5B). Hence, the high velocity
276 in the flow is more likely due to the presence of a fast-moving, dense, basal-layer that dragged
277 the overlying dilute flow from underneath, which is consistent with the turbidity current
278 travelling model proposed by Paull et al. (2018) and Heerema et al. (2020) based on the
279 movement of very heavy objects and self-acceleration of the flow.

280 To examine the vertical change of sediment concentration, calibrations were applied to
281 convert the recorded OBS values from the engineering units (NTU, Figure 5B) to sediment
282 concentration. For a given concentration, the OBS output was much more sensitive to fine
283 sediments than to their coarse counterpart. For example, it requires a concentration of 2.5% of
284 coarse sediment to produce the same OBS output of 1400 NTU that would only need a mere
285 0.1% concentration for the fine material (Figure 8). Hence, particle size must be determined
286 when the OBS is used as an indirect measure of sediment concentration. According to the
287 sediment collected at 11 masf during the turbidity current, the suspended sediment in the January
288 15 flow contained a wide range of grain sizes (Maier et al., 2019), the 600-800 NTU readings
289 during the first 30 minutes (Figure 5B) could result from a variety of concentrations (Figure 8).
290 However, the 600-800 NTU always represents a dilute flow with the sediment concentration no

291 more than ~1%, because the grain size of the sediment from the turbidity current (Maier et al.,
292 2019) was well within the range of calibration experiments.



293
294 **Figure 8.** OBS output (NTU) versus sediment concentration from our laboratory experiments
295 using fine (D50=12 microns) and coarse grained (D50=483 microns) natural sediments. Symbols
296 denote measurements from the two experiments; solid lines are linear curve fitting.

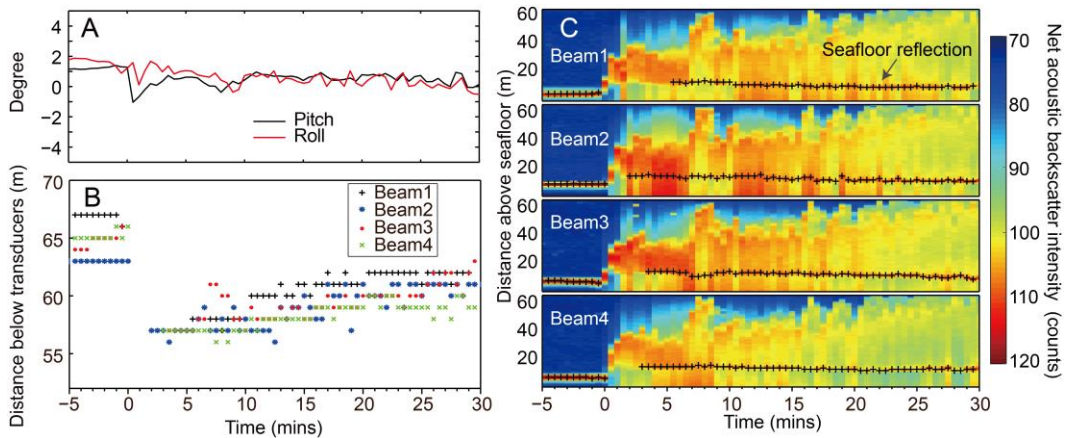
297 These observations suggest that the 15 January 2016 turbidity current featured a two-
298 layer structure, a dense basal layer whose concentration was as 12% or possibly higher, overlain
299 by a dilute flow with concentration below 1.0%. Moreover, there seems to be a steep
300 concentration gradient between the basal layer and upper dilute layer because 1) the OBS
301 recorded a dilute flow during the event, 2) the recovered sediment trap showed no signs of strong
302 abrasion as might be expected in a dense layer, and 3) parts of the flow imaged by the ADCP
303 were also dilute (< 1%).

304 4.3 The 11 minutes delay of the CT measured concentration peak

305 The discrepancy between the CT-derived sediment concentration (gradual increase until
306 the sensor was clogged at minute 12) and ADCP backscatter (rapid jump to maximum and then

307 gradually decline) is believed to have resulted from a combined effect of the two-layer structure
308 of the flow, the mooring tilt due to the drag by the very fast flow and the bedform migration (or
309 net deposition).

