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Efficient preservation of young terrestrial organic carbon in sandy turbidity-current deposits

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ABSTRACT

Burial of terrestrial biospheric particulate organic carbon in marine sediments removes CO_2 from the atmosphere, regulating climate over geologic time scales. Rivers deliver terrestrial organic carbon to the sea, while turbidity currents transport river sediment further offshore. Previous studies have suggested that most organic carbon resides in muddy marine sediment. However, turbidity currents can carry a significant component of coarser sediment, which is commonly assumed to be organic carbon poor. Here, using data from a Canadian fjord, we show that young woody debris can be rapidly buried in sandy layers of turbidity current deposits (turbidites). These layers have organic carbon contents 10× higher than the overlying mud layer, and overall, woody debris makes up >70% of the organic carbon preserved in the deposits. Burial of woody debris in sands overlain by mud caps reduces their exposure to oxygen, increasing organic carbon burial efficiency. Sandy turbidity current channels are common in fjords and the deep sea; hence we suggest that previous global organic carbon burial budgets may have been underestimated.

INTRODUCTION

It is important to constrain the burial of terrestrial biospheric particulate organic carbon (POC) in marine sediments because it is the second-largest sink of atmospheric CO_2 after weathering of silicate minerals (Gaillardet et al., 1999), and thereby contributes to long-term regulation of climate (Berner, 1982). Rivers transfer terrestrial POC to the coast and contribute up to about half of the global organic carbon burial flux to the oceans (Galy et al., 2015). In the ocean, fine mud is key in preserving terrestrial POC because fine-grained particles can shield POC from degradation (Mayer, 1994). In contrast, the role of marine sands in global POC burial has long been overlooked (Burdige, 2007). Yet woody debris associated with sands in submarine fans is increasingly being recognized as a major terrestrial POC pool (Leithold et al., 2016; Lee et al., 2019). Submarine fans are formed by turbidity currents, which dominate sediment deposition across vast areas of the seabed (Bouma et al., 1985). Yet, the quantitative budget, age, and composition of POC within sandy turbidity-current deposits compared to that in fine sediment has not been considered.

In contrast to transport by turbidity currents, transport of POC by rivers is well studied (Galy et al., 2015). Riverine POC is a mixture of: (1) young carbon produced by photosynthesis in the biosphere (plant, wood); (2) old biospheric carbon from degraded soil organic matter; and (3) petrogenic carbon, i.e., ancient (^{14}C-free) carbon from erosion of rocks (Blair and Aller, 2012). In contrast to biospheric carbon, the burial of petrogenic carbon recycles carbon between different geologic reservoirs and does not affect long-term CO_2 levels (Galy et al., 2008). The fluxes of POC mixtures have been constrained in rivers where the POC composition is controlled by erosion rates and sediment yield (Hilton et al., 2012). However, less is known about the relative fluxes of POC types beyond the coast, in particular the effect of hydrodynamic sorting of POC by turbidity currents.

Turbidity currents form many of the largest sediment accumulations on Earth (Bouma et al., 1985). Suspended particles settle out as turbidity currents decelerate, resulting in deposits called turbidites (Bouma, 1962). Turbidites generally fine upward and are subdivided into units consisting of, from bottom to top, massive coarse sand (Bouma unit Ta), parallel-laminated sand (unit Tb), cross-laminated sand (unit Tc), parallel-laminated fine sand (unit Td), and mud (unit Te). While terrestrial POC has been identified through presently active submarine canyons (Biscara et al., 2011; Kao et al., 2014; Stetten et al., 2015), so far, no study has assessed the distribution of POC types into each unit of recent (<2 months old) turbidites. The turbidite units in which each POC type resides affect its burial depth and hence final burial efficiency. The distribution of POC mixtures in turbidites is significant, because one turbidity current can transport more sediment than the annual suspended sediment flux of the world's rivers combined (Talling et al., 2007).

For the first time, here we assess the distribution of three POC types (young biospheric, old biospheric, and petrogenic POC) buried in turbidites that resulted from a turbidity current that was directly measured in Bute Inlet, British Columbia, Canada. These new results determine the preservation potential of coarse, young, terrestrial POC in a modern sandy submarine system, where turbidites can be directly linked to one turbidity current that can be traced back to the river mouth.

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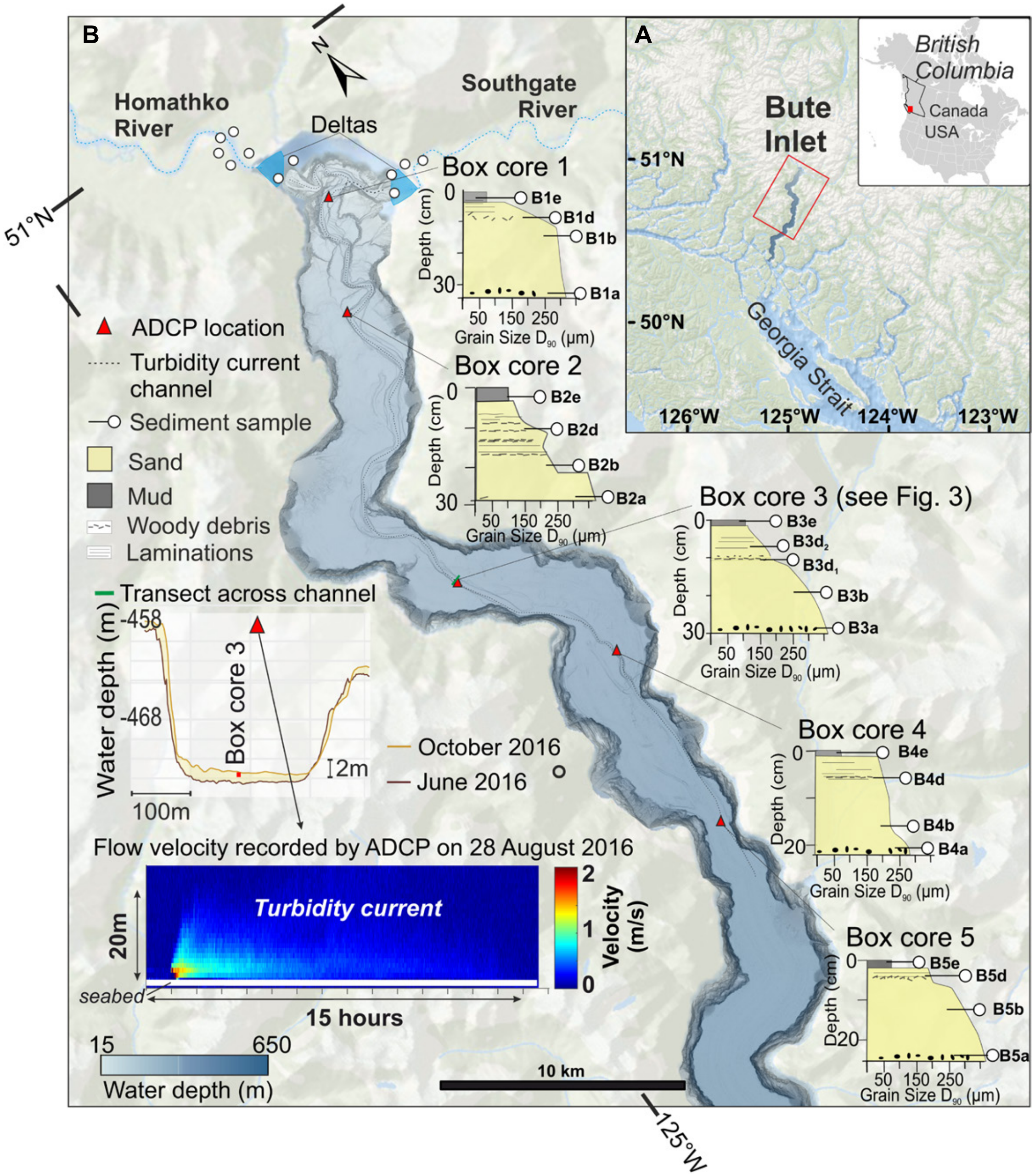

Figure 1. Study site and data. (A) Bute Inlet location (British Columbia, Canada). (B) Bute Inlet bathymetry showing the submarine channel that stretches ~50 km away from the river deltas; example of one turbidity current measured by an acoustic Doppler current profiler (ADCP) 20 m above seabed; and locations of sediment cores and samples used in this study. Box cores 1–5 were collected at 216 m, 315 m, 478 m, 555 m, and 615 m water depth, respectively. *D_{90}*—the particle diameter where 90% of the distribution has a smaller particle size.