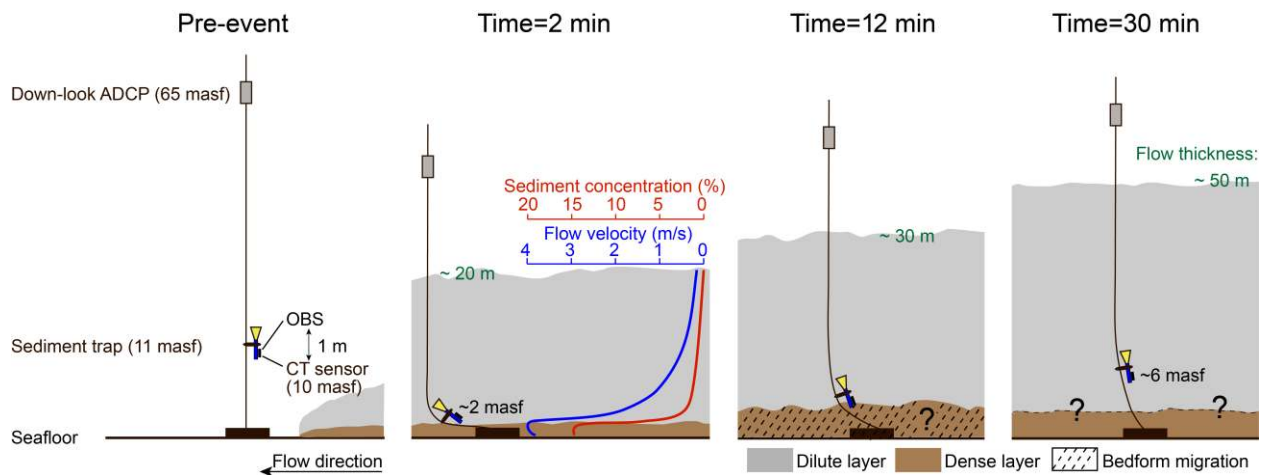
310 ADCPs measure vertical profiles of the entire water column below. The downward-
311 looking MS5 ADCP recorded the arrival of the flow with a rapid increase of backscatter
312 intensity. In contrast, the CT sensor only records parameters at the height where it is positioned.
313 Moorings of similar design are prone to tilting (Symons et al., 2017), which can move both the
314 ADCP and CT sensor toward the seafloor. We therefore have to determine how far the CT sensor
315 and ADCP were pulled down towards the seabed.



316
317 **Figure 9.** A: ADCP pitch and roll of MS5. B: Location of the highest magnitude acoustic
318 backscatter for all four beams (Beam1~Beam4), which can be used to estimate the position of the
319 seafloor (as shown in C). C: Net acoustic backscatter intensity profiles of individual beams
320 during the first 30 minutes of the flow, the plus signs denote the position of the seafloor echoes

321 Maximum echo intensity of the backscatter signal from the ADCP can be used to
322 estimate the position of the seafloor. The pre-event seabed position was used as the reference for
323 the ADCP profiles. Figure 9C shows the highest magnitude acoustic backscatter for all four

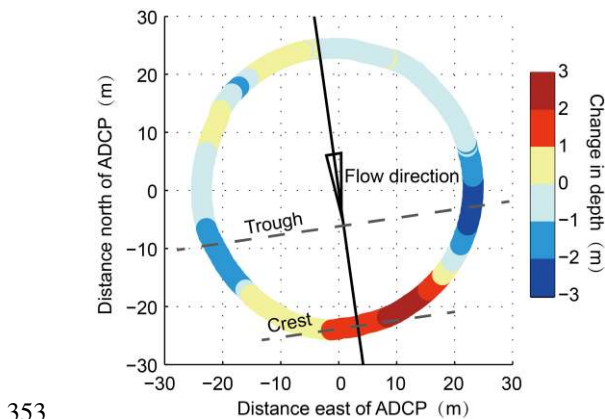
324 beams (Beam1~Beam4). However, during the first 2 minutes of the flow, the ADCP cannot
 325 penetrate the high concentrated flow and get clear seafloor echoes, which makes it impossible to
 326 estimate the seabed position. But after minute 2, the distance from the ADCP to seafloor was
 327 several meters less than its pre-event value (Figure 9B). This could be due to tilting of the
 328 mooring by the fast flow, bed aggradation, or both. The pitch and roll (Figure 9A) showed only a
 329 very slight wobble when the flow hit the mooring, and the maximum tilt angle of the ADCP was
 330 < 2 degrees, which would increase the range to the seafloor by less than ~4 cm. Hence, the
 331 ADCP itself is nearly straight when the lower part of the mooring was severely tilted by the flow.
 332 The CT sensor was thus estimated to be ~8 m lower than its initial height (10 masf), with an
 333 actual height of ~2 masf after the arrival of the flow (minute 2), and gradually rose to ~6 masf at
 334 minute 30 (Figure 9B, Figure 10). Because of the assumptions to this approach, these estimated
 335 values of sensor's height are not exact, despite the fact that the CT sensor did experience a sharp
 336 deepening at the arrival of the flow, before gradually returning to the pre-event position.