RIVER AND TURBIDITE SAMPLING

Bute Inlet is an 80-km-long, 4-km-wide fjord in British Columbia, Canada (Fig. 1). Water depths range between 200 and 650 m. Waters are density stratified throughout the year, with low dissolved oxygen (<2 mg/L) in deep water (Pickard, 1961). At the fjord head are two deltas fed by the Homathko and Southgate Rivers, which provide 75% and 19% of the freshwater input to the fjord, respectively (Farrow et al., 1983). The Homathko River has a mean annual sediment load of 4.3×10^6 t/yr (Milliman and Syvitski, 1992). The major source of sediment for both rivers is glacial till made of granodiorite and quartz diorite from the Canadian Cordillera. River discharges are controlled by annual melt of glaciers (Prior et al., 1987). Seafloor mapping reveals a 50-km-long submarine channel maintained by turbidity currents in the freshet (Prior et al., 1987).

To characterize the composition of POC flushed into the fjord, we sampled both rivers (Fig. 1B). Samples were analyzed for grain size, total organic carbon content, and carbon stable-isotope composition ($\delta^{13}C$; Fig. 2). $\delta^{13}C$ values are commonly used to characterize organic matter provenance (discriminating marine from terrestrial sources; Gaines et al., 2009). Similar bulk analyses were performed on all samples from five box cores collected on the fjord floor. Box cores reveal 20–30-cm-thick turbidites that resulted from flows measured by five acoustic Doppler current profilers (ADCPs) deployed in the fjord from June to October 2016 (Fig. 1B).

To characterize the distribution of multiple organic carbon (OC) sources in river sediments and turbidites, we used the ramped oxidation system (RPO; Hemingway et al., 2017). This system identifies POC fractions based on thermal lability by heating each sample from 20 to 1000 °C in an oxygenated carrier gas, thus sequentially combusting POC into CO_2. The CO_2 collected between temperature intervals ("fractions") was measured for $\delta^{13}C$ and radiocarbon content (fraction modern, F_m, a measurement of the deviation of the $^{14}C/^{12}C$ ratio of a sample from "modern") on selected samples (i.e., two river samples and samples from box core 3; Fig. 3; Fig. S9 in the

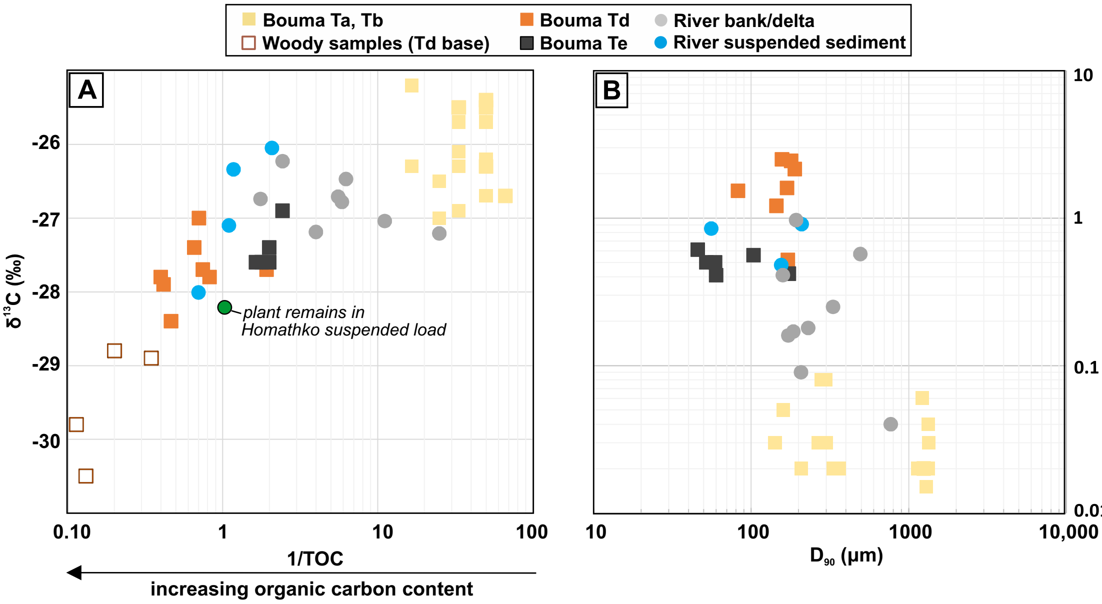

Figure 2. Bulk organic carbon and grain size. (A) Total organic carbon (TOC) content versus carbon stable isotope ratios ($\delta^{13}C$) for bulk samples (Fig. 1). (B) Sample grain size (D_{90} [particle diameter where 90% of the sample has a smaller particle size]) versus TOC content. Ta, Tb, Td, and Te refer to Bouma sequence units, from bottom to top (see text).

Supplemental Material[1]) to characterize the distribution of POC source and age. Finally, we used RPO combustion profiles to calculate the distribution of energy needed to combust OC (activation energy, E_a; Hemingway et al., 2017). E_a is used as a proxy to characterize OC bond strength, which reflects the thermal energy required to oxidize each carbon atom when exposed to a particular reaction pathway (Hemingway et al., 2019).

[1]Supplemental Material. Supplementary methods (ramped oxidation system and sedimentation rate estimates). Please visit https://doi.org/10.1130/GEOL.S.12307436 to access the supplemental material, and contact editing@geosociety.org with any questions.

ORGANIC CARBON IN RIVERS AND TURBIDITES

Bulk measurements for total carbon and total organic carbon content reveal that all samples from rivers and turbidites contain exclusively organic carbon (no carbonates; Fig. S5). We describe below the composition of POC in the rivers, the properties of the turbidity currents