338 **Figure 10.** A conceptual diagram of mooring movement and the two-layer structure of the 15
 339 January 2016 turbidity current, inferred from instruments layout on the mooring, ADCP pitch

340 and roll, and the position of the seafloor. The blue and red lines denote the conceptual velocity
341 and concentration profiles within the flow at around 2 minutes after the arrival of the flow.

342 Considering that the mooring didn't moved during the Jan 15 turbidity current because 1)
343 the slight of ADCP sway (pitch and roll) when the flow hits the mooring (Figure 9A), indicating
344 that the mooring didn't experience a hydrodynamic drag on the upper ADCP and floats which
345 would cause the mooring to slant backwards as the anchor moved more rapidly at the base, 2) the
346 ADCP range to seafloor before and after Jan 15 event showed a same bedform (Figure S1). The
347 bathymetric difference of the ADCP beam footprint on seafloor was thus obtained by comparing
348 the distance from the ADCP to seafloor before and after the 15 January 2016 turbidity current
349 (Figure 11), which shows similar magnitudes (± 3 m) of both erosion and deposition on the circle
350 with ~ 25 m radius. It seems to show a blue 'trough' (closer to the center) and a red 'crest', both
351 perpendicular to the flow direction, suggesting the presence of a bedform downstream from the
352 mooring, roughly where the sediment trap was pulled down toward the seafloor.



354 **Figure 11.** Bathymetric difference of the ADCP beam footprint on seafloor before and after 15
355 January 2016 turbidity current.

356 Based on the above analyses and the velocity measurements by ADCP, the flow can be
357 inferred to have a two-layer structure with a fast (up to 4 m/s), thin and dense basal layer
358 overlain by a thicker more dilute and slower current. And between the two layers there was a
359 steep concentration gradient (Figure 10). Then the 11 minutes lag between CT-derived maximum
360 concentration and peak ADCP backscatter can be interpreted as follows. About 2 minutes after
361 the arrival of the turbidity current, the thickness of the dilute flow had already reached 20 m.
362 Although the flow was relatively slow at 10 m above the seafloor, the sediment trap package
363 (trap, CT and OBS) was pulled down to the faster flowing layers until the CT sensor at the
364 bottom of the package reached a region just above the dense layer. In this case, the CT sensor
365 recoded the increase in sediment concentration (Figure 5A, Figure 10). Shortly after recording
366 the peak concentration of 12% (minute 11), the CT sensor was clogged at minute 12. It appears
367 that, at this moment, the CT sensor was dipped into the dense layer or even touched the seafloor
368 because of the bedform migration. The CT sensor probably stayed clogged even after rising
369 above the dense layer when the flow began to slow down and the mooring returned upright
370 (Figure 10).

371 The dense near bed layer of the January 15 flow can thus be several meters thick (Figure
372 10), which is consistent with the conceptual model proposed by Paul et al. (2018) and Heerema
373 et al. (2020) that a fast and dense basal layer exists at the flow front, which drives the diluted
374 flow above it. Future work is now needed, but also a challenge, to figure out the actual type of
375 the basal layer, be it a high-density turbidity current (Talling et al., 2012) or special thick
376 bedload layer which is only a few grains thick in rivers (van Rijn, 1984), such as by identifying

377 the deposits form the turbidity current, or via detailed measurements of sediment concentration
378 by ADCP.

379 **5 Conclusions**

380 The 15 January 2016 turbidity current in Monterey Canyon possessed a dense basal layer
381 overlain by a thicker (~50 m) dilute flow. At the interface of these two layers, there seems to be a
382 sharp steep concentration gradient. The maximum sediment concentration in the dense basal
383 layer, measured by a novel conductivity method, was 12%. Concentrations deeper into this layer
384 could have been even higher. The temporal duration and longitudinal length of this dense basal
385 layer remains unknown.

386 The basal layer's presence is consistent with reports of movement of heavy objects at
387 high speeds (Paull et al., 2018), but concentration as high as 12% is the first ever measurement
388 inside the basal layer of field-scale turbidity currents. Understanding whether turbidity currents
389 are entirely dilute and fully turbulent or contain a dilute cloud overlying a thin dense basal layer
390 is critically important because the two types of flows behave in fundamentally different ways,
391 and present very different hazards to seabed structures. Our study also shows how super-high
392 concentrations in basal layer can be successfully measured, thereby provides the necessary
393 means to test turbidity currents models.

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