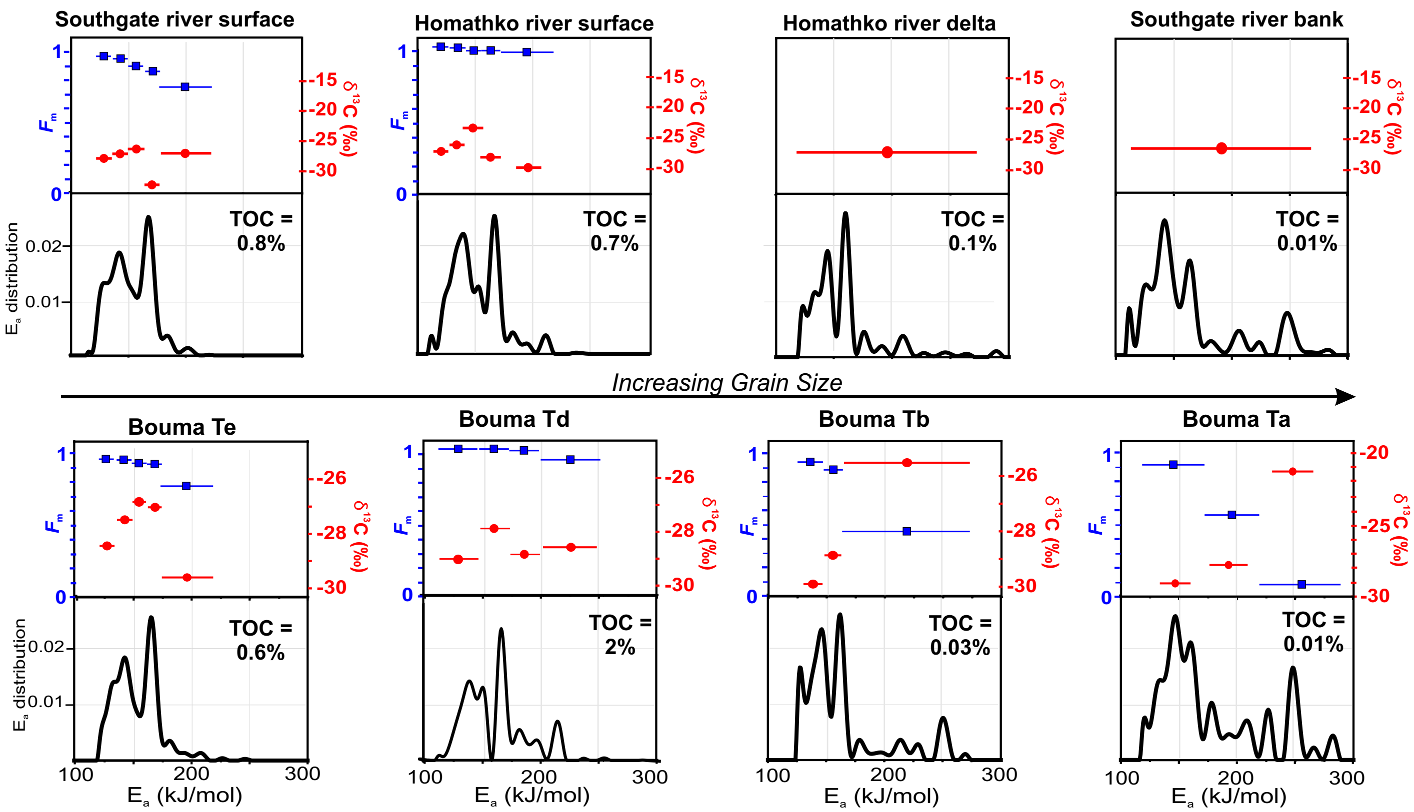

Figure 3. Separation of organic carbon mixtures by ramped oxidation for river and turbidite samples (box core 3; see Fig. 1B). Ta, Tb, Td, and Te refer to Bouma sequence units, from bottom to top (see text). Black lines show distribution of activation energy (E_a) (thermogram). Blue squares show radiocarbon ages (in fraction modern, F_m). Red dots show carbon stable isotopes ($\delta^{13}C$, in ‰). Red and blue bars represent the E_a range to which each red dot and blue square applies. TOC—total organic carbon content.

flowing down the fjord, and the composition of POC in the resulting turbidites.

Suspended samples from rivers have relatively elevated total organic carbon (TOC) values (as high as 1%), while sands sampled from banks and deltas show lower TOC values (as low as 0.01%; Fig. 2B). River banks and deltas show POC mixtures spanning a higher E_a range and becoming more complex (i.e., containing more CO_2 spikes in the RPO thermograms; Fig. 3) compared to the river suspended-sediment samples. Bulk carbon stable-isotope compositions are depleted (−28‰ to −25.5‰) for all river samples (Fig. 2A), which is in line with a terrestrial plant origin of POC (Gaines et al., 2009; Mook and Tan, 1991). Although sampling occurred only in October, the samples cover a wide range of grain size and environments (banks, suspended load, deltas).

Once the riverine POC mixtures reach the fjord head, they are carried offshore by turbidity currents, which can be as much as 20 m thick, run out for as much as 40 km, last for >15 h, and reach velocities of 2.5 m/s (Fig. 1B). Difference maps between June and October 2016 reveal that the 16 measured flows produced areas of net erosion or net deposition of >1 m thick (Fig. 1B).

We now describe the distribution of POC mixtures found in the turbidites sampled by five box cores through those areas of recent deposition. We infer that these turbidites were emplaced by the last monitored flow, which was detected by five ADCPs on 28 August 2016 (Fig. 1B). A layer of pebbles at the base of turbidites is interpreted as a gravel lag representing the first sediment deposited by the turbidity current (Mutti et al., 2003).

Turbidites in the five box cores show low $\delta^{13}C$ values (−31‰ to −25.5‰), implying negligible addition of marine organic carbon (Fig. 2A; Macdonald et al., 1991). Similarly to the sandy river samples, coarse sands at the turbidite base (units Ta and Tb) show low TOC content and span moderate to high activation energy (E_a between 150 and 290 kJ/mol; Fig. 3). ^{14}C compositions from box core 3 reveal that those coarse sands are dominated by aged carbon (F_m = 0.65 and 0.73 in units Ta and Tb, respectively). We note that Tc unit was not observed in the box cores. The turbidite fine sands (unit Td) show a TOC enrichment (TOC = 2%–5%) compared to their riverine counterpart (TOC = 0.5%–1%). This enrichment is due to the presence of wood that is visible to the naked eye. Wood-rich samples show low $\delta^{13}C$ values (−32‰ to −28‰), have modern radiocarbon signatures (F_m > 1, based on box core 3), and comprise POC fractions that span low to moderate activation energy (E_a < 225 kJ/mol; Fig. 3; Fig. S8). Finally, the turbidite mud cap (unit Te) has a similar composition to the muddy samples collected in the river suspended sediments (TOC = 0.5%–0.8%, $\delta^{13}C$ = −27.5‰ to −26.5‰, E_a < 210 kJ/mol; Fig. 3). ^{14}C activities reveal that POC found in this mud cap is older (F_m = 0.92) compared to the underlying fine sands.

ABUNDANCE OF WOODY DEBRIS IN TURBIDITES

We found three types of POC, which are defined based on $\delta^{13}C$, E_a, and ^{14}C from box core 3 (Fig. 4; Fig. S7). We note that the RPO method does not result in a perfect separation of POC mixtures into highly resolved peaks representing pure carbon types, hence the following three types correspond to the major component included in each mixture. First, young biospheric terrestrial POC dominates (≥90%) Bouma unit Td and corresponds to non-degraded woody debris. Second, old biospheric terrestrial POC is found in all Bouma intervals but in different proportions. This second type shows F_m values <1, suggesting that it results from aging in soils. Third, petrogenic POC is found in significant amounts in coarse intervals Ta and Tb.

We extrapolated the proportions of those three POC types to each turbidite division and TOC content of the studied turbidites (Fig. 1). We found that a turbidite sequence captures (Fig. 4C): (1) ~75% of non-degraded woody debris mostly associated with fine sand (unit Td); (2) ~24% of aged and altered POC from soil, dominantly found in the mud cap (unit Te); and (3) ~1% of petrogenic POC, mainly associated with sand (units Ta, Tb). Hydrodynamic sorting by turbidity currents thus concentrates woody debris in the uppermost sandy layer (base of Td). Density fractionation of organics by turbidity currents has been inferred to concentrate light woody particles settling out as suspended fine sand due to their size and shape (McArthur et al., 2016). The OC-rich Td layer is rapidly buried under 1–3-cm-thick mud units (Te). This is important because the young POC associated with woody debris is then protected from oxidation by the mud cap, which prevents oxygen penetration (Hartnett et al., 1998), even in oxygen-rich waters that could characterize other fjords. This protection depends on the thickness of overlying mud (Te), which can range from a few centimeters, as in Bute Inlet, to tens of meters in other locations (Rothwell et al., 1998). Our results contrast with the general idea that most of the organic matter preserved in marine sediments is associated with mud, whose inorganic matrix would physically protect organic matter from oxidation (Mayer, 1994). Physical protection is likely to occur in the mud cap described at the top of the studied turbidites, and is supported by ^{14}C depletion (F_m = 0.92) of the mineral-bound organic matter present in the mud cap.

WIDER IMPLICATIONS

Although our findings relate to the deposit of one turbidity current in a sandy channel likely to be reworked by successive flows (Conway et al., 2012), they provide insight into the hydrodynamic sorting of POC by

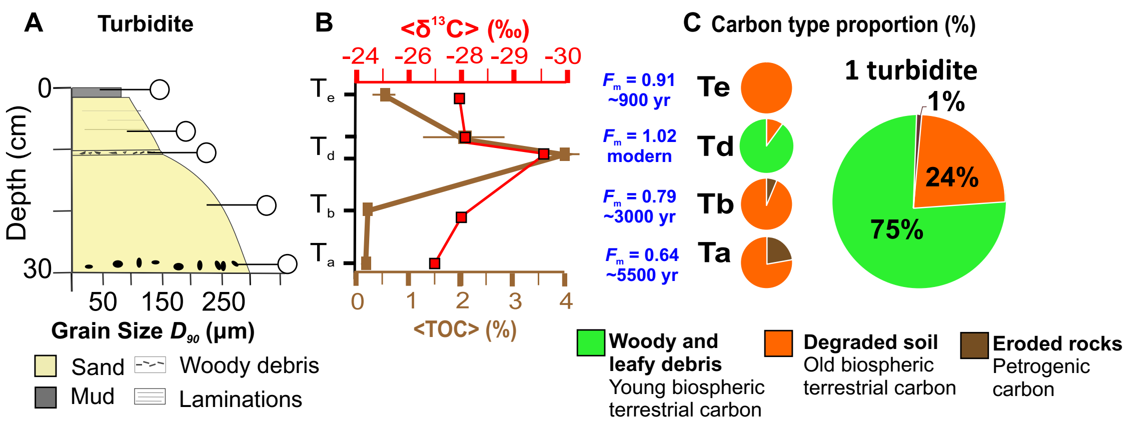

Figure 4. Summary of organic carbon composition in a turbidite sequence. (A) Turbidite with sample locations. D_{90}—the particle diameter where 90% of the distribution has a smaller particle size. (B) Total organic carbon content (TOC; brown) and carbon stable (red) and radiocarbon (blue) isotopes averaged between measurements made on all bulk samples shown in A. Brown bars represents the standard deviations between TOC measurements made on all samples shown in A. F_m is a measurement of the deviation of the $^{14}C/^{12}C$ ratio of a sample from "modern". Ages in years given below F_m values corresponds to years before present. Ta, Tb, Td, and Te refer to Bouma sequence units, from bottom to top (see text). (C) Carbon type proportions calculated based on unit thickness, TOC, and separation by ramped oxidation (Fig. 3; Fig. S7 [see footnote 1]).

sandy turbidity currents. Constraining such processes in fjords (e.g., Bute Inlet) is key, because fjords are estimated to account for 11% of organic carbon burial in marine sediments globally (Smith et al., 2015). Here, we suggest that this POC budget may have been underestimated, because the global study did not consider the sandy parts of the fjord floors nor the role of turbidity currents in burying particles across fjords. Furthermore, our results show the importance of river inputs (transported further by turbidity currents) compared to mass-wasting events previously suggested to control OC transport in fjords (Smith et al., 2015). The sandy submarine channel in Bute Inlet has a high sedimentation rate (>40 mm/yr; Table S1 in the Supplemental Material) but covers only 16% of the total fjord area. While this areal proportion seems small, the channel preserves large quantities of terrestrial young organic matter (as much as 5% TOC) in rapidly deposited (a few hours) thin layers of sand. These young OC-rich sands are buried within a turbidite that has an overall weighted mean of 0.7% TOC (Fig. S7). The rest of the fjord area (84%) is made of mud, which may include older and 10× less-abundant TOC (0.5%; Table S1), with a sedimentation rate of 10 mm/yr (Table S1). We thus estimate that the sandy channel buries similar amounts of organic carbon as the mud in the remaining fjord area (Table S1). Such estimates remain to be tested for other turbidites in Bute Inlet and for other fjords that may be characterized by different oxygen levels, water stratification, and seafloor morphology.

Beyond fjords, our case study is likely to be relevant for a large number of river-connected submarine systems, especially where mountainous topography drives erosion of biospheric POC and its delivery to the ocean (Galy et al., 2015). Current estimates of carbon fluxes in the ocean (Burdige, 2007; Blair and Aller, 2012) posit that sandy fractions are POC free. Yet a recent study (Lee et al., 2019) has found that abundant wood has been buried in sands in the Bengal Fan (Bay of Bengal, Indian Ocean) for the last 19 m.y. Other studies have described organic-rich layers in sandy deep-sea turbidites (Saller et al., 2006; Zavala et al., 2012; Sparkes et al., 2015; Leithold et al., 2016), in some cases even within sands of units Ta and Tb, depending on the density and size of organic debris (McArthur et al., 2016; Schnyder et al., 2017). There is thus a need to update global carbon fluxes (Burdige, 2007) by quantifying the abundance of coarse POC (woody debris) relative to fine POC. The RPO method used here provides a method to quantify this relative abundance. Rigorous estimates for the abundance of young coarse POC are key because its burial in marine sediment is a sink of atmospheric CO_2 over geologic time scales (Berner, 1982).

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